DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

ETL 1100-2-1

CECW-CE
CECW-P

Technical Letter
No. 1100-2-1

30 June 2014

EXPIRATION DATE (30 March 2019)
Global Changes
PROCEDURES TO EVALUATE SEA LEVEL CHANGE:
IMPACTS, RESPONSES, AND ADAPTATION

1. Purpose. This technical letter provides guidance for understanding the direct and indirect physical and ecological effects of projected future sea level change on USACE projects and systems of projects and considerations for adapting to those effects.

2. Applicability. This Engineer Technical Letter (ETL) applies to all USACE elements having responsibility for Civil Works.

3. Distribution Statement. Approved for public release; distribution is unlimited.

4. References. References are listed in Appendix A.

5. Discussion. USACE missions, operations, programs, and projects must be resilient to coastal climate change effects, beginning with sea level change (SLC). This ETL addresses adaptation to changing sea levels for every USACE coastal activity as far inland as the extent of estimated tidal influence. It includes a broadly applicable method encompassing four USACE mission areas and also provides insight into use for multipurpose projects. The information presented here is applicable to the full range of USACE projects and systems, from simple to complex, from small to very large, and over the full life cycle. This ETL integrates the recommended planning and engineering to understand and adapt to impacts of projected SLC through a hierarchy of decisions and review points that identify the level of analysis required as a function of project type, planning horizon, and potential consequences.

FOR THE COMMANDER:

7 Appendices
See Table of Contents

JAMES C. DALTON, P.E., SES
Chief, Engineering and Construction Division
Directorate of Civil Works

THIS PAGE INTENTIONALLY LEFT BLANK

Technical Letter
No. 1100-2-1 30 June 2014

EXPIRES 30 March 2019
Global Changes
PROCEDURES TO EVALUATE SEA LEVEL CHANGE:
IMPACTS, RESPONSES, AND ADAPTATION

TABLE OF CONTENTS

Subject	Paragraph	Page
List of Acronyms		iii
Chapter 1		
Introduction		
Purpose	1-1	1-1
Key Concepts	1-2	1-1
Chapter 2		
Understanding and Estimating Sea Level Change		
Background	2-1	2-1
Changes in Global Mean Sea Level	2-2	2-1
Local MSL Factors	2-3	2-2
Determination of Historical Trends in Local MSL	2-4	2-3
Estimating Future Change in Local MSL	2-5	2-4
Magnitude of Changes and Frequency of Events	2-6	2-6
Overall Process- or Performance-Driven Impacts and Other Factors	2-7	2-7
Chapter 3		
Effect of Sea Level Change on USACE Decision-Making Processes		
Sea Level Change, Uncertainty, and Risk in Decision-Making	3-1	3-1
Changes in Decision-Making Necessary to Consider SLC	3-2	3-3
Applying a Tiered Planning and Analysis Approach to the Incorporation of SLC	3-3	3-12
Chapter 4		
Layout of Mission Area / Project Type Appendices		
Appendices	4-1	4-1
Layout of Appendices	4-2	4-1
Principles and Processes	4-3	4-1
Chapter 5		
Conclusions		
Long Service Life	5-1	5-1
Future Conditions	5-2	5-1
Level of Effort	5-3	5-1

Framework 5-4 5-1
Consequences 5-5 5-2
Staged Decision-Making 5-6 5-2

Appendices

Appendix A. References
Appendix B. Data Requirements and Development of Sea Level Change Curves
Appendix C. Navigation Projects
Appendix D. Coastal Storm Damage Reduction Projects
Appendix E. Flood Damage Reduction Projects
Appendix F. Ecosystem Projects
Appendix G. Example Project: Incorporating Sea Level Change into the Analysis and Design of a Coastal Storm Damage Reduction Project
Glossary

List of Acronyms

AEP	Annual Exceedance Probability
CCSP	Climate Change Science Program
CECW	Corps of Engineers Civil Works
CO-OPS	NOAA Center for Operational Oceanographic Products and Services
CORS	Continuously Operating Reference Stations
CSDR	Coastal Storm Damage Reduction
CVI	Coastal Vulnerability Index
CW	Civil Works
ENSO	El Niño-Southern Oscillation
EC	Engineer Circular
EM	Engineer Manual
ER	Engineer Regulation
ETL	Engineer Technical Letter
FDR	Flood Damage Reduction
GMSL	Global Mean Sea Level
HSDR	Hurricane Storm Damage Reduction
IPCC	Intergovernmental Panel on Climate Change
LRSL	Local Relative Sea Level
MSL	Mean Sea Level
NAO	North Atlantic Oscillation
NAVD88	North American Vertical Datum of 1988
NCA	National Climate Assessment
NED	National Economic Development

NEPA	National Environmental Policy Act
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
NOAA-NOS	NOAA National Oceanographic Service
NRC	National Research Council
NTDE	National Tidal Datum Epoch
PDO	Pacific Decadal Oscillation
PDT	Product Development Team
P & G	Planning Guidance Notebook
P & O	Problem and Opportunity
PSMSL	Permanent Service for Mean Sea Level
SLC	Sea Level Change
SRES	Special Report on Emissions Scenarios
UKCIP	United Kingdom Climate Impacts Program
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey

CHAPTER 1

Introduction

1.1 Purpose. USACE missions, operations, programs, and projects must be resilient to coastal climate change effects, beginning with sea level change (SLC). This Engineer Technical Letter (ETL) addresses adaptation to changing sea levels. It includes a broadly applicable method encompassing four USACE mission areas and also provides insight into use for multipurpose projects. The information presented here is applicable to the full range of USACE projects and systems, from simple to complex, from small to very large, and over the full life cycle. Adequately incorporating potential SLC into the planning, engineering, and operations process should improve the resilience[1] of project systems and maximize performance over time.

a. SMART Planning. This ETL integrates the recommended planning and engineering to understand and adapt to impacts of projected SLC through a hierarchy of decisions and review points that identify the level of analysis required as a function of project type, planning horizon, and potential consequences. This approach supports SMART (S: Specific, M: Measurable, A: Attainable, R: Risk Informed, and T: Timely) planning. SMART planning is risk-informed, decision-focused planning transparently performed with the full vertical USACE team, partners, and stakeholders. Key decision matrix concepts address sustainability, resilience, adaptive and anticipatory planning, and system and cumulative effects to help the practitioner determine the sensitivity of a particular project or system to SLC, while at the same time emphasizing robust project or system performance that is both flexible and adaptable to a range of future conditions. Information in the appendices supports the development of risk registers used to streamline the planning process.

b. Longer Planning Horizon. The planning, design, and construction of a large water resources infrastructure project can take decades. Though initially justified over a 50-year economic period of analysis, USACE projects can remain in service much longer. The climate for which the project was designed can change over the full lifetime of a project to the extent that stability, maintenance, and operation may be impacted, possibly with serious consequences, but also potentially with beneficial consequences. Given these factors, the project planning horizon (not to be confused with the economic period of analysis) should be 100 years, consistent with ER 1110-2-8159. These concepts are further discussed in Section 1-2 below.

1-2. Key Concepts. The key issues that climate change poses for USACE are in many ways common to all infrastructure agencies and organizations. Therefore, this guidance recognizes the essential role of collaboration with other Federal agencies and our state and community partners, and the development of outputs necessary to meet external review, stakeholder, and USACE expectations. Important background and framework information can be found in the

[1] Resilience has been defined by the IPCC (2007) as: "…the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change." USACE (2013) describes resilience as "the ability to anticipate, prepare for, respond to, and adapt to changing conditions and to withstand and recover rapidly from disruptions with minimal damage."

National Climate Assessment (http://www.globalchange.gov/what-we-do/assessment) and its underlying technical reports (Parris et al. 2012, Burkett and Davidson 2013). General concepts relevant to the approach of this ETL are provided below (for other terms and definitions, please see the Glossary).

a. Stationarity and Nonstationarity. Stationarity assumes that hydrologic or coastal processes "vary within an unchanging envelope of natural variability," so that the past accurately represents the future (Milly et al. 2008). The assumption of stationarity has facilitated management of water supplies, demands, and risks by planners and engineers (Webb and White 2010). Moser et al. (1990) suggested that "…thus far the evaluation and selection of Federal coastal protection investments has assumed stationarity of climate and mean sea level." However, hydrologic engineers have long recognized and accounted for nonstationary processes (Chow 1964, Hirsch 2011) using a variety of methods (e.g., Kiang et al. 2011). The dynamic nature of climate change as it affects coastal and hydrologic processes requires us to fully explore whether plans, designs, operations, and maintenance based on the principle of stationarity are still valid (e.g., Milly et al. 2008). USACE SLC adaptation addresses the potential for nonstationary conditions through the use of a multiple scenario approach, which includes a range of future potential sea level change rates.

b. Responses or Management Approaches. Uncertainty about the future can be identified not just with regard to sea level change or wider climate change processes but also with regard to morphological, ecological, and socioeconomic change. An overall adaptive management approach provides a process for dealing with all of these uncertainties and involves developing plans for the future that envisage a range of futures, incorporate ongoing monitoring, and permit transitions from one engineering approach to another. The approach gives freedom for different decision pathways to be followed depending on the magnitude and rate of sea level and other changes. This flexible and responsive adaptive management philosophy may require the consideration of modifications to how we think about project life, maintenance actions, ongoing decision-making, and funding methods, including increasing use of nonstructural measures for reducing the consequence element of risk.

c. Framework for Robust Analysis. Due to the uncertainty and variability of future SLC, social, economic, and ecological changes, and their associated interactions, USACE employs a robust framework for project performance that is flexible and adaptable to multiple future scenarios. Emphasis should be placed on both how the project operates within a larger system and how project decisions made today can influence future system responses to perturbations through adjustments, feedbacks, or cascading impacts. Robustness here is considered to be the ability of a project or system of projects, or their adaptation strategies, to continue to perform satisfactorily under changing conditions and over a wide range of conditions (Moser et al. 2008).

d. Robustness and Resilience. Robustness and resilience are related but contrasting concepts. Both describe how a decision or system responds to perturbations relative to functional expectations and performance goals. Robust systems, designs, and projects are sturdy. They function and perform within specifications regardless of external stressors. External stressors are absorbed or deflected without internal change. Resilient systems, designs, and projects adapt, adjust, and change in response to internal and external stressors. Resilient

systems, designs, and projects have response gradients and thresholds or tipping points. Their performance may shift to alternate states or regimes.

e. Scaled Analysis and Decision-Making. Given the potentially large uncertainties in future climate, USACE should be proactive in preparing for the maintenance and performance of a very wide range of projects. Economic and other constraints require that the level of effort undertaken to assess climate impacts and to plan and engineer adaptation measures should be commensurate with the scale of the decision being made and its potential consequences. This decision scaling helps to make sense of the issues climate change poses and helps to characterize the appropriate level of effort for analysis and design for the large array of USACE projects (Brown et al. 2011).

f. Screening Tools. A key component of scaled decision-making processes is the effective use of early screening tools. A screening tool is a mechanism to sort out the most applicable and appropriate planning and design steps given the potential consequences. A risk- informed decision matrix format can help direct the planning and design approach and the level of analysis required. A risk matrix is used during risk assessment to define the various levels of risk as the product of the probability and consequence categories. This is a simple mechanism to increase the visibility of risks and assist management decision-making (Willows and Connell 2003, Moser et al. 2008).

g. Epochs of Analysis. The period of analysis for USACE projects can range from 20 to 100 years, depending on the type of project. However, USACE guidance states that "…appropriate consideration should be given to environmental factors that may extend beyond the period of analysis" (ER 1105-2-100). Different planning horizons should be considered throughout a project evaluation to help identify the degree of urgency of future actions as well as the expected resilience or robustness of selected alternatives. At a minimum, 20-, 50-, and 100-year epochs of analysis are recommended. The period of economic analysis for USACE projects has generally been limited to 50 years because economic forecasts beyond that time frame were not considered reliable. However, the potential impacts of SLC over a 100-year period can be used in the formulation of alternatives and the comparison of their resiliency. This ETL does not recommend using the same level of analysis for all three epochs, but it does strongly recommend that some predictions of how the project or system might perform, as well as its ability to adapt beyond the typical 50-year economic analysis period, be considered in the decision-making.

h. Adaptation Horizon. Infrastructure often stays in place well beyond the economic period of analysis. With continued operations, maintenance, repair, replacement, and rehabilitation (OMRR&R), projects may be in place indefinitely and therefore may experience greater impacts of climate change than expected during the initial design (see Figures 1 and 3). Many of the SLC projection scenarios include an increased rate of sea level rise further into the future (e.g., Bindoff et al. 2007, Nicholls et al. 2007, Parris et al. 2012). Using a longer adaptation horizon enables us to improve robustness and resilience compared to planning for shorter time frames. The adaptation horizon addresses the time of service of the project that can extend past its original design life.

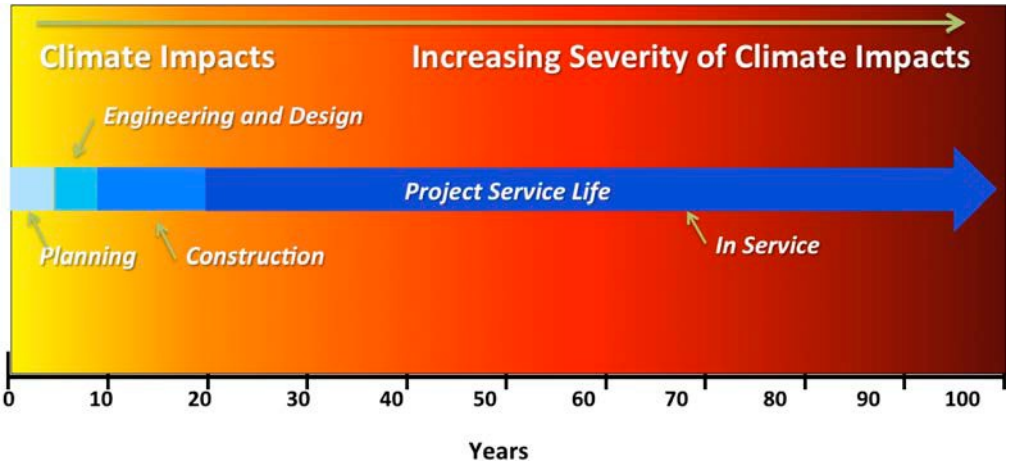


Figure 1. Water resources infrastructure time frames vs. climate impacts.
(After Savonis 2011.)

i. Scenario Analysis. Because of the uncertainty about future changes in climate, it is necessary to examine a range of scenarios that reflect complete, coherent, and internally consistent descriptions of plausible future states. This allows an examination of cases for exposure to extreme events and performance for the project alternatives. As Moser et al. (2008) pointed out, "Rather than focus on a single without project condition as the base, scenario planning acknowledges uncertainty by considering an array of futures based on different potential values of key uncertainties. In this context, plans are formulated that both address each of the possible futures but also are robust in achieving the desired objectives regardless of the future." An example could be the assessment of several potential SLC values in conjunction with different infrastructure development rates in the project area. This is not the traditional singular "most probable future condition" approach; comparison and selection of alternatives in a multi-scenario setting is an approach to integrating nonstationarity and SLC-related uncertainty into decision-making and represents a new challenge for planning USACE Civil Works (CW) projects.

j. Cumulative and System Effects. The USACE infrastructure operates in a system, even though projects may have originally been designed in isolation. Cumulative and system-scale effects can be important, as well as cascading impacts and surprise combinations. Any of these effects can load a project to a higher degree than had been expected during its design phase. The risk and uncertainties associated with cascade failures are one reason the National Research Council and others insist that coordinating systems and applying the precautionary principle to management of known and suspected intersystem linkages and interfaces is critical (NRC 2009). Project loading refers to the forces that can destabilize a project. Understanding the relationships between critical systems and infrastructure may point to novel solutions or combinations of existing solutions that improve resilience. While a project may either remain stable or change but perform in an acceptable manner, if the system that it operates within fails to function, if other larger processes are impacted (such as storm water drainage or power supply), or if benefits assumed are not realized, then the project itself may be either not viable or not sustainable (Moser et al. 2008). Ecological, economic, social, cultural, and infrastructure systems have properties that require special attention.

k. Tipping Points and Thresholds. Identifying thresholds beyond which performance is adversely affected is an important way to understand current and future vulnerability. IPCC (2007) defines a threshold as the level of magnitude of a system process at which sudden or rapid change occurs. Thresholds can take a wide range of forms, including physical, economic, social, and environmental thresholds. A tipping point is a point or level at which new properties emerge in an ecological, economic, or other system, invalidating predictions based on mathematical relationships that apply at lower levels. It is especially important to note these tipping points, because the performance of the system can deteriorate rapidly once these thresholds are exceeded. Understanding thresholds can inform the urgency of action, the range of feasible actions, any necessary transition points from one type of measure to another, and the selection of extreme conditions for design, as well as larger system effects (Environment Agency 2009).

l. Stability and Performance Functions. Projects and systems of projects can be assessed in terms of both their stability against the design loading and their ability to perform their function under these loadings. Stability and performance may have different sensitivities to SLC. In addition, project performance may shift dramatically if structural failure occurs. An example of a stability function within the flood damage risk reduction mission area would be the ability for a floodwall or levee to retain its cross section without failing as it is exposed to higher water levels and greater forces. In contrast, the floodwall may remain stable (i.e., not fail catastrophically), but if it is overtopped excessively, it may not perform the function that it was designed for, and the benefits assumed for its construction may no longer be provided as intended. Design loading for a given project will vary with project type. This term refers to the forces (or for ecosystem projects, stressors) that the project was designed to withstand. For navigation and coastal storm damage reduction structures, design loading is typically a combination of wave height and water level. The design loading for flood damage reduction structures depends primarily on extreme water level. Ecosystem projects are more likely to be defined by stressors such as depth of inundation, sediment and nutrient availability, and salinity.

m. Consequences. Consequences are the end result or effect caused by some event or action, and they may be beneficial, neutral, or detrimental. Consequences may be expressed descriptively, categorically (e.g., high, medium, low), or quantitatively (e.g., monetary value, number of people affected). Developing a good understanding of consequences is important in scaled decision-making. Managing consequences is a key part of good flood risk management and includes building elevation, flood proofing, land use planning, victim relief, and insurance.

THIS PAGE INTENTIONALLY LEFT BLANK

CHAPTER 2

Understanding and Estimating Sea Level Change

2-1. Background. USACE climate change adaptation guidance will be periodically reviewed and revised as new information becomes available. This chapter presents key information needed to understand SLC: nonstationarity and changes in global mean sea level, which in turn lead to changes in relative local sea level. Appendix B contains more detailed information on SLC to provide scientific context drawing from ER 1100-2-8162, NOAA (2010b) and other publications (e.g., Church and White 2011, NRC 2012, Parris et al. 2012).

2-2. Changes in Global Mean Sea Level.

a. Understanding Global Mean Sea Level. USACE water resources management projects are planned, designed, constructed, operated, and maintained locally or regionally. At any location, changes in local relative sea level (LRSL) reflect the integrated effects of global mean sea level (GMSL) change plus local or regional changes of geologic, oceanographic, or atmospheric origin. Atmospheric origin refers to the effects of the climate oscillations such as the El Niño-Southern Oscillation (ENSO) and North Atlantic Oscillation (NAO), which in turn impact coastal SLC at decadal time scales. It is important to understand the processes resulting in changes to GMSL. Appendix B contains detailed information on changes in GMSL. Recent climate research has documented observed global warming during the 20th century and has predicted either continued or accelerated global warming for the 21st century and possibly beyond (Bindoff et al. 2007). One impact of continued or accelerated climate warming is thus continued or accelerated rise of GMSL due to continued thermal expansion of ocean waters and increased volume due to the melting of Greenland and Antarctic ice masses (Bindoff et al. 2007).

b. Recent Research. Recent research has addressed potential ranges of GMSL rise by year 2100 (NRC 1987, 2012, Rahmstorf 2007, Horton et al. 2008, Pfeffer et al. 2008, Vermeer and Rahmstorf 2009, Jevrejeva et al. 2010, Katsman et al. 2011), as shown in Figure 2. The caption "USACE 2013" represents the guidance in this ETL and ER 1100-2-8162. The most recent NRC report (2012) projects an upper bound of approximately 1.4 m, which is very close to the upper bound of 1.5 m used in this guidance. (See Appendix B for additional background.) The 2012 report by NOAA (Parris et al. 2012) states that "…we have very high confidence (>9 in 10 chance) that global mean sea level will rise at least 0.2 meters (8 inches) and no more than 2.0 meters (6.6 feet) by 2100." A credible upper bound for 21st century GMSL is about 2 m. There are other research papers that suggest the upper bound may be larger than 2.0 m (see Grinsted et al. 2010). However, the consensus of reports such as Bindoff et al. (2007) and Parris et al. (2012) is that exceeding 2.0 m by 2100 is not likely. Additional discussion is provided in Appendix B. As shown in Figure 2, IPCC (2001, 2007, 2013) gives a range of sea level rise, but at the high end there is an unknown additional potential contribution from major ice sheets, which is not shown for these IPCC ranges. The other estimates shown in Figure 2 do not have this limitation.

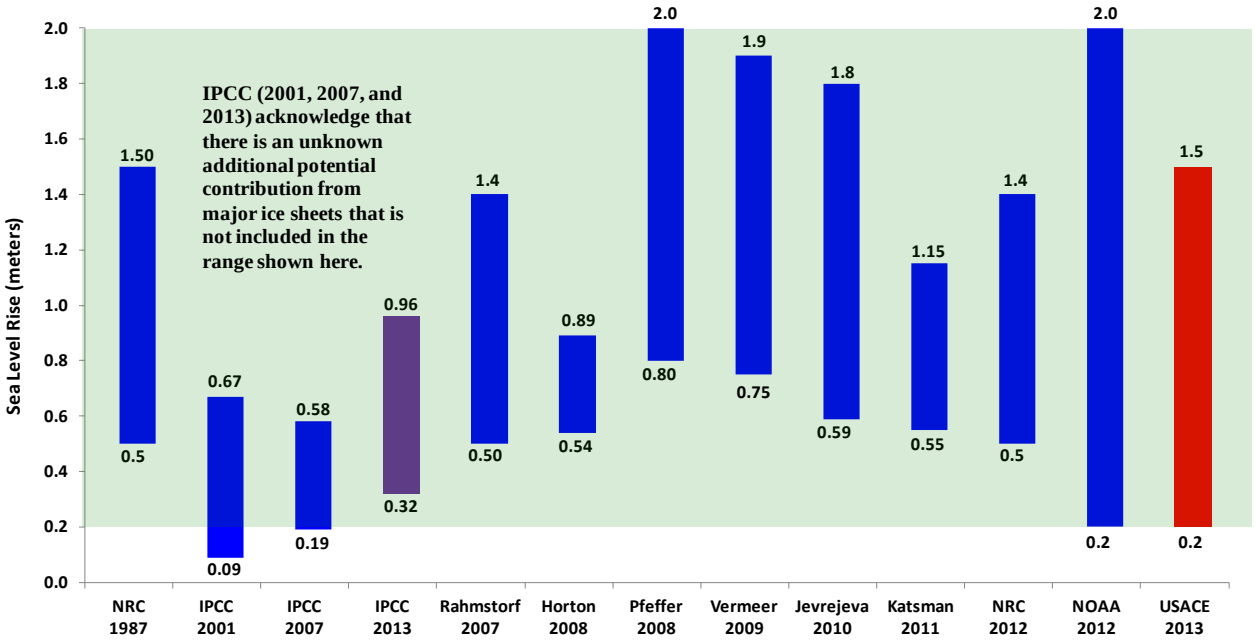


Figure 2. Comparison of maximum and minimum estimates of global sea level rise by 2100.

2-3. Local MSL Factors.

a. For USACE projects, the sea level changes that are of interest are the local or regional changes that impact project performance. Local mean sea level (LMSL) reflects relative mean sea level variations due to a combination of regional vertical land motion, regional oceanographic change, and global mean sea level change. In practice, LMSL can be measured using tide gauge data, repeat land leveling or GPS survey techniques, and InSAR remote sensing. Local relative sea level (LRSL) change can cause a number of impacts in coastal and estuarine zones, including changes in shore erosion or accretion, inundation or exposure of low-lying coastal areas, changes in storm and flood damages, shifts in the extent and distribution of wetlands and other coastal habitats, changes to groundwater levels, and alterations to salinity intrusion into estuaries and groundwater systems (e.g., Nicholls et al. 2007, CCSP 2009, Parris et al. 2012).

b. Appendix B contains a thorough discussion of geologic factors, which are a primary component of LRSL, that can impact project performance. Fortunately, in many locations, direct estimates of local vertical land uplift or subsidence can be obtained from co-located tide gauges and Continuously Operating Reference Stations (CORS). The National Geodetic Survey (NGS), an office of NOAA's National Ocean Service, manages a network of Continuously Operating Reference Stations (CORS) that provide Global Navigation Satellite System (GNSS) data consisting of carrier phase and code range measurements in support of three-dimensional positioning, meteorology, space weather, and geophysical applications. CORS enhanced post-processed coordinates approach a few centimeters relative to the National Spatial Reference System, both horizontally and vertically. As of November 2011, the CORS network contained over 1,800 stations, contributed by over 200 organizations, and the network continues to expand.

Vertical land movement can be caused by many factors, such as regional tectonic movement, regional vertical land subsidence or uplift, compaction of sedimentary strata, crustal rebound in formerly glaciated areas, and subsidence due to local withdrawal of subsurface fluids (water or hydrocarbons). Appendix B also discusses atmospheric factors that can affect local or regional water levels. Decadal-scale phenomena include the Pacific Decadal Oscillation (PDO), El Niño–Southern Oscillation (ENSO), and the North Atlantic Oscillation (NAO), among others. [See Bindoff et al. (2007) or Parris et al. (2012) for a more complete discussion.] Regional mean sea level change is most easily seen in satellite altimeter trend maps (Parris et al. 2012).

c. Decadal and seasonal water level variation should be considered in addition to SLC; it is discussed in detail in Appendix B. Although the effects of episodic storm events are important to consider throughout the project life cycle, the incorporation of the influence of tropical or extratropical storms on the application of sea level trends is outside the scope of this document.

2-4. Determination of Historical Trends in Local MSL.

a. Historical and Future Trends. The planning, management, engineering design, construction, operation, and maintenance of USACE water resource projects in and adjacent to the coastal zone must consider the potential that future accelerated rise in GMSL will affect the local MSL trend. At the same time, USACE project planners and engineers must be aware of the historical trend in local MSL, because it provides a useful minimum baseline for projecting future change in local MSL. Awareness of the historical trend of local MSL also can contribute to an assessment of the impacts that SLC may have had on regional coastal resources and problems in the past, although these impacts may be difficult to determine. The length of time that the historical local trends in MSL can be validly projected into the future depends on at least the following factors:

(1) Confidence in the present trend,

(2) Future variability in the local rate of change,

(3) Future variability and changes in trends of global mean sea level, and

(4) Future changes due to changes in rates of vertical land motion and ocean circulation.

b. Use of Tide Gauge Records. Historical trends in local MSL are best determined from tide gauge records. ER 1110-2-8162 identifies the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) and the Permanent Service for Mean Sea Level (PSMSL), which is a component of the U.K. Natural Environment Research Council's National Oceanographic Centre, as authoritative sources of tide gauge data inside and outside the U.S., respectively (see http://www.co-ops.nos.noaa.gov/index.html and http://www.psmsl.org/). Appendix B contains a detailed discussion of the use of tide gauge data in estimating historical trends.

c. Length of Tide Gauge Records. The length of the tide gauge record impacts the robustness of the estimated historical relative mean sea level change. Interannual, decadal, and multi-decadal variations in sea level are sufficiently large that misleading or erroneous sea level

trends can be derived from periods of record that are too short (Douglas 2001, Zervas 2009). For example, Breaker and Ruzmaikin (2013) observed that decadal-scale variability can induce scatter into calculated acceleration rates for periods that are shorter than about 40 years. *The Manual on Sea Level Measurement and Interpretation* (IOC 1985, 2012) suggests that a tidal record should be of at least two-tidal-epoch duration (about 40 years) before being used to estimate a local MSL trend. Time series of 50–60 years are preferred in order to have reasonable confidence intervals for determining trends (Douglas 2001). Using trends in relative mean sea level from records shorter than 40 years is not advisable. If estimates based on shorter terms are the only option, then the local trends must be viewed in a regional context, considering trends from simultaneous time periods from nearby stations to ensure regional correlation and minimize anomalous estimates. The nearby stations should have records that are long enough (greater than 40 years) to determine reasonable trends, which can then be compared to the shorter, local sea level records. Experts at NOAA-NOS should be able to assist when periods of record are short or records are otherwise ambiguous.

d. Standard Error of Estimate. For project planning and design supporting the entire project life cycle, the actual standard error of the estimate should be calculated for each tide gauge data trend analysis, and the estimates should not be used as the sole supporting data.

(1) For many locations along the U.S. Atlantic and Gulf of Mexico coastlines, tide station data are likely to have adequate spatial density and record duration to permit extrapolations between stations with an adequate degree of confidence.

(2) Recognized exceptions are the coastlines between Mobile, Alabama, and Grand Isle, Louisiana, and in Pamlico/Albemarle Sounds, North Carolina, which contain no acceptable long-term tide gauge records.

(3) Coastal Louisiana is subject to the highest natural rates of subsidence in the nation. Where a tide gauge is close to a project but has a short historical data duration, and another tide gauge is farther away but has a longer historical data duration, a tidal hydrodynamics expert (e.g., from NOAA-NOS) should be consulted as to the appropriate use of the closer tide gauge data.

2-5. Estimating Future Change in Local MSL.

a. The relative sea level rates considered shall include, as a minimum, a low rate, which shall be based on an extrapolation of the historical tide gauge rate, and intermediate and high rates, which include future acceleration of GMSL. The influence of location on future conditions shall be addressed in all analyses. Nonstationarity is included and addressed with a reasonable upper bound based on the published scientific literature. The analysis may also include additional intermediate or high rates, if the project team desires [e.g., from Parris et al. (2012)]. The sensitivity of each design alternative to the various rates of SLC shall be considered. As in previous USACE sea level change guidance, designs should be formulated using the wide body of currently accepted design criteria for each applicable mission area.

b. The use of sea level rise scenarios as opposed to individual scenario probabilities underscores the uncertainty in how LRSL will actually play out into the future. The use of

"curves" is mathematically smooth, but it is unlikely that actual variations will have that attribute. The uncertainty is magnified when the responses of coastal systems and processes are considered or when the combined effects of sea level rise and altered storm frequency or intensity are evaluated.

c. ER 1100-2-8162 requires the use of three scenarios, at a minimum, to estimate future sea levels. These are a low rate that shall be based on an extrapolation of the historical tide gauge rate, and intermediate and high rates that include future acceleration of GMSL.

(1) The historical rate of relative SLC at relevant local tide stations should be used as the low rate for analysis of the effects of future changes in LRSL. The current, historically based rate of change shall be estimated from local tide station records if oceanographic and geologic conditions at the tide station are determined to be similar to and consistent with those at the project site. The present tide gauge trends (Zervas 2009) are due to a combination of global sea level change and the influences of regional sea level change and local and regional vertical land motion. In most instances, acceleration of rates of global mean sea level have not been identified as main drivers of those local and regional rates. This lowest curve is primarily controlled by regional sea level change projection and land uplift or subsidence.

(2) The intermediate and high rates are calculated using the following equation:

$$E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2) \quad (1)$$

where t_1 is the time between the project's construction date and 1992 and t_2 is the time between a future date at which one wants an estimate for sea level change and 1992 (or $t_2 = t_1$ + number of years after construction) (Knuuti 2002). The variable b is equal to 2.71E-5 for modified NRC Curve I and 1.13E-4 for modified NRC Curve III. The year 1992 is used to start these curves because 1992 is the center year of the NOAA National Tidal Datum Epoch (NTDE) of 1983–2001. The NTDE is the period used to define tidal datums (Mean High Water, for instance, and local MSL) (Flick et al. 2013). For example, if a designer wants to know the projected eustatic sea level rise at the end of a project's period of analysis, and the project is to have a 100-year life and is to be constructed in 2013, $t_1 = 2013 - 1992 = 21$ and $t_2 = 2113 - 1992 = 121$.

(3) The low, intermediate, and high curves can be calculated using the USACE on-line calculator at www.corpsclimate.us/ccaceslcurves.cfm. Figure 3 shows an example of the three curves for Grand Isle, LA.

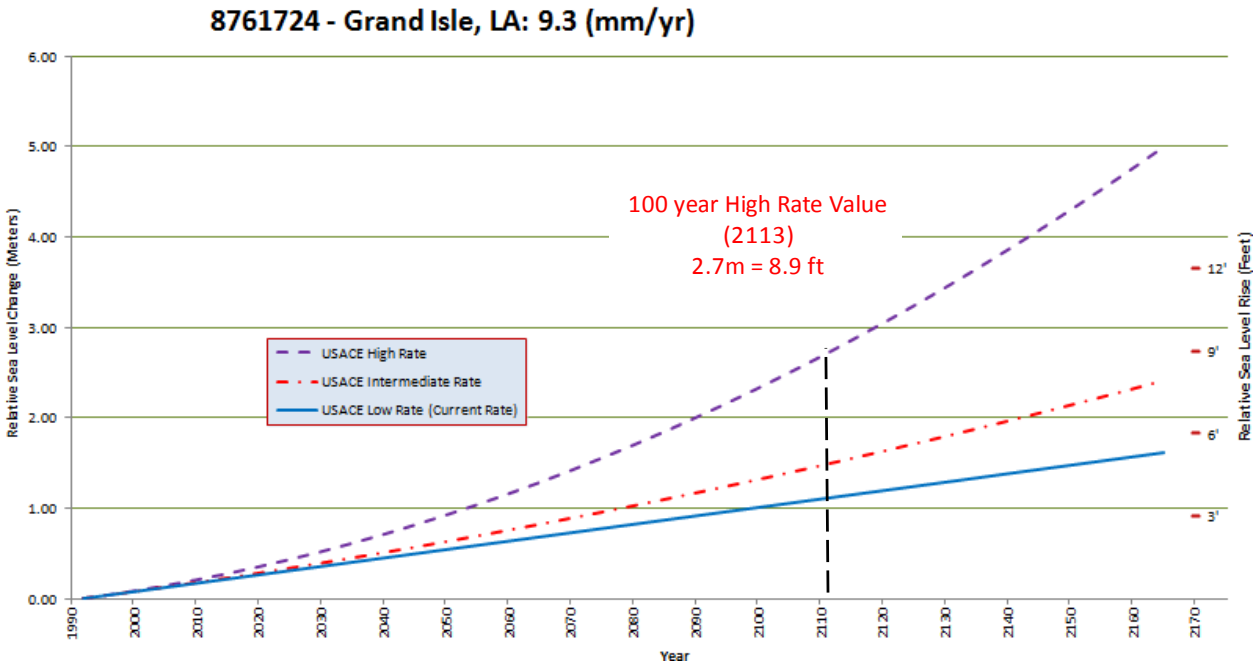


Figure 3. USACE SLC curves for Grand Isle, Louisiana. These curves include eustatic sea level rise values and subsidence rates.

2-6. Magnitude of Changes and Frequency of Events. To achieve a realistic assessment of future vulnerability, the incorporation of SLC (or other climate factors) will need to describe the change from two general perspectives: magnitude and frequency.

a. Magnitude of Changes. Identifying the potential magnitude of water level changes at the project site due to SLC begins with the future projection of local SLC as described in the three SLC curves. Note that with the exception of the extrapolation of the historical trend given by the low curve, the rate of change is projected to increase with time. This is an important consideration for potential project area changes in the future. Since modifications or adaptations in some project areas can take a significant amount of time, it is recommended that tipping points and thresholds that may require design adjustments be evaluated at shorter intervals of time. Evaluating potential impacts or project changes at 10-year intervals could help to identify the types of changes that impact performance and trigger adaptation decisions. Different planning horizons should be carried throughout the project in order to identify the degree of urgency of future actions as well as the expected resilience of selected alternatives. Recommended ranges of time to evaluate impacts and adaptation strategies are 20, 50, and 100 years.

(1) Water Level Excursions. Once the range of projected changes in sea level is identified for the project site, the influence of that change on the natural variability of the water level excursions, as well as potential effects on other variables such as storm surge or wave height, can be evaluated. Local extremes refer to the frequency distribution of the maximum and minimum observed water levels. NOAA CO-OPS compiles monthly time series of maximum and minimum water levels at each NOAA water level station. A complete discussion of these excursions is

presented in Appendix B and in Figure B-17. For potential future extreme water levels, the potential for nonstationary components should be addressed.

(2) Shifts of Datum. It is important to consider the potential shift in datum for the low, intermediate, and high SLC estimates. For projects that are sensitive to SLC, a more detailed wave and surge analysis should be conducted at a later stage in the study.

(3) Site-Specific Analysis. Tide gauge data are representative of the site at which the data were collected. Other locations could be impacted by fewer or additional factors. For example, tide gauges that are located interior to an estuary or embayment may not include loading parameters such as wave run-up and open coast storm surge that are appropriate for a project site located along the open coast shoreline. Other extreme sudden changes, such as rapid subsidence due to an earthquake, should also be considered, depending on the project site.

(4) Low vs. High Water Levels. Both extremes of low and high water levels should be considered. In many cases, changes in extreme highs for the project area may represent the controlling loading case, but the shift in extreme low water levels can also be important for some projects. For example, ecosystem, water supply, and drainage projects will be impacted by a shift in the normal and extreme low water levels. Extreme lows would also be important, for example, for a project where performance is connected to gravity flow canal or drainage systems.

b. Frequency of Events. The second area of primary concern in terms of defining future project area vulnerability involves assessing the potential increase in the frequency of water level events or loading conditions. In the case of relative sea level rise, a given flood or storm surge event will occur on top of a higher mean sea level, so the frequency of flooding will increase even if all other factors remain equal. Future extreme water level excursions will reach higher elevations than past storms and will do so more frequently, impacting both flooding and structural loading (e.g., Kriebel 2012). Appendix B addresses frequency in greater detail.

2-7. Overall Process- or Performance-Driven Impacts and Other Factors.

a. Physical Context. A thorough physical understanding of the project area and project purpose is required in order to effectively assess the project's sensitivity to SLC. Depending on the project's purpose and level of exposure, some USACE projects will be impacted by average annual conditions, such as navigation conditions at an open ocean navigation project, while others may be more vulnerable to extreme events. The potentially catastrophic failure of a levee or floodwall would fall into the latter category. Some projects may be vulnerable to both types of impacts, e.g., stability issues for the reliability of the infrastructure (often driven by extreme events) and performance issues related to changes in annual conditions, such as the frequency or return interval of overtopping and flooding or changes in ecosystem characteristics due to modified hydraulics.

b. Response. Assessment of a project area's response to potential SLC should include an analysis of natural long-term process response mechanisms. Different antecedent geologies and geomorphic characteristics of coastal shoreline units will present very different long-term responses to SLC (see Appendix D). Each project area may also include exposure to other

climate change factors (e.g., storm wave frequency and intensity, precipitation) as well as significant interconnections with systems (natural or man-made) within the project area. In these cases, SLC will need to be assessed with other factors to determine the cumulative effect on project stability and performance. One loading alone or one climate change factor alone may not produce significant impacts, but multiple impacts can result in a failed system. This is particularly true if the project area is already stressed or has low resilience to change. An example is the combined impacts of increased sea level, increased storm wave height and storm surge, and increased precipitation on the storm drainage system of a coastal community. Some additional discussion of these factors can be found in Chapter 3 and Table 7 of this document. Ongoing research and guidance is being developed for these subject areas.

CHAPTER 3

Effect of Sea Level Change on USACE Decision-Making Processes

3-1. Sea Level Change, Uncertainty, and Risk in Decision-Making.

a. Decisions made in USACE CW missions rely on technical assessments and models evaluating complex physical processes such as erosion, sediment transport, waves, saltwater intrusion, and storm surge. Sea level change must be incorporated into these assessments and models (both at the mean and at the extremes). SLC is unlike other factors that have influenced the development of decision-making processes in USACE. It has a high degree of uncertainty, it could potentially lead to severe effects, and it has a long time horizon. Consequently, USACE must use a modified decision-making approach when considering the effects of SLC. At the same time, SLC is just one of many factors to be considered in the evaluation of USACE project maintenance and development. Adequately incorporating potential SLC into decision-making processes will improve the resilience of systems and maximize sustainability over time. This chapter provides details on how SLC affects USACE decision-making as well as recommendations that will improve its incorporation into the process.

b. A tiered analysis is recommended for the inclusion and assessment of SLC impacts on the project and the project alternatives. After each analysis tier, there are review and decision points that allow the engineers and planners to reassess whether or not the required data and analysis are sufficient to answer the essential problem statements and risk questions of the study. The three primary tiers include: (1) establishing a strategic decision context, (2) determining project area exposure and vulnerability, and (3) developing and evaluating alternatives for addressing sea level change at the project site.

c. The approach to decision-making in the planning phase of USACE project development is the formal six-step planning process detailed in ER 1105-2-100 and in the Water Resources Council's 1983 *Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies* (P&G) (USACE 1983). The planning process is a structured approach to decision-making that explicitly requires the identification and description of areas of risk and uncertainty in analyses so that decisions can be made with knowledge of the degree of reliability of the estimated benefits and costs and of the effectiveness of alternative plans. The conundrum of the planning process, and any decision support process, is in doing sufficient work to support a decision while avoiding decision paralysis or, worse, making decisions that ignore important uncertainties. The tiered approach to incorporating SLC addressed in this document melds easily with the USACE six-step planning process and will facilitate decision-making within the context of high uncertainty.

d. Decision-making during other phases of the project life cycle may be less formal and require differing levels of detail, but the basic concepts of the six steps provide a strong foundation for decision support and are adaptable to any level of detail. Figure 4 provides specific focus areas at each planning step that may require additional attention when addressing SLC and multiple scenarios at a project. In this figure the six planning steps (along with the

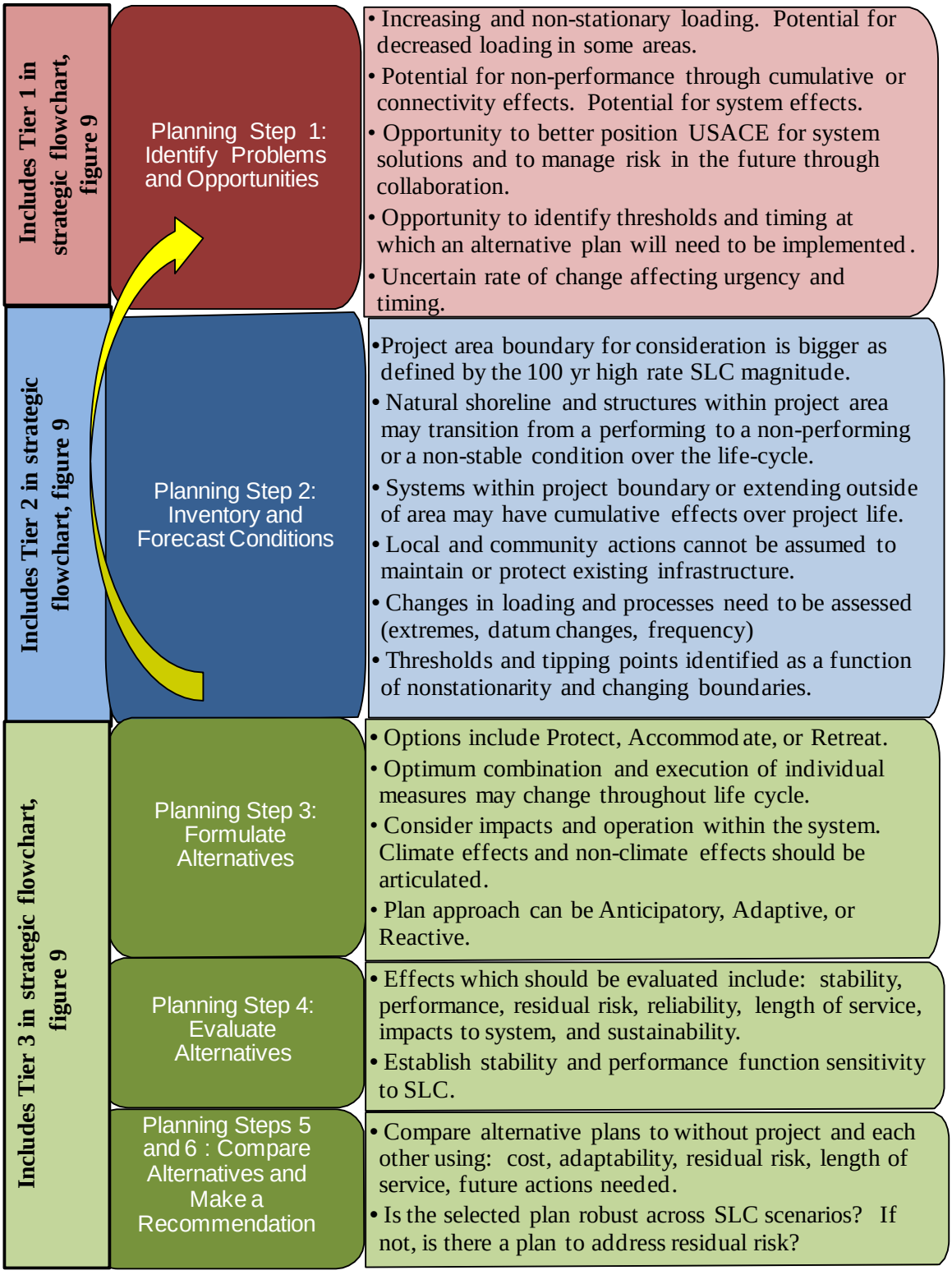


Figure 4. Specific SLC and multiple scenario-related actions that may be needed at the various USACE planning process steps.

three tiers) are displayed on the left hand side of the figure. On the right hand side, beside each planning step, are specific aspects of each step that may need to be approached differently when incorporating SLC. The concepts and ideas in Figure 4 can be used at any stage in a project, from initial planning to operations and maintenance. For USACE projects, the without project can range from an evaluation of project performance impacts and maintenance increases for an existing project to the initial assessment of sustainable project location for a new project.

3-2. Changes in Decision-Making Necessary to Consider SLC.

a. Multiple Scenarios. The USACE planning process calls for the comparison of plan performance to a single, most-likely future condition. This is a requirement of the National Environmental Policy Act (NEPA) and ensures that all alternatives are evaluated against a common baseline so that the impacts of the alternatives are accurately described. Through this comparison, USACE planners also can identify the plan that maximizes expected net benefits or, in the case of ecosystem restoration, the plan that is most cost effective in achieving its objectives. However, when considering climate change or other broadly uncertain drivers, currently available data and techniques do not provide the ability to estimate probabilities associated with future scenarios. Therefore, even though a single future must still be used in NEPA evaluations, methods are needed to compare project performance across a range of possible futures.

(1) Range of Potential Futures. Scenario analysis is proposed for those problems that have large uncertainties with large potential consequences. Scenarios are not forecasts of the future but are plausible future states that are used to examine potential outcomes and assess the performance of USACE projects. According to ER 1110-2-8162, at a minimum, three distinctly different scenarios represent the range of plausible future rates of low, intermediate, and high SLC. Both with- and without-project conditions should be evaluated using low, intermediate, and high rates of future SLC. The multiple-scenario approach is designed to provide a flexible and robust framework that, within existing decision processes, can be modified as needed and as new information is obtained. An example of such an approach is the assessment of two different future extreme water levels combined with two different commercial development options or two different critical infrastructure configurations (EM 1110-2-1619, Swart et al. 2004, Moser et al. 2008).

(2) Strategies for Evaluating Alternatives for Multiple Scenarios.

(a) One approach to evaluating multiple scenarios is to work within a single SLC scenario, formulating, evaluating, and comparing alternatives and then identifying the preferred alternative under that scenario. That alternative's performance would then be evaluated under the other SLC scenarios to determine its overall potential performance. This approach may be most appropriate when local conditions and plan performance are not highly sensitive to the rate of SLC.

(b) Another approach is to formulate alternatives under all SLC scenarios and then evaluate and compare all alternatives against all SLC scenarios rather than determining a "best" alternative under any specific future scenario. This approach avoids focusing on an alternative

that is only best under a specific SLC scenario, and it prevents rejecting alternatives that are more robust in the sense of performing satisfactorily under all scenarios. This comprehensive approach may be more appropriate when local conditions and plan performance are very sensitive to the rate of SLC.

(c) A third approach is to employ either approach (a) or (b) and then to incorporate the robust features of the evaluated alternatives to improve the project's performance over its entire life cycle.

b. Adaptation Options. For all of the USACE mission areas, adaptation options can be developed based on two fundamental categories: (1) purpose and magnitude (Table 1) and (2) resilience and adaptability (Tables 2–4). These options will vary with the level of development and natural resilience in the project area as well as the project sponsor's position on residual risk. The basic purpose/magnitude options to address SLC over the project life cycle fall into three general categories: *Protect*, *Accommodate*, or *Retreat.* Note that an alternative plan may consist of a combination of adaptation approaches that crosses boundaries from protect to accommodate to retreat or may consist of a transition from one approach to another over the project life cycle. Table 1 summarizes potential adaptation approaches by project type, addressing purpose and magnitude of action.

c. Resilience and Adaptability. Coastal risk reduction can be achieved through a variety of approaches, including natural or nature-based features (e.g., wetlands and dunes), nonstructural interventions (e.g., policies, building codes, and emergency response such as early warning and evacuation plans), and structural interventions (e.g., seawalls and breakwaters). Natural and nature-based features can attenuate waves and provide other ecosystem services (e.g., habitat, nesting grounds for fisheries). Nonstructural measures are most often under the jurisdiction of state and local governments (and individuals) to develop, implement, and regulate, and they cannot be imposed by the Federal government. Perhaps better known are the structural measures that reduce coastal risks by decreasing shoreline erosion, wave damage, and flooding (USACE 2013). Tables 2–4 provide examples of nature-based (NBI), nonstructural (NS), and structural (S) measures (USACE 2013).

d. USACE Integrated Strategy. The USACE planning approach supports an integrated strategy for reducing coastal risks and increasing human and ecosystem community resilience through a combination of the full array of measures: nature-based, nonstructural, and structural. This approach considers the engineering attributes of the component features and the dependencies and interactions among these features over both the short and the long term. It also considers the full range of environmental and social benefits produced by the component features. Renewed interest in coastal risk reduction efforts that integrate natural and nature-based features reveals the need for improved quantification of the value and performance of nature-based defenses for coastal risk reduction. Federal, state, local, NGO, and private sector interests connected to our coastal communities possess a complementary set of authorities and capabilities for developing more integrated coastal systems (USACE 2013).

Table 1. Potential adaptation approaches by project type, addressing purpose and magnitude.

Project Type	Protect	Accommodate	Retreat
Navigation	Upgrade and strengthen existing primary structures Expand design footprint and cross section of existing structures, including raising for clearance and access Add secondary structures Add structures to protect backshore Improve resilience of backshore facilities	Upgrade drainage systems Increase maintenance and dredging Adjust channel location and dimensions Modify operational windows Flood proof interior infrastructure Add sediment to shoreline or underwater morphology	Relocate interior harbor infrastructure due to relative sea level rise or fall Abandon harbor/port Re-purpose project area
Coastal Storm Damage Reduction	Upgrade and strengthen existing structures Expand design footprint and cross section of existing structures Add secondary structures Dune/beach construction	Increase maintenance of shoreline protection features Sediment management Beach nourishment/ vegetation Upgrade drainage systems Upgrade and modify infrastructure Flood proof buildings Implement building setbacks Modify building codes	Relocate buildings and infrastructure Land-use planning and hazard mapping Modify land use
Flood Risk Reduction	Upgrade and strengthen existing structures Expand design footprint and cross section of existing structures Construct levees or implement floodproofing measures Add secondary structures Dune/beach construction	Increase maintenance of flood risk protection features Upgrade and modify infrastructure Improve natural shoreline resilience (vegetation) Flood proof buildings Implement building setbacks	Relocate buildings and infrastructure Land-use planning and hazard mapping Modify land use
Ecosystems	Construct drainage systems Construct shoreline protection structures, dikes or cells Construct tidal gates, install salt water intrusion barriers	Accept changes to ecosystems Sediment management Change water extraction Freshwater injection /diversion Modify land use Migrate landward	Allow/facilitate habitat conversion Forbid hard defenses Ecosystem migration Abandon ecosystem

Table 2. Natural and nature-based features at a glance. General coastal risk reduction performance factors include storm intensity, track and forward speed, and surrounding local bathymetry and topography (USACE 2013).

Dunes and Beaches	**Vegetated Features**	**Oyster and Coral Reefs**	**Barrier Islands**	**Maritime Forests/Shrub Communities**
Benefits/Processes				
Breaking of offshore waves Attenuation of wave energy Slow inland water transfer	Breaking of offshore waves Attenuation of wave energy Slow inland water transfer Increased infiltration	Breaking of offshore waves Attenuation of wave energy Slow inland water transfer	Wave attenuation and/or dissipation Sediment stabilization	Wave attenuation and/or dissipation Shoreline erosion stabilization Soil retention
Performance Factors				
Berm height and width Beach slope Sediment grain size and supply Dune height, crest, and width Presence of vegetation	Marsh, wetland, or SAV elevation and continuity Vegetation type and density	Marsh, wetland, or SAV elevation and continuity Vegetation type and density	Marsh, wetland, or SAV elevation and continuity Vegetation type and density	Marsh, wetland, or SAV elevation and continuity Vegetation type and density

Table 3. Nonstructural features at a glance. General coastal risk reduction performance factors include collaboration and shared responsibility framework, wave height, water level, and storm duration (USACE 2013).

Floodplain Policy and Management	**Floodproofing and Impact Reduction**	**Flood Warning and Preparedness**	**Relocation**
Benefits/Processes			
Improved and controlled floodplain development Reduced opportunity for damages Improved natural coast environment	Reduced opportunity for damages Increased community resiliency No increase in flood potential elsewhere	Reduced opportunity for damages Increased community resiliency Improved public awareness and responsibility	Reduced opportunity for damages No increase in flood potential elsewhere Improved natural coast environment
Performance Factors			
Wave height Water level Storm duration Agency collaboration	Wave height Water level Storm duration	Wave height Water level Storm duration	Wave height Water level Storm duration

Table 4. Structural features at a glance. General coastal risk reduction performance factors include storm surge and wave height/period, water level (USACE 2013).

Levees	Storm Surge Barriers	Seawalls and Revetments	Groins	Detached Breakwaters
Benefits/Processes				
Surge and wave attenuation and/or dissipation Reduced flooding Reduced risk for vulnerable areas	Surge and wave attenuation Reduced salinity Intrusion	Reduced flooding Reduced wave overtopping Shoreline stabilization behind structure	Shoreline stabilization	Shoreline stabilization behind structure Wave attenuation
Performance Factors				
Levee height, crest width, and slope Wave height and period Water level	Barrier height Wave height Wave period Water level	Wave height Wave period Water level Scour protection	Groin length, height, orientation, permeability, and spacing Depth at seaward end Wave height Water level Longshore transportation rates and distribution	Breakwater height and width Breakwater permeability, proximity to shoreline, orientation, and spacing

Figure 5 illustrates some aspects related to the typical range of project options by mission area. Consideration should be given to the project purpose as well as to the level of development in the project area. Some mission areas have a broader range of potential options as well as an array of nature based options that can influence level of vulnerability. For example, a navigation project is unlikely to have much flexibility for retreat since, by definition, the project has to remain at the land/ocean interface. For this type of project, the majority of viable options will fall into the protect and/or accommodate categories.

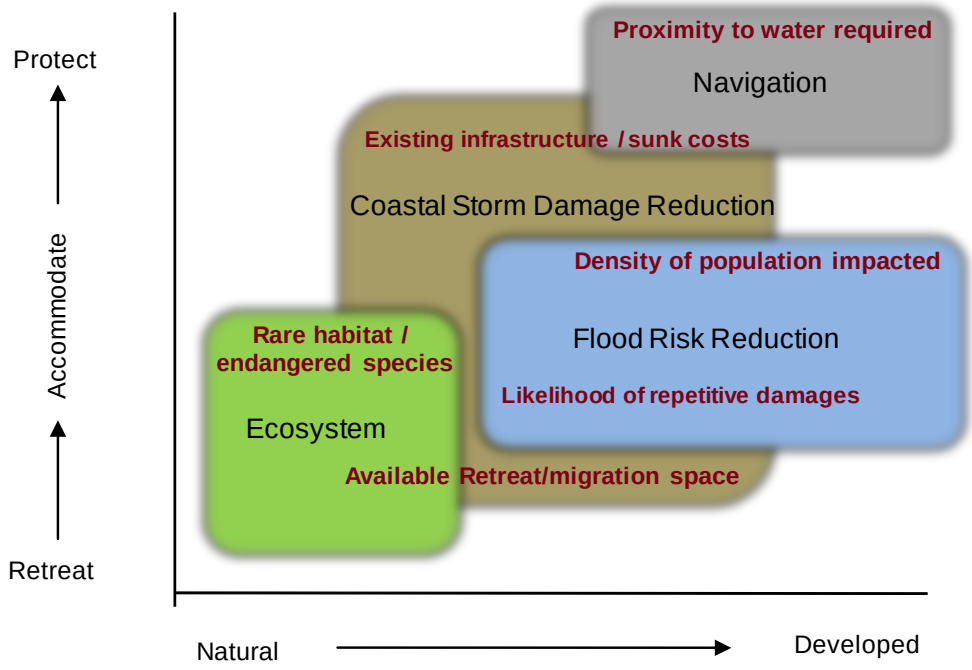


Figure 5. Example of adaptation options by mission area and stage of development in a project area.

e. Incorporating Risk and Uncertainty.

(1) Uncertainty is the result of imperfect knowledge concerning the present or future state of a system, event, situation, or (sub)population under consideration. Uncertainty about future SLC presents two related but distinct hazards to a project: the risk of a project's useful life being much different than anticipated, and the risk of the project's level of performance at a given time in the future being much different than anticipated. Both risks exist for every project, but one may be more significant than the other, depending on the project's design, its intended function, and the evolution of future sea level over time (i.e., the shape of the curve, rather than the endpoint alone).

(2) A recognition of the potential range of uncertainties and risks involved with each project can facilitate the appropriate level of risk-informed decision-making. Figure 6 illustrates some general approaches to project execution given the continuum of risk and uncertainty. At the low end of risk and uncertainty, best management practices might be executed efficiently without a high level of risk of potential impacts. If the level of risk is low and the level of uncertainty is high, an adaptive approach may meet project needs. If there is a relatively high level of certainty about potential future conditions combined with a very high risk, extra efforts in a preparedness and response plan may be appropriate. Climate-sensitive, high-risk projects will likely require a more extensive analytical and scenario-based approach to ensure adequate incorporation of potential future consequences or a determination in plan formulation that loss or conversion is acceptable.

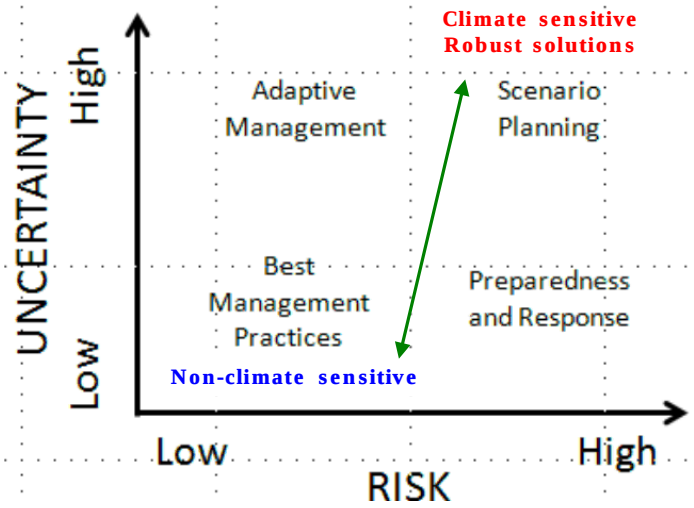


Figure 6. Consideration of risk and uncertainty in climate-change-related decision-making.

(3) USACE projects, programs, and activities often involve the development and management of long-lived systems. Decisions made now have long-term implications, yet decisions made now may not be revisited for some time, or they may unintentionally preclude some future responses to SLC or other uncertainty. The longer the life of engineered systems and their related socio-economic and ecological systems, the more important it becomes to evaluate, throughout the project life cycle, the sustainability and resiliency of these combined systems in the face of climate change effects.

(4) Alternative plan selection should explicitly provide a way to address uncertainty, describing a sequence of decisions allowing for adaptation based on evidence as the future unfolds. Decision-makers should not presume that the future will follow exactly any one of the SLC scenarios. Instead, analyses should determine how the SLC scenarios affect risk levels and plan performance, and identify the design or operations and maintenance measures that could be implemented to minimize adverse consequences while maximizing beneficial effects.

f. Decision Timing Strategies. The initial assessment that evaluates the exposure and vulnerability of the project area over the 100-year adaptation horizon will assist planners and engineers in determining the long-term approach that best balances risks for the project. The three general approaches are anticipatory, adaptive, and reactive strategies. These strategies can be combined, or they can change over the life cycle of the project. This is particularly important to consider under a climate change condition where loading and response mechanisms are likely to transition over the life of the project. Figure 7 illustrates potential SLC approaches over the project timeline. Figure 8 provides a United Kingdom example of how an anticipatory approach (called precautionary in the figure) might compare to an adaptive approach.

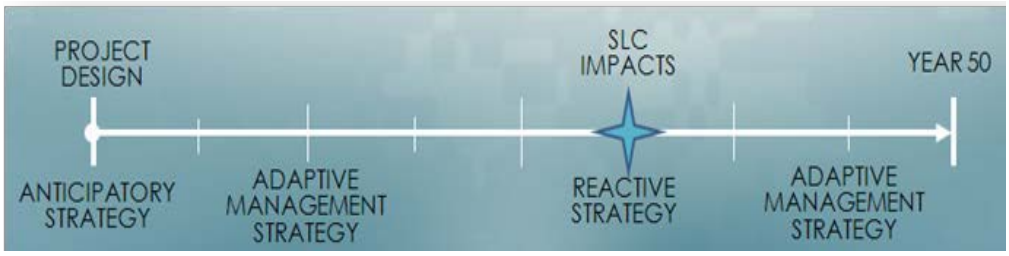


Figure 7. Conceptual comparison of different project alternative strategies.

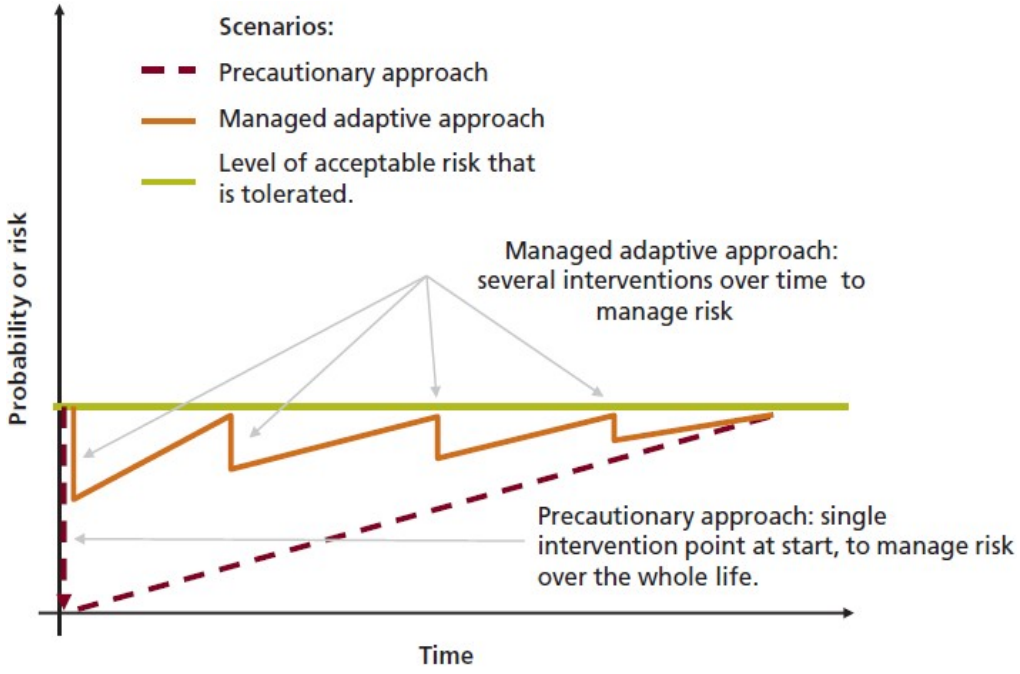


Figure 8. Precautionary (i.e., anticipatory) and managed adaptive approaches. (Courtesy of DEFRA 2009.)

(1) Anticipatory. The anticipatory strategy implements features and design parameters that decrease the vulnerability to future SLC and/or enhance the project adaptability before impacts are incurred. This strategy can either implement features now or facilitate the next adaptive management strategy should it be needed in the future. An example of this strategy is the design of hard structures for initial construction with a design crest height that also reduces risk for expected increases in SLC in the future. Another example of an anticipatory action is the acquisition of additional lands for wetland migration or future structure construction and/or expansion. The major risk of large anticipatory investments is that their future costs and benefits are functions of uncertain future sea levels: they may either provide less performance for less time than anticipated, or they may be constructed long before they are ultimately needed, leading to costs out of balance with performance.

(2) Reactive. The reactive strategy may be planned or ad-hoc and is not implemented until required by the impacts of SLC. The major risks of this strategy are that impacts will already be occurring by the time SLC becomes apparent, and it may be more difficult to take the action at the time of the response due to lack of preparation. Because the occurrence of impacts drives the investment decisions when using a reactive strategy, some impacts are guaranteed, and investments do not provide as much return as if they had been made earlier. Furthermore, reactive strategies may be wasteful and repetitive if they are independent projects rather than part of a larger plan.

(3) Adaptive. The adaptive management strategy (Brown et al. 2011) uses sequential decisions and implementation *based on learning and new knowledge*. In Figure 7 the multiple managed adaptive occurrences along the timeline indicate that actions are likely to be spread out over the project timeline as additional adaptation action is required or new information is obtained. For this strategy, implementation of the alternative measure occurs prior to SLC impacts and requires advance planning to maintain the ability to adapt to SLC. An example of adaptive management is designing berms, seawalls, or barriers to accommodate future additional height, with design and construction tied to a threshold prior to the time that the future impact is expected to occur. While the adaptive strategy allows flexibility compared to the anticipatory and reactive approaches as we monitor and learn, it implies trust in future managers to actually implement required adaptations. If future engineers, planners, and politicians fail to execute adaptive management successfully, the strategy becomes a de-facto reactive one with the resultant incurred impacts. In this sense, some forward-thinking institutional changes have the ability to facilitate a cost-effective approach to future climate change.

(4) Combinations. It is important to note that no one strategy is, by itself, better than any other, as each strategy carries its own advantages and tradeoffs that depend on the circumstances of the particular investment decision. The USACE process requires the inclusion of a wide range of factors in evaluating and comparing the alternative plans. Because of the characteristics of SLC, additional information regarding project area sensitivity, potential consequences, available response time, and benefit/cost tradeoffs are needed to decide the best approach. The selected alternative will be a function of the decision criteria that have been identified by USACE and the other stakeholders. In most cases a portfolio of mixed strategies will be the best overall approach.

g. Identifying Thresholds and Tipping Points. The identification of thresholds and tipping points within the impacted project area will inform both the selection of adaptation options and the decision timing strategies. A critical threshold is intended to identify a water surface elevation at which a structural condition changes or system performance changes. For example, a structure can either fail or be overtopped at a certain water elevation, and a drainage system might start to back up at a certain water elevation. A tipping point refers to a critical point, after the threshold, when stability and/or performance begin to rapidly decline and impacts increase dramatically. Determining tipping points that would generate a necessary action in the future is an essential element of alternative development with respect to SLC.

3-3. Applying a Tiered Planning and Analysis Approach to the Incorporation of SLC.

a. Tiered Approach. Introducing a multiple scenario approach to the USACE planning process, and other USACE decision support processes, has the potential to introduce additional

layers of analysis. Because of the resulting complexity, the approach recommended here involves three tiers of analysis that provide an overall framework intended to guide the user through the process. Figure 9 illustrates the basic stages of screening recommended here for incorporating SLC in the project assessment and analysis of alternatives. This approach maps directly into the normal USACE planning process and the 3×3×3 SMART planning recommendations.[2] The critical goals of the tiered approach are to:

(1) Encourage both planners and engineers to step outside of the normal assumptions they would make in assessing both with- and without-project conditions,

(2) Assess the strategic decision context with respect to SLC, and

(3) Develop a defensible level of detail required to address the potential and residual risk.

Decision points exist after each tier, allowing engineers and planners to reassess the level of required data and analysis sufficient to answer the essential problem statements and risk questions of the study. This tiered approach is consistent with the iterative planning process.

b. Key Questions. Early in the process, the goal is to determine to what extent different future sea level rates may impact alternative selection. If all alternatives are affected equally by SLC, then the selection of a sea level rate to design for is less critical. However, if alternative responses differ significantly for different rates of change, more detailed analysis may be needed so that the residual risk, in terms of both costs and impacts, is captured. Some key questions relevant to SLC to be incorporated in the analysis are:

(1) When might you expect to see SLC impacts in the project area and what might the magnitude of those impacts be?

(2) What is the relative scale of the potential impact of SLC in the project area within the larger context of natural variability of loading and processes?

(3) How might the potential extreme loading conditions in the project area affect impacts and what are the potential impacts if the estimates of extreme conditions are wrong?

(4) Do historical rates of long-term shore recession indicate that recession as a whole (i.e., erosion plus inundation from SLC) needs to be taken into consideration?

(5) Are all alternatives expected to be affected equally by SLC?

(6) What is the range of SLC over which the alternatives will be adaptable?

(7) Does inclusion of different rates of SLC affect the decision that is being made?

(8) Do some alternatives require additional preparation in order to plan for their implementation under SLC?

[2] See http://planning.usace.army.mil/toolbox/smart.cfm?Section=11&Part=1

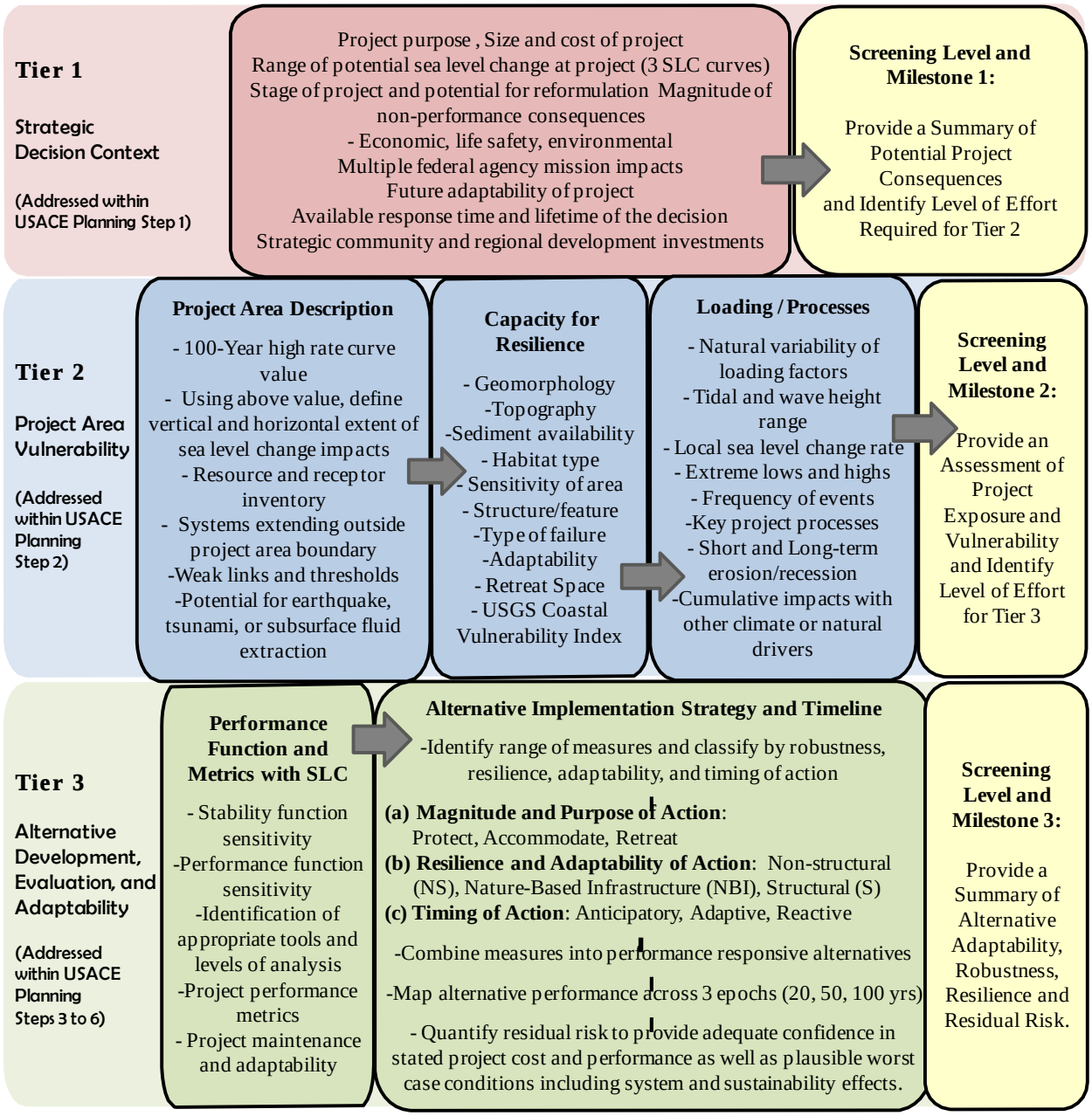


Figure 9. Screening process flowchart for analyzing and incorporating SLC throughout the project life cycle.

(9) What is the expected range of costs of the project?

(10) How much lead time might be needed for the different alternatives?

c. Tier 1 - Establish a Strategic Decision Context. The first stage, Tier 1, noted in Figure 9 as the red tier at the top, establishes the decision context. Establishing a strategic decision context for the incorporation of SLC into USACE project planning has multiple purposes.

Delivering quality products and services that appropriately address the Nation's water resources needs in a timely and cost-effective manner is vital. The incorporation of potential climate change into that process will require an active focus on risk-based scoping to define pertinent water resources needs and opportunities and the appropriate level of detail for conducting investigations. In particular, close attention is needed at the beginning of each study in order to screen planning and scoping decisions. A risk-based approach to study execution facilitates the appropriate study layout and selection of tools.

(1) The purpose of this initial stage of project scoping assessment is to achieve an understanding of what could go wrong if the problems and uncertainty are not adequately addressed. In essence, what is being assessed is whether there is potential for significant or catastrophic consequences to life safety, property, critical infrastructure, and ecosystems. At this stage it should be identified who should be involved in the evaluation of input and potential impacts, including essential other Federal, state, and community partners. It will also be important at this stage to flag any projects that could impact strategic development investments, such as major port expansion or flood risk reduction system upgrades, which have the potential to shape future long-term community development.

(2) At this level, only data and information that are readily available are used. The project's purpose and the stage of the project in the life cycle are defined. Projects can range from reconnaissance studies that will determine the existence of a Federal interest to an examination of potential vulnerabilities and future operations and maintenance requirements for existing infrastructure.

(3) The potential range of SLC at the project location is determined by calculating three curves (low, intermediate, and high) for SLC into the future, as required by this ETL. At some project locations (e.g., Alaska), the SLC identified may result in a sea level fall rather than a sea level rise. Typically, although not exclusively, climate change or sea level change will not be identified as the primary problem or opportunity. Rather, Problems and Opportunities (P&O) will continue to be stated in the context of the relevant water resource issues, how those issues affect conditions in the study region, and how those conditions relate to USACE missions. The influence of SLC on future conditions must be specifically identified in the assessment of problems and opportunities.

(4) The size and cost of the project, as well as the potential magnitude of non-performance consequences, provide a level of impact definition. Is this an existing or new project? Does the project encourage public and private investment that will influence future risk? In particular, are there larger-scale strategic community and regional development investments connected to the project?

(5) Non-performance consequences can include excessive maintenance requirements, increasingly frequent flooding, loss of essential ecosystem habitat, impacts on operations of the project and a corresponding reduction in provided services and life safety, or an unacceptable level of uncertainty regarding project performance and costs. These impacts could result from a lack of understanding of the degree of exposure that the project might have, a lack of understanding of the key climate drivers, or a decision made by the stakeholders regarding the level of risk reduction that is justified.

(6) Cumulative system impacts or impacts to other Federal agency missions should also be identified at this stage. The term "cumulative system impacts" refers to the additive effects of several parameters, such as flooding caused by both storm surge and heavy precipitation. This would also include the impacts of USACE projects on other systems in the project area.

(7) It is important at this stage to describe the possible adaptability of the project as well as the lifetime of the decision being made. The physical life of the project, the acceptable period of benefits, and whether or not conversion or loss can be accepted should be addressed. Sustainability and resiliency should be explicitly stated as an element of the planning objectives, so that the effects of sea level change *over time* can be assessed and evaluated.

(a) For some projects that have a relatively low possible consequence level and low investment level, adaptive management in the future as changes are observed (with the appropriate lead time built in) will be the most cost-effective and responsive plan. However, early in the tiered approach, it should also become clear the projects for which a more proactive and perhaps risk-averse approach might be recommended or at least strongly considered. In areas where either impacts are already being experienced, or cumulative or system impacts to an area have the potential to be large and catastrophic, a more anticipatory approach for at least the most vulnerable portions of the system should be strongly considered.

(b) Other projects that involve new structures or significant layout modifications of existing structures, projects that are essential components of larger systems or communities, or projects that through their construction will encourage a certain level of strategic development in the region will require a much more proactive and comprehensive analysis of alternatives.

d. Tier 2 – Project Area Vulnerability. The purpose for conducting the "Project Area Vulnerability" phase is to provide a relatively low-level examination of the project area, which will raise the awareness of how SLC may alter project stability or performance in the future. The second level of Figure 9, the blue tier, provides a simplified approach to assessing the project area exposure and vulnerability. Due to the shifted loading and performance context that climate change introduces to our standard planning and engineering process, it is important at this stage and at all future stages to question assumptions and realistically estimate expected impacts. This tier is a part of the normal USACE Planning Step 2, as shown in Figures 4 and 9. The Project Area Vulnerability stage includes three primary components: 1) project area description, 2) capacity for resilience, and 3) loading and processes.

(1) Data Needs for Tier 2. As with all USACE studies, the description of the future without-project condition is the foundation for any analysis or additional work. This ETL adds another dimension to the without-project description since there is a range of potential futures, as illustrated by the three SLC curves. All of the information and data required to move through the second level of Figure 9 should be readily available from the initial screening stage. If the level of risk is shown to be high, later stages of the study may improve on the quality or quantity of data in order to better capture the risks associated with project area vulnerability.

(2) Goals of Tier 2. This is where future baseline conditions will be estimated, where the technical analysis is scoped for estimating the effects of future SLC scenarios, and where a set of metrics, or evaluation criteria, will be developed to represent the social, environmental,

engineering, and/or economic characteristics that are most important in the given setting and for the identified problems. Typical evaluation criteria include project costs, National Economic Development (NED) benefits, habitat units, and life safety. If any of these criteria would experience a significant[3] change under the different scenarios of SLC, then conditions should be deemed sensitive to the rate of change, and formulation and evaluation procedures should be structured to explicitly compare the available adaptation responses.

(3) Project Area Description. To simplify the initial steps of this phase of the study and yet capture the real areas of potential risk for use in the initial screening, the following bracketing and risk assessment steps are recommended.

(a) Using the high SLC curve elevation at 100 years, the potential future affected area is defined. On Figure 3, the high 100-year (2113) SLC value would be 8.9ft (2.7 m). This area defines a first estimate of both the vertical and horizontal extents of potential SLC impacts. Since this is an initial screening level, detailed modeling may not have occurred yet. This basic approach will provide a first-level assessment of how the project and project area might be impacted. More detailed engineering analysis will be conducted later. The more detailed and comprehensive the topographical data are in the project area, the more useful this stage of analysis will be.

(b) Using the future affected area as defined by the 100-year high rate elevation, an inventory can be conducted to identify the density of impacted resources, including critical infrastructure (schools, roads, water supply, community buildings, etc.), impacted property, and ecosystems. Table 5 is an example of such an inventory table that provides a snapshot of the potential magnitude and severity of consequences within an example project area. The consideration of the potentially larger area of impact facilitates the discussion of what actions may need to be considered at certain trigger points. Community as well as other stakeholder expectations will be better defined. Potential system and cumulative effects should be explored. Also included in this table is a qualitative assessment of the expected risk from SLC.

(c) The qualitative matrix such as shown in Table 5 is a reasonable place to start gauging the sensitivity of a study area to SLC. Critical resources in the project area are identified by density. “Density” is a qualitative term that provides an idea of how prevalent the resource is in the study area. Similarly, since this table is developed prior to any detailed analysis, “risk from sea level rise” is an estimate primarily based on the location and elevation of the resource.

(d) The analysis should not yet focus on a specific alternative, but on the project area and the critical resources on which it depends. The idea behind looking at the entire system around a study area is that, while risks to the coastal infrastructure may be reduced for 50 years, the infrastructure depends on critical resources (e.g., roads, storm drainage) that may be impacted before that time. The assumption should not be made that those critical resources will remain in place or functioning. The potential interaction of other parts of the system (such as storm drainage) may influence the overall vulnerability of the area and thus impact the possible benefits and costs that may be experienced. Similarly a project such as a navigation structure may continue to provide services for many years, despite SLC, but SLC could impact the hinterland to which the service benefits are provided, which would affect the benefit calculation.

[3] Generally speaking, “significant” can be defined in this context as sufficient to change the decision outcome.

Table 5. Example of a qualitative inventory of resources and their susceptibility to SLC for a study area. (After USACE 2009.)

Critical Resources in Study Area	Density of Resource*	Relevant Notes	Risk from Sea Level Rise*
Structures (residential, commercial)	2	Mostly residential. Highly developed between main evacuation route and ocean. Risks are reduced for approximately 6% of the project area by revetments or seawalls.	1
Environment and habitat	3	Existing dune is 10–15 feet. Estuary and other wetland partially surrounds the study area. No endangered species identified.	2
Infrastructure (roads, water/sewer lines, boardwalks, navigation structures)	2	State highway (hurricane evacuation route) and secondary roads, power and service lines servicing residents.	1
Critical facilities (police, fire, schools, hospitals, nursing homes)	1	One fire station, critical services rely on A1A to reach residents.	1
Evacuation routes	3	State highway (hurricane evacuation route) is located landward of the dune line, within the project area.	2
Recreation	3	Significant recreational use of beaches.	1

* 3 = high, 2 = medium, 1 = low

(e) Table 5 can also include references to systems that extend outside the project area boundary but are likely to be impacted by project-related decisions. The analysis during this stage should identify weak links in the project performance or benefit framework. Figure 10 shows the ocean side of an example project area, along with some relevant project elevation, loading information, and threshold data. This information is presented in part to further illustrate that the SLC project vulnerability assessment portion of this process does not need to be excessively detailed or data-intensive. Figure 11 shows a topographical illustration of the project area's sensitivity to future SLC magnitudes and rates as illustrated by the SLC curves.

(f) Information from typical data displays such as Figures 10 and 11, and basic inventory data from the project area, can help define the project area's sensitivity to SLC and its capacity for resilience. In Figure 10, the shore cross section shows a relatively narrow beach fronting a disarrayed revetment. A significant transportation route is located immediately behind the dune crest, leaving little space for either overtopping runoff or cross-shore profile horizontal translation (i.e., natural recession of the dune line would not normally be allowed in this situation).

(g) The general project area description can also identify if the project area has a higher than normal potential for earthquake, tsunami, or subsurface fluid extraction, all of which can result in higher impacts related to SLC.

Pertinent Data:	elevations are averages of reaches	
	Project location	Flagler County, FL
	Analysis initiation date	2014
	Project area length	9.03 miles (shoreline length)
	Project area width	from MHW line to 400 feet inland
	Natural berm width	0 ft (no "flat" berm)
	Natural foreshore slope	0.4
	Natural berm height	11.0 ft NAVD88 11.46 ft MSL
	Upland height	14.5 ft NAVD88 14.86 ft MSL
	Natural dune height	19.0 ft NAVD88 19.46 ft MSL
	measured SLR	2.40 +/- 0.31 mm/yr (0.0076 ft/yr)
	NOS gage 8720218 - Mayport, Florida	
Relative SLR rates:	baseline	+2.40 mm/year (0.0079 ft/year)
	intermediate	+4.90 mm/year (0.0161 ft/year)
	high	+13.05 mm/year (0.0428 ft/year)

Flagler County Combined Total Storm Tide Values for Various Return Periods

Return Period TR (years)	Combined Total Storm Tide Level* above NAVD88 (ft.) Middle Profile (R-55)	Relative to MSL (ft.)
500	15.67	16.13
200	12.87	13.33
100	10.77	11.23
50	8.37	8.83
20	5.37	5.83
10	3.87	4.33

*Includes contributions of: wind stress, barometric pressure, dynamic wave set-up and astronomical tide.
0 ft NAVD88 = 1.03 ft NGVD

Figure 10. Ocean-side portion of an example project area with some relevant project elevation, loading information, and threshold data.

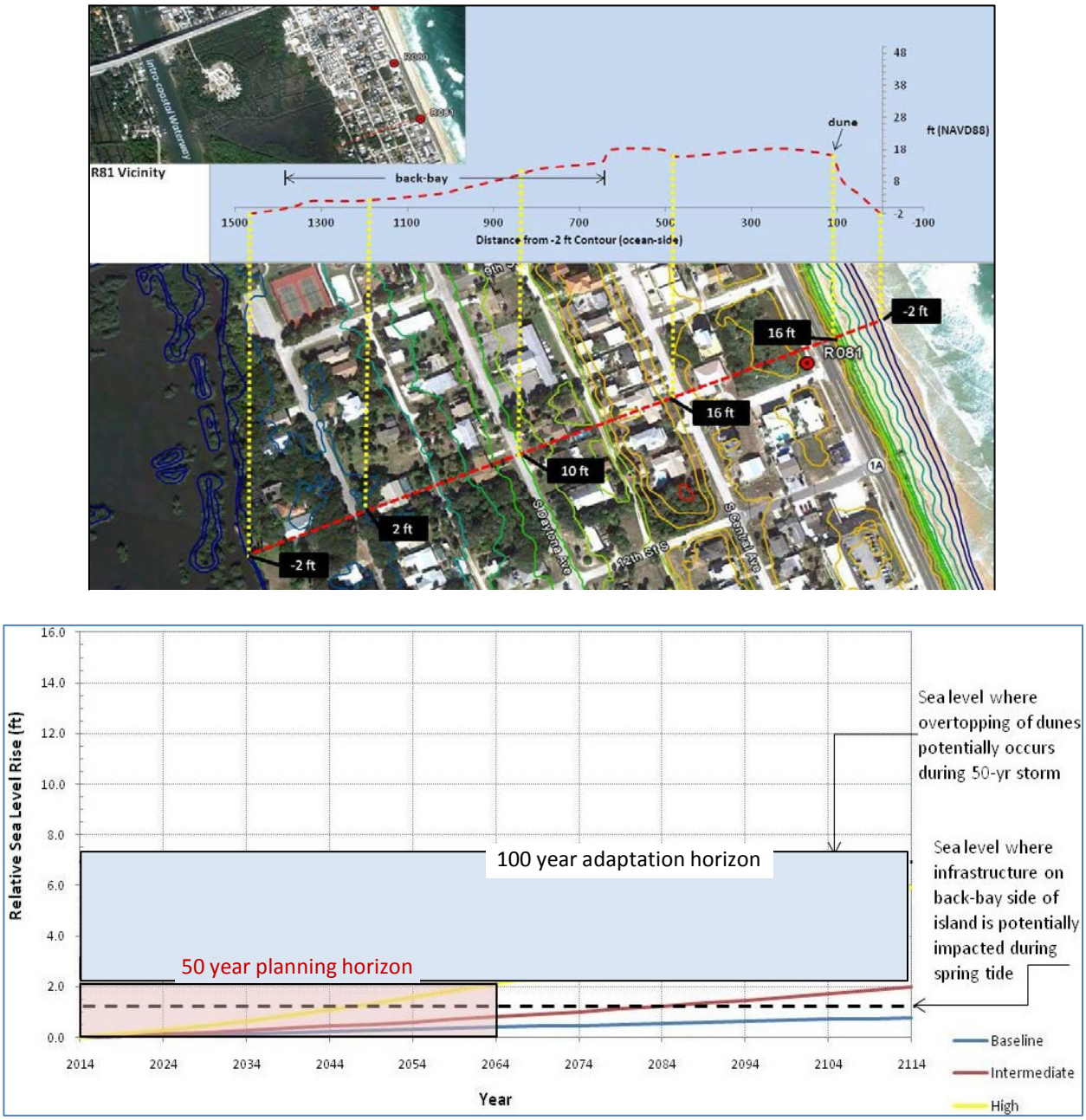


Figure 11. Topographical illustration of the project area's sensitivity to future SLC magnitudes and rates.

(4) Capacity for Resilience. Climate resilience can be defined as "…the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change" (IPCC 2007). This step will assess conditions and enable a summary of the resilience characteristics of the project area, which will differ by project type. A project area's capacity for resilience is a combination of physical characteristics, topography, and sensitivity as well as available buffer for adjustments. For example, in the case of coastal storm damage reduction

projects, a natural shore can range from a wide beach, high dune-protected backshore to a sediment-starved, minimal dune area. Similarly, while some structures are relatively flexible under increased loading or are easily adaptable, others can fail catastrophically and are difficult to adapt. Concrete flood walls are an example of the second category of non-flexible structures.

(a) Erosion bridges the category between "Capacity for Resilience" and "Loading and Processes." Sea level rise and erosion are inexorably linked, since long-term relative sea level rise will typically lead to long-term erosion. In the long term for some areas, the amount of recession attributable just to erosion can be much greater than the amount of recession attributable just to inundation alone. Obviously, this depends on the geology and slope of the coastal plain for that area. But when considering a long-term horizon, say 30 years or more, knowledge of the effects of long-term erosion on structures and infrastructure is critical.

(b) Figure 12 shows USACE project locations, NOAA sea level trends, and USGS Coastal Vulnerability Index (CVI) values. The black dots on the map identify USACE project locations. The purple graduated circles identify ports, and the size of the dot is related to the tonnage that goes through the port. Gray relief on the map indicates population density, and the arrows around the perimeter of the map identify the historical NOAA sea level trend for that location.

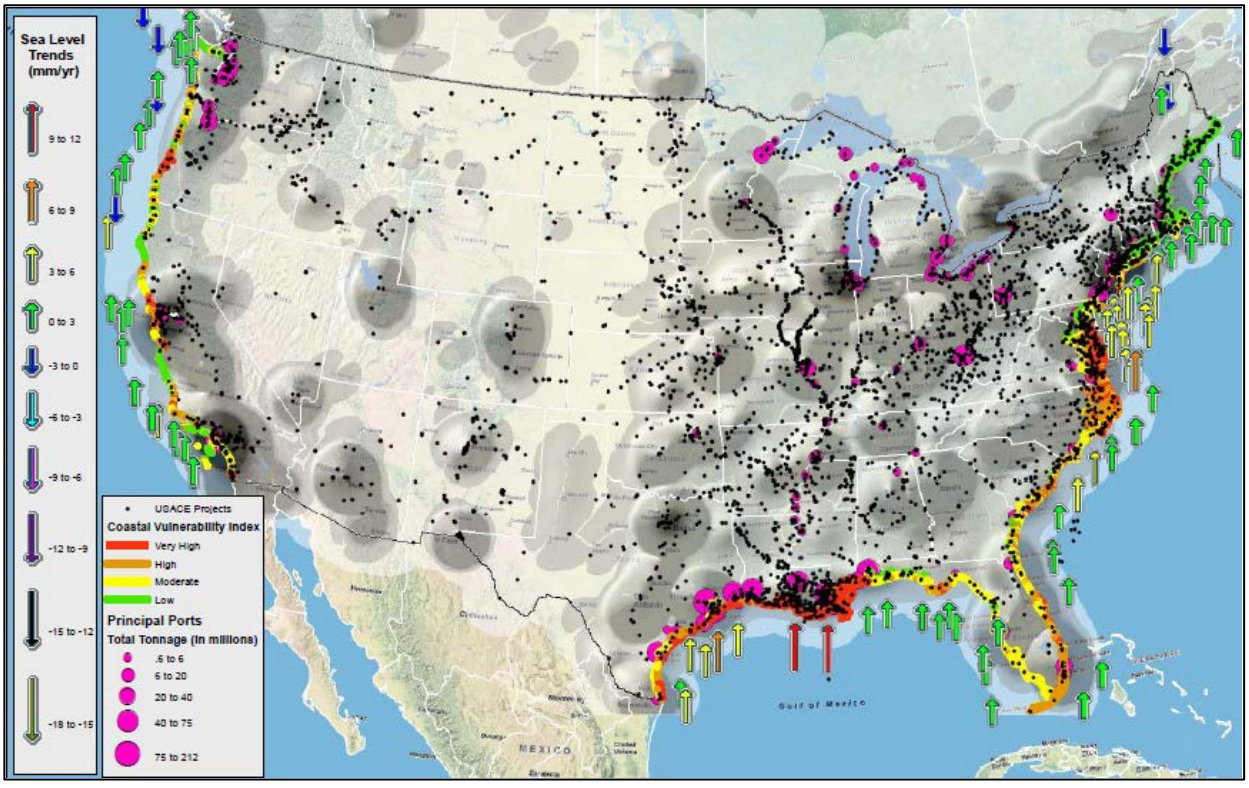


Figure 12. National map illustrating all USACE project locations, NOAA sea level trends, and USGS Coastal Vulnerability Index values. The gray relief shown in the figure (light to dark) indicates population density.

(c) Both Figures 12 and 13 show results from the U.S. Geological Survey (USGS) assessment of natural shore coastal vulnerability to SLC. The CVI is a product of a USGS sensitivity analysis based on six parameters for assessing vulnerability (Thieler and Hammar-Klose 2000a): geomorphology, coastal slope, relative sea level change, shore erosion or accretion rates, mean tide range, and mean wave height range. On Figure 12, the USGS CVI is shown as a multicolored ribbon along the edge of the coastline. Green represents low vulnerability, and red represents very high vulnerability. USGS is working on a more sophisticated analysis that will help define risks to USACE projects at a finer resolution. The USGS CVI values and background information can be found at the following link: http://woodshole.er.usgs.gov/project-pages/cvi. Other vulnerability tools or scales can be used if they are more applicable to the project type. Examples might be the sensitivity or scarcity of habitat type, the role of ecosystems in a larger watershed system, a navigation or flood control structure type, and typical failure modes.

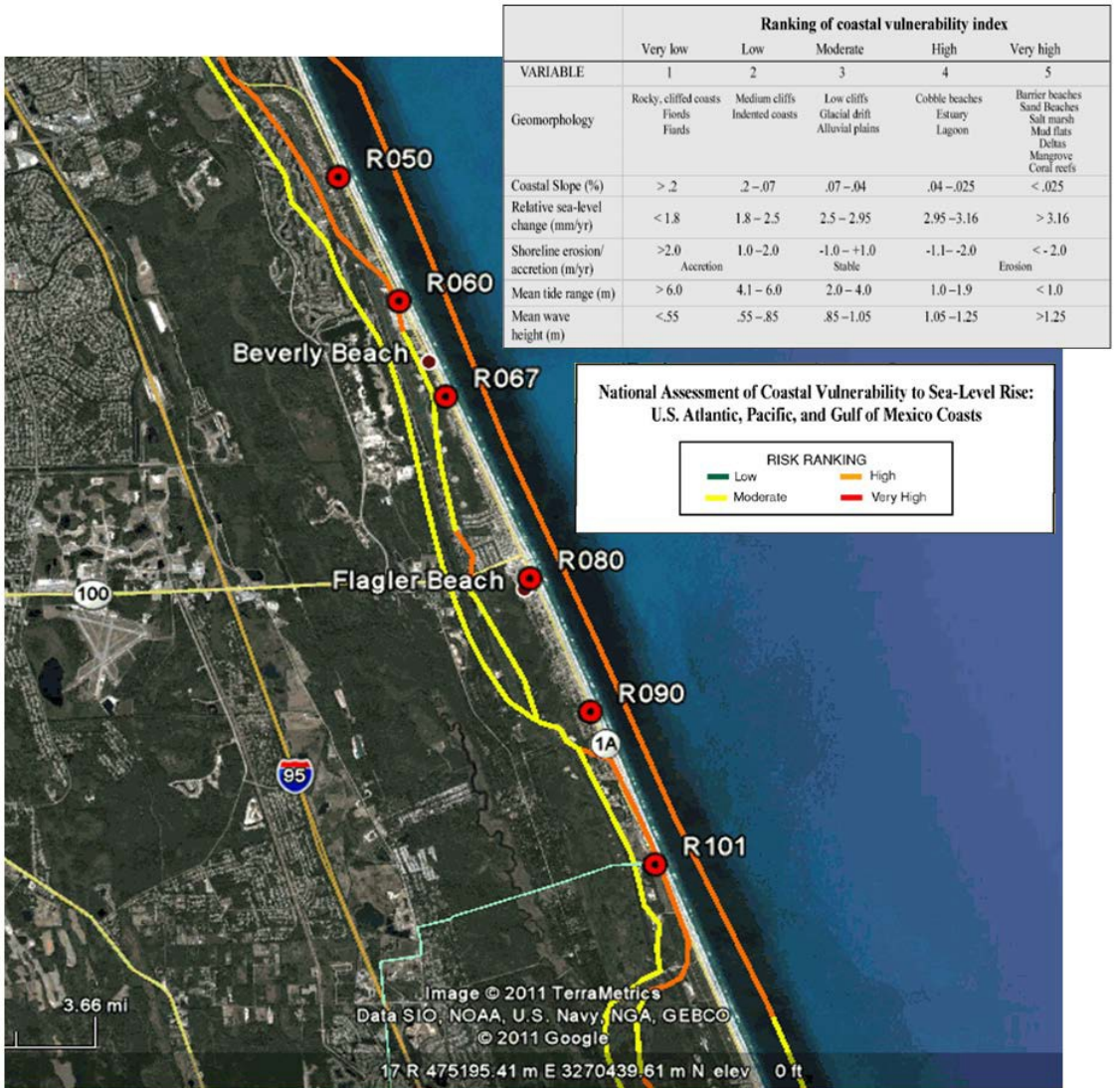


Figure 13. USGS Coastal Vulnerability Index values for an example project area.

(5) Loading and Processes. Once the project area's resilience, resources, and systems are categorized, the level of project area loading and critical processes relevant to the project's performance need to be identified. The intent is to compare and relate SLC to the overall range of loading parameters and define the level of sensitivity to SLC. Regionally, the significance of SLC within the natural variability of the loading parameters will vary. In areas that already experience a significant tidal and wave height range, the project area is likely to have developed some natural resilience to a range of conditions. Conversely, for areas whose water level and wave height range has been relatively small, a change in SL can be more significant.

(a) While SLC will be just one of the factors considered in this overall summary, SLC also has the potential to increase the magnitude and frequency of some of the other loading parameters, as well as to enlarge (both vertically and horizontally) the area that is exposed to the loading. The enlargement of the exposed area will influence the identification and the extent to which key thresholds play a role in future scenarios.

(b) The types of loading and processes that are important will change with project type. For example, while navigation projects will be more sensitive to modifications to depth-limited wave height and wave run-up, ecosystem projects may be sensitive to changes in wave energy, hydroperiod, and water quality (salinity and turbidity). Ecosystem projects are likely to be sensitive to the *rate* of SLC. Factors that should be assessed at this stage include tidal and wave height range (typical and extremes), possible interaction with local ground or surface water flow, frequency of events, and rate of change of key variables. Project-specific appendices at the end of this document outline typical loading and processes that are relevant to each mission area. Table 6 summarizes primary processes by project type that may be impacted by SLC.

(c) SLC is just one component of water level that has the ability to impact projects and shores. Other parameters that vary significantly from region to region include tidal range, storm surge, and vertical land movement. Placing the magnitude and uncertainty of SLC within the larger framework (i.e., quantifying changes due to SLC within the natural variability of a project site) provides additional information regarding the relative importance of SLC in the overall picture, as well as the potential for cumulative effects.

(d) An essential element of developing a good understanding of the project area's exposure and vulnerability is assessing how quickly the individual scenarios might necessitate an action due to thresholds and tipping points. It will be important to identify key milestones in the project timeline when impacts are expected. Building on an approach from the United Kingdom Climate Impacts Program (UKCIP), three epochs are addressed: 20, 50, and 100 years. This approach provides an assessment of when in the planning horizon the SLC impacts are expected. For some projects, for instance, flooding is a problem during normal spring tides, and SLC impacts might be felt almost immediately. For those projects, the level of urgency would be elevated. Summarizing the loading and processes under Tier 2 will indicate if the project area is already experiencing problems.

Table 6. Primary physical processes sensitive to SLC by project type.

All Processes	Navigation	Coastal Storm Damage Reduction	Flood Risk Reduction	Ecosystems
Wave Attack				
wave runup and overtopping	X	X	X	X
wave transformation	X	X	X	X
depth-limited wave	XX	X	X wave and storm	
surge	X	X	X	X
rubblemound damage rate	X	X		
ship wake impacts	X			X
Inundation				
wave runup and overtopping	X	X	X	X
wave and storm surge	X	X	X	X
tailwater effects		X	X	X
hydrologic regime			X	X
Short- and Long-Term Erosion				
wave runup and overtopping	X	X	X	X
depth-limited wave	X	X	X	X
wave and storm surge	X	X	X	X
shoreline change rates (storm event, seasonal, longterm)	X	X	X	X
Inland Waterways/Drainage Hydraulics				
seasonal and extreme backwater profiles			X	X
canal/drainage system profiles	X		X	X
groundwater flow characteristics			X	X
Harbor, Basin, Channel Hydrodynamics				
harbor resonance	X			
vessel excursion and movement	X			
wave transmission (diffraction, overtopping, permeability)	X			
water quality circulation characteristics	X			X
Morphological Change and Shoaling				
foundation scour	X	X		
adjacent shoreline change	X	X		X
disposal site dispersiveness	X			
sediment transport and deposition (subaqueous and subaerial)	X	X		X
subsidence/uplift	X	X	X	X
Water Quality Changes (surface and ground)				
salinity	X			X
nutrients and dissolved oxygen				X
circulation	X			X
mixing of ocean/estuarine/river water	X			X
Management Practices				
catchment management	X	X	X	X
dredging and material placement	X	X		X
groundwater or fluid withdrawal	X	X	X	X
beach nourishment	X	X	X	X
shoreline stabilization measures	X	X		X

(e) Figure 14 illustrates how the projected rate of change might alter the amount of lead time available prior to an action. A tipping point can be tied to a physical elevation or process, or it can be connected to how a system or societal body responds. In either case, the tipping point moves the project performance into an unacceptable category. In addition, some project actions might take more lead time than others to execute. For example, if the rate of SLC was expected to threaten significant critical infrastructure or development areas, relocation or large-scale risk reduction of those areas may involve extensive community involvement and take years to accomplish. Similarly, any response that requires additional authority before USACE can act may require years of lead time.

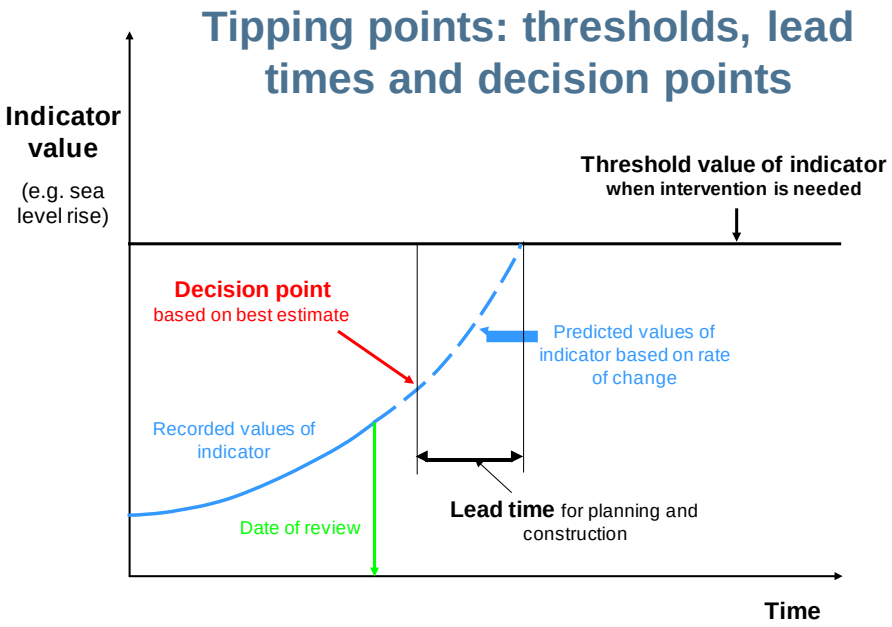


Figure 14. Impacts of thresholds and tipping points on future decision points. (From Environment Agency 2009.)

(f) After the Project Area Vulnerability assessments, it should be possible to summarize whether the projected SLC is expected to provide a significant contribution to the overall loading of a project, what level of vulnerability the project area has to sea level rise, and the critical infrastructure and potential consequences of actions in the project area. The assessment of the robustness of the thresholds or the relative weakness of particular links in the system will also be identified. All of this information will help determine the required level of analysis for the project area with respect to SLC and should lead to an intermediate decision point. It should also be possible at this point to determine, given the potential SLC, whether protect, accommodate, or retreat is likely to be a more viable and sustainable option.

e. Tier 3 – Alternative Development, Evaluation, and Adaptability.

(1) Tier 3 in the screening analysis, shown as the green bottom tier in Figure 9, incorporates USACE Planning Steps 3 through 6. As noted previously, SLC may be only one of

the considerations for alternative development. The Tier 2 analysis will inform the study team regarding the relative importance of SLC on without-project and with-project alternatives. Based on the project's purpose and the project area's vulnerability, alternatives are proposed to either protect, accommodate, or retreat from the effects of SLC.

(2) The degree to which SLC is addressed when making any project investment decision will be directly related to the level of exposure and vulnerability posed by SLC, as well as how soon that vulnerability occurs within the project's life cycle. Throughout the decision-making process, it should be determined how sensitive alternative plans and designs are to the range of potential future rates and magnitudes of SLC. *SLC rates* will inform the timeline, while the *SLC magnitudes* will inform vulnerability, viability, etc. over that timeline. Further assessments should include determining how this sensitivity affects calculated risk, and what design or operations and maintenance measures should be implemented to minimize adverse consequences while maximizing beneficial effects.

(3) The basic steps to incorporate SLC into the formulation of alternatives (Planning Step 3) include:

(a) Develop measures to address the identified problems and opportunities.

(b) Identify each measure's implementation strategy (anticipatory, adaptive, reactive, or combinations).

(c) Develop qualitative and quantitative performance metrics for later use in comparing the plans.

(d) Combine measures into alternatives that are as resilient and robust to SLC as possible over the planning horizon, including actions by others. These combinations may include changes from one to another type of measure over time as sea level changes.

(e) Establish start and finish points at which alternatives remain viable and determine if alternatives remain adaptable at the end of the planning period.

(4) Plan formulation is typically guided by four criteria: completeness, acceptability, efficiency, and effectiveness. These criteria may be viewed differently when SLC is considered in a planning effort. Over the course of the planning horizon, the formulated plans must be judged against these criteria *under the changing conditions expected in each scenario*. The ability of plans to meet the criteria at various times throughout the planning horizon may provide a path and breakpoints for adaptation to help identify a robust strategy. Measures can be structural (e.g., seawall, revetment) or nonstructural (e.g., retreat).

(5) Sea level rise may require very difficult choices in high-risk areas. Managed retreat, in particular, is a complex and controversial strategy that may be unpopular but necessary. Strategies cannot be limited to USACE actions alone. For example, managed retreat should be evaluated as part of coastal storm damage reduction studies. If it is not examined in a credible way during a planning study, it may become a situation of unplanned ad-hoc retreat in the event that rapid SLC occurs.

(6) Table 7 provides a summary of potential system effects of SLC, along with possible adaptation approaches useful in addressing those effects. Since it is recognized that SLC is not occurring in isolation, the table includes both climate- and non-climate-related interacting factors. Some interacting factors appear twice because they can be influenced both by climate and non-climate factors. These factors should be considered during alternative development.

(7) Some of the entries in Table 7 refer to secondary project impacts that will influence whether the project continues to deliver the assumed benefits. For example, adequate drainage of the port facilities may be relevant to navigation projects if it affects the ability for the project to realize the assumed benefits or it affects the function and viability of the port operation. Coastal storm damage reduction project options will be somewhat controlled by existing development associated with the project. Ecosystem projects may perhaps have the highest level of flexibility in that some areas may allow conversion of one type of valuable ecosystem or habitat into another type. Also, marshes have some ability to accrete with sea level.

(8) The general SLC-related categories of investigation at this tier include 1) assessing the measure's sensitivity to SLC, in terms of both project stability and project performance, and 2) evaluating the expected alternative implementation strategy with consideration of the project performance timeline. Stability refers to the ability of the structure or project to withstand the additional loading that SLC and its cumulative effects add to the structure or project. In the case of a breakwater, increases in loading include bigger waves attacking the structure as well as a greater overtopping rate, which has the potential to destabilize the lee side of the structure.

(9) Increasing the design water level can exceed the limit state for many coastal engineering design loading scenarios. This can be of particular concern where depth-limited waves are encountered and the design loading scenario is a non-linear function of wave height or total water depth. Table 8 provides an example of the effect that a potential sea level rise (SLR) may have on several performance modes for coastal zone attributes and infrastructure. In the case of a floodwall designed to resist 10ft (3m) of surcharge water depth and a depth-limited wave height of 6ft (1.8m), adding a 2.4ft (0.7m) SLR to the structure's design water level will increase the force of total dynamic wave loading by 120%, compared to the structure's current designed condition.

(10) Wave-induced overtopping is a design limit state that is highly sensitive to total water depth and depth-limited wave height (at the toe of the structure). In the example in Table 8, a water level increase of 2–3ft (0.6-0.9m) increases wave-induced overtopping by more than 100%. Overtopping of coastal levees and floodwalls can complicate overall flood-control system reliability by compromising the stability of the back side of the overtopped levee or flood wall and/or by inundating the protected interior area (via overtopping). During a three-hour storm/flood, the volume of water that can collect behind 100 m of flood control barrier being overtopped by a transient rate of 0.001 m^3/s/m (effectively realized during 10% of the storm duration) is about 110 m^3. If the affected flood control barrier is 1,000 m long, the volume of water introduced to the interior area is 1,100 m^3, assuming a very small transient overtopping rate of 0.001 m^3/s/m. Given the uncertainty in overtopping estimation, the interior area could be subjected to a significant volume of unexpected water. The back side of the flood barrier or

interior infrastructure such as pump stations can be compromised if the overtopping water volume is higher than expected.

Table 7. System effects of relative sea level rise and possible adaptation approaches. [Adapted from Nicholls (2010, 2011) and Linham and Nicholls (2010).]

System Effects		Possible Interacting Factors		Possible Adaptation Approaches
		Climate	Non-Climate	
Increased Frequency / Severity of Storm Inundation	a. Coastal (flooding directly from the sea)	Waves, storm climate, erosion, rainfall, runoff, sediment supply, wetland loss and change	Sediment supply, flood management, erosion, land reclamation, land management	Revetments, seawalls, surge barriers (P-hard) Dune/beach construction, vegetation (P-soft) Building codes, flood-proof buildings (A) Land-use planning, hazard mapping, flood warnings (A/R) Abandonment, re-purpose (R)
	b. Inland (flooding due to tailwater effects)	Rainfall, runoff, wetland loss and change	Catchment management, land use, river and canal system, drainage system, geology	Dikes, surge barriers, closure dams (P-hard) Building codes, flood-proof buildings (A) Land-use planning, hazard mapping, flood warnings (A/R) Abandonment, re-purpose (R)
Accelerated Wetland loss and change		CO2 fertilization, sediment supply, migration space, rainfall, runoff	Sediment supply, migration space, land reclamation (i.e. direct destruction), species population changes	Nourishment/ sediment management, hydraulic adjustments (P-soft) Land-use planning (A/R) Realignment, forbid hard defenses (R) Abandonment, re-purpose (R)
Accelerated Erosion (of "soft" morphology)		Sediment supply, wave/storm climate, wetland loss and change	Sediment supply, structural measures	Coastal defenses / seawalls / land claim (P-hard) Nourishment, vegetation (P-soft) Building setbacks (R)
Infrastructure Damage		Sediment supply, wave/storm climate, wetland loss and change	Structure type, erosion, secondary structures	Coast defenses, seawalls, adjust/improve structures (P-hard) Nourishment (P-soft) Building setbacks (R)
Salt water intrusion	a. Surface waters	Runoff, saltwater intrusion to ground water, temperature	Catchment management (over-extraction), land use	Salt water intrusion barriers (P) Change water extraction (A/R)
	b. Groundwater	Rainfall, saltwater intrusion to surface waters, temperature	Land use, aquifer use (over-pumping)	Freshwater injection (A) Change water extraction (A/R)
Impeded drainage, higher water tables		Rainfall, runoff	Land use, acquifer use, catchment management	Drainage systems / polders (P-hard) Change land use (A) Land-use planning / hazard delineation (A/R)

Example adaptation approaches are coded: P = Protect (Hard, Soft), A = Accommodate, R = Retreat
d d f i h ll ( ) i h i h ll ( ) i h ll

Table 8. Example effect of sea level rise (SLR) on various performance functions for infrastructure along the coastal margin.

Physical Process or Loading Condition at a nearshore location where **PRESENT Wave action is depth-limited**	**Performance Function** cast in terms of **SLR-affected parameters**	**Potential Sea Level Rise (SLR), ft**		
		Low Value	**Intermediate Value**	**High Value**
		0.7	1.1	2.4
		Depth-Limited Wave Height (H_{SLR}) due to SLR, ft		
Present Depth-Limited Wave Height (H_p), ft = 6	$H_{SLR} \sim = H_p + SLR$	6.7	7.1	8.4
Present Water Depth @ Structure ($Depth_p$), ft = **10**	$Depth_{SLR} = Depth_p + SLR$	**Relative Change in Performance Function due to SLR**		
Conventional Structure Stability (rigid)				
Wave Loading - Dynamic Pressure	Minikin: f (H)	12%	18%	40%
Wave Loading - Total Dynamic Force	Minikin: f (H^2, Depth)	33%	45%	119%
Compliant Structures (Armor Unit Stability)				
Direct Wave Action (armor unit weight)	Hudson Equation: f (H^3)	39%	66%	174%
Overtopping (wave action) - Volume	USACE: f ($H^{1.5}$, $\exp^{freeboard}$)	88%	152%	522%
Overtopping Wave Action (armor unit weight)	Van Gent: f ($\exp^{H}$, $\exp^{freeboard}$)	56%	95%	250%
Nearshore and Structure Foundation Stability				
Foreshore Slope (rise/run)	Kamphuis: f ($H^{-0.5}$)	-5%	-8%	-15%
Sediment Transport Potential (morphology change)	Kamphuis: f (H^2)	25%	40%	96%
Wave Run-up, Along Shoreface				
Run-up Distance	USACE: f (H)	12%	18%	40%
Run-up Speed	USACE: f ($H^{0.5}$)	6%	9%	18%

Note: The increase in coastal infrastructure loading or effects on the "performance function" are shown in terms of the increase in nearshore wave height (H) due to sea level rise (SLR). For this case, the nearshore wave height (H) is depth-limited, and an increase in water level of by SLR will increase the depth-limited wave height by a corresponding Δ value. For "overtopping" and "lee-side armor" performance functions, the following values were used: Water level = 7.1ft (2.2m), incident wave height/period = 6ft (1.8m)/12 s, structure crest elevation = 10ft (3m), to elevation = –2.9ft (0.9m), structure slope = 1v:3h. All other performance functions were evaluated on a relative basis using the change in depth-limited wave height due to SLR, compared to the present condition (p). Relative change in performance function = [(future value – present value)/present value] × 100.

(11) In the case of rubble-mound design (armor units sized for breakwaters, revetments, or jetties based on wave height), adding an SLR of 2.4ft (0.7m) to the design water level produces an increase in depth-limited wave height of approximately 2ft (0.6m). Because rubble-mound armor unit stability is proportional to wave height cubed (H^3), a relatively moderate increase in water depth (from 10 to 12ft) (3 to 3.6m) produces a much higher load on the armor units. In one example, a rubble-mound structure armor layer designed for a 6ft (1.8m) wave, but subjected to an 8.4ft (2.6m) wave (due to a SLR of 2.4ft/0.7m), would have its design limit state exceeded by 174%. The result could lead to a failed rubble-mound structure. See Table 8 for additional details.

(12) Figure 15 illustrates an example of armor unit size sensitivity to SLC using the Hudson equation (EM 1110-2-1100). In contrast, impacts to performance might include a higher wave height in the lee of the structure or a greater inundation frequency and magnitude of the port facilities. A determination will be made as to whether the expected impacts are driven by extreme events or by overall processes. Examples of a process-driven impact are increased salinity in an estuary or habitat area or a gradual change in the overall mean or high tide range. For each set of measures, analyses will determine how inundation, erosion, and wave attack may change with SLC.

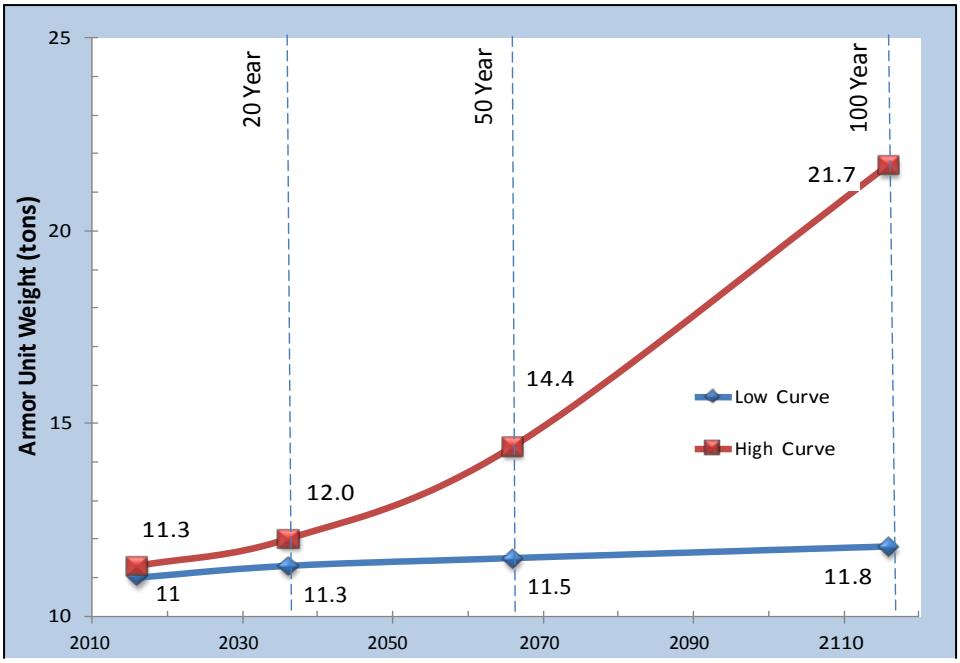


Figure 15. Sensitivity to SLC of frontside design armor for a rubble-mound structure (EM 1110-2-1100).

(13) In the third tier, measures are combined into alternatives that provide resiliency to SLC over the planning horizon. Implementation strategies range from a conservative anticipatory approach, which constructs a resilient project at the beginning of the life cycle, to a reactive approach, which consists of doing nothing until the impacts are experienced. Between those extremes is an adaptive management strategy, which incorporates new assessments and actions throughout the project life based on thresholds and triggers. Basic definitions of these strategies are summarized in Section 3-2d. Once adequately screened for project condition, including SLC, alternative plans (routes or pathways) can be developed. A single measure may not be robust enough to address the range of outcomes resulting from SLC over the 100-year adaptation horizon. An alternative plan may include multiple measures adaptable over a range of SLC conditions and over the entire timeline, with different measures being executed as the need indicates.

(14) Evaluation of Alternatives (Planning Step 4)

(a) Evaluation. In the evaluation step, the significant contributions or effects of individual measures and plans are quantified and judged. The first task is to estimate the with-project values of the metrics or evaluation criteria identified in the inventory and forecast (Planning Step 2). Models can be used to measure the outputs for each alternative under each scenario. The effects of SLC on coastal processes may be even more uncertain than the rate of SLC, as the uncertainties compound. Assuming that methods can be developed to incorporate SLC into the analysis, values for each evaluation criterion under each plan and each scenario would be estimated.

(b) Assessment. Once these values have been estimated, the second task is to assess each plan's performance, i.e., to measure the future with-project condition against the future without-project baseline condition established in Planning Step 2. Consideration should be given to the timing and magnitude of effects. In particular, the effects of the different rates of SLC on the timing and magnitude of project outputs should be explicitly considered. For example, assess each measure's stability and performance sensitivity to SLC, evaluate each measure's adaptability and potential conversion (in the case of ecosystems), and/or identify any thresholds or tipping points related to the implementation of the given measure.

– Typical evaluation criteria include project costs, National Economic Development (NED) benefits, habitat units, and life safety. If the evaluation indicates a significant change in any of these areas under the different scenarios of SLC, then the conditions should be deemed sensitive to the rate of change, and formulation and evaluation procedures should be structured to explicitly compare the available adaptation responses. Generally speaking, a change would be considered significant in this context if it would change the decision outcome. Essentially, the same types of engineering tools that have traditionally been used can be used to evaluate different plans and determine how sensitive they might be to SLC. In the case of SLC, where the loading conditions and the exposure of the project area may change over the project's life, it is important to assess the alternative's sensitivity to both project stability and project performance and to identify how those might change over the project timeline.

– A series of key questions are considered:

- Are residual risks manageable and does a plan exist to manage them?
- Is the strategy sustainable? Are resources available for the system to remain viable?
- How do the alternatives compare given the defined performance metrics?
- What can go wrong, how can it happen, what are the consequences, and how likely is it?
- Does implementation of this strategy preclude future decisions or opportunities?

– Figure 16 illustrates a range of alternative pathways considered for a coastal storm damage reduction project. The project was intended to reduce risk through a moderate dune shoreline fronting a developed barrier beach upland area. The figure connects the stability and performance of a range of alternatives to the degree of SLC in the project area. The actual preferred plan will be a result of a trade-off analysis between the project costs (both initial and maintenance), the expected impacts, the expected benefits, and the level of risk tolerance of the stakeholders. The horizontal dashed lines indicate the points along each SLC curve at which the measures lose their viability and necessitate a change in pathway to another measure. Here, the viability of an alternative is assessed for a projected magnitude of SLC rather than for a specific point in time. For this project, the threshold at the back side of the barrier island factors into the decision analysis. The SLC between the beginning and ending thresholds indicates the amount of change over which the measure is adaptable. At the same time the height of each column is directly related to the degree of robustness of each alternative. A robust measure should be resilient or adaptable across all of the SLC scenarios. For this project it was determined that seawalls would not be needed right away nor could that alternative be immediately implementable due to local ordinances or environmental regulations. It could, however, be implementable later

in the project life cycle if nourishment options are no longer as effective under higher sea level magnitudes. This is shown as a slight offset of the seawall measure along the vertical axis. The three pathways represent potential alternative plans. They are not necessarily parallel, although they could be. For instance, it could be decided that a project area should begin "flood proofing" the most vulnerable structures while also beginning beach nourishment by constructing dunes and planting vegetation. The alternatives could be combined or implemented individually. The plan that is "preferred" or implemented is very project specific and depends on projected benefits and costs, considering environmental and engineering considerations.

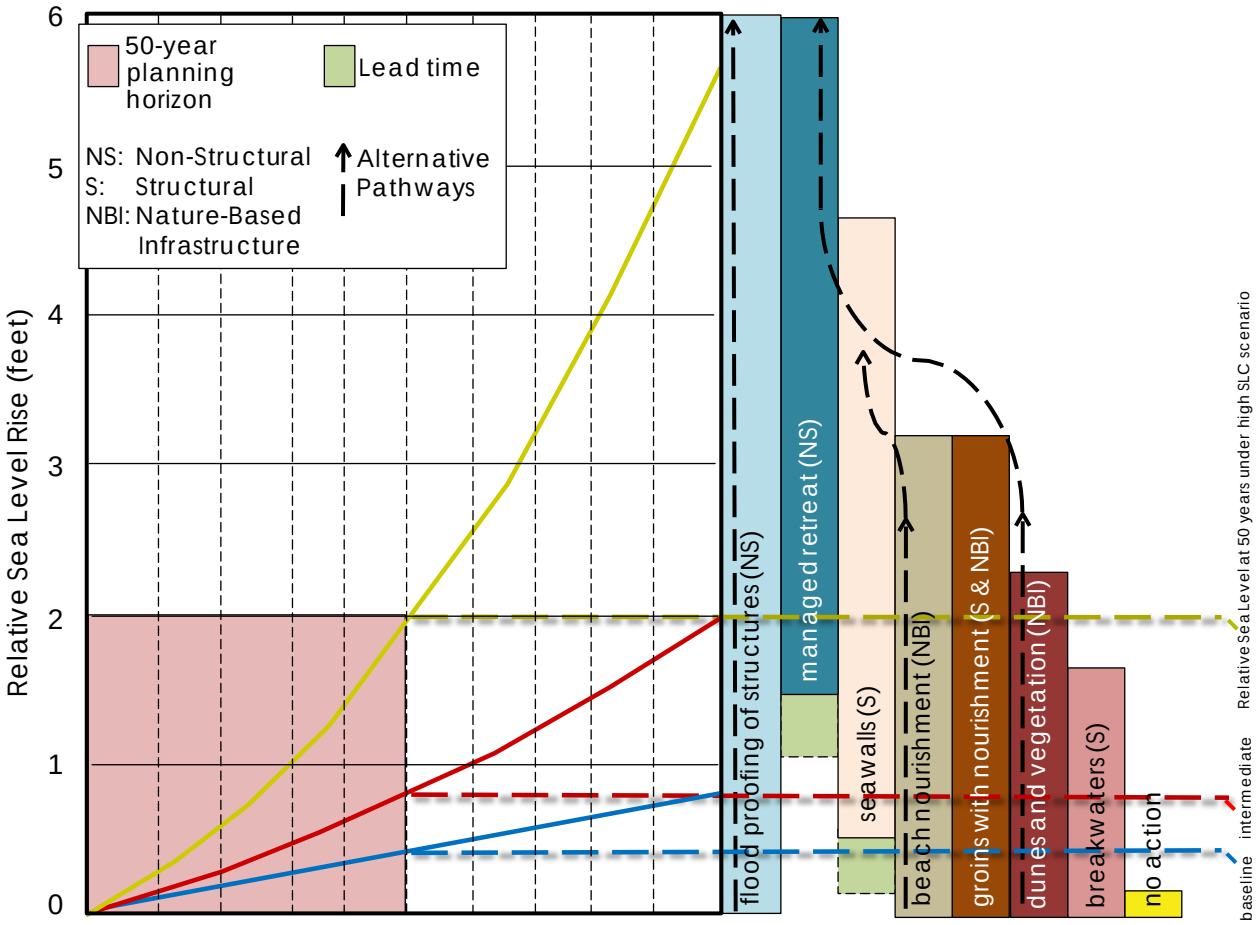


Figure 16. Example alternative pathways for a coastal storm damage reduction project.

(15) Comparison of Alternatives and Making a Recommendation (Planning Steps 5 and 6)

(a) Plan Comparison. Each plan represents an alternative strategy for achieving the planning objectives. The purpose of the plan comparison is to identify the strengths and weaknesses of each plan and ascertain which meets the formulation criteria and performs best according to the evaluation criteria. Each plan's performance, however, may be influenced by the effects of SLC, so a plan that satisfies all four formulation criteria under one scenario (or SLC curve) may fail one or more criteria under other rates of change. This may require

revisiting the formulation process, looking for additional measures that improve plan performance under a given scenario. On the other hand, this may be unnecessary if the initial formulation strategy ensured that the list of plans represents a full range of options, including variations in timing of implementation.

(b) Ranking. The ranking of plans should reflect the plan's robustness. A plan is robust if it performs well across the full range of scenarios. The questions asked in the evaluation of individual plans should be revisited to compare costs, benefits, residual risk levels, adaptive capacity, sustainability, resiliency, and other performance metrics.

(c) Recommendation. Since the P&G guidance (USACE 1983), the USACE decision rule has typically been to maximize net NED benefits, with a recent expansion to include National Ecosystem Restoration as an equal objective. These have typically been numerically driven answers that could be identified by comparing incremental costs and benefits. Since 2005 there has been a push to explicitly include life safety in the decisions leading to the recommended project rather than leaving it to be implicitly managed through separate activities.

(d) Decision Drivers. Climate change and other large-uncertainty drivers require that decision criteria change focus from optimal solutions towards solutions that emphasize adaptability or robustness. Applying these decision criteria is one step in a much larger decision analysis process. Consequently, the quality of the decision depends on the quality of the work in formulating alternative plans and developing the metric set. A good decision is the outcome of an iterative, interactive process that weighs the trade-offs among available options. Important value judgments will be required with respect to societal benefits and costs.

– Trade-Offs: Costs. If the trade-offs are primarily between different forms of costs (now versus later, or project costs versus damages), the 1983 P&G still governs and an NED plan will have to be identified. A regret-based calculation (refer to ER 1105-2-100 for a discussion of different types of trade-off analyses) can be made among the scenarios, as illustrated in the following statement:

> "Whether it is beneficial to design coastal infrastructure to anticipate rising sea level depends on economic analysis of the incremental cost of designing for a higher sea level now, and the retrofit cost of modifying the structure at some point in the future. Most long-lived infrastructure in the threatened areas is sufficiently sensitive to rising sea level to warrant at least an assessment of the costs and benefits of preparing for rising sea level." (CCSP 2009, p. 427)

– Trade-Offs: Public Health and Safety. If costs must be balanced against safety or public health, then decisions should be precautionary with respect to the safety risk. In that case, we may seek to minimize the worst-case outcomes among the scenarios. Accordingly, while beach nourishment for erosion control may present a trade-off among the timing of costs, a seawall or coastal levee introduces a safety consideration, because it seeks to reduce inundation of populated areas. In this case, a careful analysis of residual risk levels should inform the decision.

(16) At this point in the analysis, alternatives are compared and a recommendation is made to either proceed with the project or conduct further analysis and re-evaluation. The adequacy of the measures to address the problems and opportunities and the planning objectives are reassessed.

CHAPTER 4

Layout of Mission Area / Project Type Appendices

4-1. Appendices. Appendices C–F provide more detailed information relevant to each USACE mission area that may be impacted by SLC. Those primary areas include navigation, coastal storm damage reduction, flood risk reduction, and ecosystems. It is important to note that some projects may need to refer to more than one appendix if the project purpose or impacts involves more than one mission area. Each appendix begins with general background and a discussion of principles, issues, and methods related to the mission area. In the context of this ETL, principles are those concepts that are commonly accepted to be true and that underpin assessments of the effects of SLC on USACE projects. Issues are matters specific to each principle that should be considered in properly addressing the effects of SLC. Issues do not necessarily have a single solution. Methods encompass a range of tools from first-level screening (e.g., rules of thumb) to higher-level modeling (e.g., complex computational models) used to address each of the issues.

4-2. Layout of Appendices. Each appendix includes the categories noted below:

a. General background for each mission area or project type.

b. Key questions and concepts pertinent to that mission area. To highlight areas that might change for a project under a sea level rise scenario, principles and issues are listed that identify the characteristics of a project that will need to be assessed and re-evaluated under potential future SLC.

c. Discussion regarding relevant stability and performance function sensitivity to SLC.

d. Typical tipping points and thresholds that would generate an impact or an action.

e. Appropriate levels of analysis and the variety of available tools.

f. Examples that illustrate how SLC might be included in a typical project analysis.

g. Expected regional differences.

4-3. Principles and Processes. The foundation of each appendix can be found in the list of principles toward the beginning of each appendix. Table 9 summarizes the identified principles by mission area. In addition to a summary of each mission area's goals, Table 9 provides key principles in the following subareas for each mission area: coastal and hydrodynamic forces and processes, morphological response, infrastructure vulnerability or biological response (ecosystems), human response, and project feature or system response.

Table 9. SLC-related principles by mission area.

	Navigation	Coastal Storm Damage Reduction	Flood Risk Reduction	Ecosystems
Mission Goals	Provide safe, reliable, and efficient waterborne transportation systems for movement of commerce, national security needs, and recreation Reduce maintenance of existing structures.	Reduce damage from wave attack and erosion Reduce damage from inundation Reduce emergency costs Reduce maintenance of existing structures	Reduce frequency of damaging levels of flood inundation Reduce flood damages without significantly altering the nature or extent of flooding	Assist in the recovery of degraded riparian, wetland, and aquatic ecosystems and establish ecological processes necessary for their sustainability, resiliency, and health under current and future conditions.
Coastal and Hydrodynamic Forces and Processes	Navigation projects are generally located along the open coast and are typically exposed to the direct impacts of the coastal environment. SLC will result in changes to incident loading parameters as well as to cumulative effects of multiple parameters. Coastal processes related to navigation project performance will be impacted.	SLC has the potential to act directly on the landscape and affect other coastal forces that act on the landscape. The configurations of coastal landscapes are dictated by interactions between a site's physical characteristics and the coastal forces that act on it. Increased water levels combined with shoreline recession will increase both the magnitude and the frequency of impacts along the coastline.	As sea levels change, river discharges and flowlines will be impacted due to backwater effect. Altered sea levels will affect water levels in coastal water bodies used as sinks by interior drainage projects. Altered sea levels will affect water table depths and groundwater gradients. Altered sea levels will affect salinity of coastal aquifers.	Sub- and intertidal coastal ecosystems are dynamic over time and space and evolved concomitant with historical SLC. Sea level controls the position of intertidal ecosystems and drives direct and indirect hydrologic changes to which coastal ecosystems respond. Rate of future SLC will be important in determining response of intertidal ecosystems to SLC.

	Navigation	Coastal Storm Damage Reduction	Flood Risk Reduction	Ecosystems
Morphological Response	Relative SLC will result in morphology responses within and adjacent to navigation projects that may affect feature stability as well as project performance. SLC has the potential to modify the coastal processes affecting navigation channel stability and disposal site dispersiveness.	Coastal landscapes vary in their degree of vulnerability to SLC. Cross-shore and alongshore morphological evolution will together define how a system responds.	As sea levels change, hydraulic gradients will be impacted, affecting sediment transport in rivers. Modifications of coastal and riverine landforms and coastal marshes by increased forcing can result in increased risk of flood intensity and frequency.	SLC drives geologic and soil environmental changes to which coastal ecosystems respond. Coastal ecosystems will show a range of vertical (upward growth to drowning-in-place) and lateral (eroding/ retreating to prograding) responses to SLC.
Infrastructure Vulnerability or Biological Response (Ecosystems)	SLC has the potential to change the design loading and key processes relative to navigation features (structures, channels, disposal sites) as well as non-Federal project features over the project life cycle. Stability may be affected by SLC-induced changes to the forces that act on a feature, which might reduce the life of the feature or increase its maintenance requirement.	Man-made infrastructure may have vulnerabilities to SLC that may or may not depend on the natural characteristics of a coastal landscape. The frequency and severity of various impacts that are acceptable to human stakeholders are relevant to vulnerability.	Raising flood defenses transfers risk to other areas and may impact drainage, ecosystem services, or other elements of flood risk. As sea levels change, the extent of coastal storm impacts will move up or downriver. In estuaries, bays, and coastal rivers, floods at the same location may be caused by coastal or riverine forcings or a combination of the two.	For coastal ecosystems with a physical structure formed by organisms, ecological tolerance of these organisms to SLC and other biological interactions affecting these organisms may produce interactive effects to coastal ecosystems greater than the effects of SLC alone. Important biogeomorphic organisms have finite range of ecological tolerances to forcing factors and conditions.

	Navigation	Coastal Storm Damage Reduction	Flood Risk Reduction	Ecosystems
Human Response	SLC will, at some water level threshold, cause human responses. Some human responses to SLC may have a strong influence on the future behavior of navigation project sponsors and stakeholders. Anthropogenic responses must therefore be accounted for when determining future without-project and with-project conditions.	SLC will, at some water level threshold, cause a human response. Some human responses to SLC may have a strong influence on the future behavior of the beach system. Anthropogenic responses must therefore be accounted for when determining future existing project or future without-project conditions.	Increased flood risk due to SLC will force impacted populations to respond. The future without-project condition, given SLC, cannot be assumed to be the same as today. Reducing flood risk to a particular area may induce development, putting a larger population at risk than previously existed.	Shoreline stabilization, navigation channels, and coastal development will limit ecosystem migration opportunities. Anthropogenic stressors may interact with physical and biological factors/stressors to affect ecosystem response.
Project Feature or System Response	Individual project features (revetments, jetties, breakwaters, channels, etc.) may require modification over the project life cycle to maintain stability and function. Project features should be assessed both in plan view as well as cross section in terms of their stability and performance. Long-term maintenance required to maintain function should be addressed. Project operation and performance may be impacted on a routine basis.	On existing projects, SLC may impact both the stability and the performance of engineered features. An engineered project may result in a site being more or less sensitive to SLC compared to that site with no project. The nonstationary nature of SLC may result in the need to transition to different alternatives at different threshold water levels. An optimum project is adaptable, resilient, and cost effective and has a plan for adaptation.	Projects should be adaptable to future sea level conditions, but different project elements are adaptable to varying degrees. Increased precipitation, increased storminess, groundwater and surface water flow, and interaction with ecosystems are all areas of potential cumulative effects.	Coastal habitats vary in vulnerability to SLC as a function of whether the project is sub-, inter-, or supratidal and whether prominent habitat structure is a living (plant or animal) or geologic material. Migration space availability and character affects future ecosystem conditions. Tolerance to physical environmental change of important biogeomorphic organisms affects coastal biogeomorphic ecosystem response to SLC.

CHAPTER 5

Conclusions

5-1. Long Service Life. USACE projects, programs, and activities often involve the development and management of long-lived systems. The longer the life of engineered systems and their related socioeconomic and ecological systems, the more important it becomes to evaluate the sustainability and resiliency of these combined systems in the face of climate change effects. This document outlines the recommended planning and engineering approach at the project level for addressing impacts of projected SLC at USACE projects. The goal of this document is to provide a method to develop practical, nationally consistent, justifiable, and cost-effective measures, both structural and nonstructural, to reduce vulnerabilities and improve the resilience of our water resources infrastructure to SLC.

5-2. Future Conditions. Because of the uncertainty and variability of future SLC, the approach outlines a robust framework that is flexible and adaptable to multiple future scenarios. Emphasis is placed on both how the project operates within a larger system and how project decisions now can influence future impacts. Comprehensive recognition and identification of extremes and cumulative and system effects, along with the inherent uncertainty related to defining these, lead to a multiple scenario approach. An understanding that the identified extremes as well as project-related impacts may change over the life cycle is integral to the multiple scenario approach. The projections of global sea level rise are likely to improve with the advancement of ice sheet modeling over the next 5 years. This could enable a narrowing of the scenarios and reduction of uncertainty. USACE, along with its partner Federal science agencies, will monitor advances in the science and update the guidance as needed.

5-3. Level of Effort. The project approach framework conveys to the field the level of detail required as a function of project type, planning horizon, and potential consequences. An essential task is to identify the potential for adaptation throughout the project life or project phasing. Region-by-region information and examples are being developed through a variety of pilot studies. Within this approach, a hierarchy of decisions is developed such that, in assessing SLC, the importance of the decision being taken is recognized and an appropriate analytical approach is adopted. The essential role of USACE relationships with other Federal agencies and state and community partners is recognized.

5-4. Framework. The purpose of the framework is to define the strategic importance of potential impacts on SLC in both time and space. *SLC rates* will inform the timeline, while the *SLC magnitude* will inform the vulnerability, viability, etc. over that timeline. For ecosystem projects, the *rate* of change will affect vulnerability. The assessment of alternatives is motivated by the potential magnitude in the project area, as well as the potential changes in those impacts. The required level of analysis is determined by using key review points to analyze the consequences of a wrong answer. Essential to this approach is a comprehensive knowledge of the system within which the project operates, including key elevations, weak links, and thresholds. Identified thresholds and tipping points may alter the acceptable choice and the timing of alternatives. Project stability and performance functions may have different

sensitivities to SLC. Robustness to the range of future conditions is recommended as a criterion in evaluating and selecting alternatives.

5-5. Consequences. Being able to adequately express the potential impacts of a wrong answer, in both economic and operational terms, is very important. The connectivity within the system, as well as the potential for cumulative or system effects, will help in assessing the potential level of impacts. The essential role of extreme events will help in identifying vulnerability and residual risk. The analysis facilitates the development of a graduated level of response that can be applied using a range of planning strategies over the adaptation horizon of the project. The final product is a plan that articulates what could go wrong over the lifetime of the project as well as possible solutions. In addition, plans will be developed that monitor new developments in both climate science and adaptation plans so that adjustments can be made to the approach.

5-6. Staged Decision-Making. While the actual methods and the level of detail will vary widely for each USACE project, depending on the size and scope, the underlying framework developed favors a staged approach with the results guiding the level of effort for each subsequent stage. Some projects (in some cases, smaller or low-impact projects) will use entirely qualitative methods with little extra effort required during the planning process to adequately address SLC, while others, based on the results of the staged screening, will require more detailed quantitative efforts and incorporate the risks for each scenario in the decision-making process.

APPENDIX A

References

A-1. Required References.

a. Federal Government Publications.

Burkett and Davidson 2012
Burkett, V.R., and M.A. Davidson (Eds.). (2012) *Coastal Impacts, Adaptation, and Vulnerability: A Technical Input to the 2012 National Climate Assessment*. Cooperative Report to the 2013 National Climate Assessment.

CCSP 2009
Climate Change Science Program (2009) *Synthesis and Assessment Product 4.1: Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region*. A report by the U.S. Climate Change Program and the Subcommittee on Global Change Research. [J.G. Titus (Coordinating Lead Author), E.K. Anderson, D. Cahoon, S.K. Gill, R.E. Thieler, J.S. Williams (Lead Authors)]. Washington, DC: U.S. Environmental Protection Agency. http://www.climatescience.gov/Library/sap/sap4-1/final-report/default.htm

NRC 1987
National Research Council (1987) *Responding to Changes in Sea Level, Engineering Implications*. Committee on Engineering Implications of Changes in Relative Mean Sea Level, Marine Board, Commission on Engineering and Technical Systems, National Research Council. Washington, DC: National Academy Press. http://www.nap.edu/catalog.php?record_id=1006

NRC 2012
National Research Council (2012) *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Committee on Sea Level Rise on California, Oregon, and Washington, Board on Earth Sciences and Resources and Ocean Studies Board. Washington, DC: National Academy Press.

Parris et al. 2012
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 U.S. National Climate Assessment*. NOAA Technical Report OAR CPO-1. Washington, DC: National Oceanic and Atmospheric Administration, Climate Program Office. http://cpo.noaa.gov/Home/AllNews/TabId/315/ArtMID/668/ArticleID/80/Global-Sea-Level-Rise-Scenarios-for-the-United-States-National-Climate-Assessment.aspx

b. Other Publications.

Bindoff et al. 2007
Bindoff, N.L., J. Willebrand, V. Artale, A. Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley, and A. Unnikrishnan (2007) Chapter 5,

Observations: Oceanic Climate Change and Sea Level. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, ed.). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter5.pdf

Burkett 2013
Burkett, V. (2013) *Coastal Impacts, Adaptation, and Vulnerabilities: A Technical Input to the 2013 National Climate Assessment*. Washington, DC: Island Press.

Church and White 2006
Church, J.A., and N.J. White (2006) A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* 33(1): L01602. doi:10.1029/2005GL024826

Church and White 2011
Church, J.A., and N.J. White (2011) Sea-level rise from the late 19th to the early 21st century. *Surveys in Geophysics* 32(4–5): 585–602. doi: 10.1007s10712-011-9119-1

Church et al. 2007
Church, J.A., P. Woodworth, T. Aarup, and W.S. Wilson (2007) Understanding sea level rise and variability. *EOS, Transactions of the American Geophysical Union* 88(4): 43.

IPCC 2001
Intergovernmental Panel on Climate Change (2001) *Climate Change 2001: The Scientific Basis* (J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson, ed.). Cambridge, UK: Cambridge University Press.

IPCC 2007
Intergovernmental Panel on Climate Change (2007) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H. L. Miller, ed.). Cambridge, UK: Cambridge University Press. http://ipcc-wg1.ucar.edu/wg1/wg1-report.html

IPCC 2013
Intergovernmental Panel on Climate Change (2013) Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. http://www.climatechange2013.org/images/uploads/WGI_AR5_SPM_brochure.pdf

Nicholls et al. 2007
Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, S. Ragoonaden, and C.D. Woodroffe (2007) Chapter 6. Coastal systems and low-lying areas. In

Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, ed.). Cambridge, UK: Cambridge University Press. http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-chapter6.pdf

c. USACE Publications.

ER 1100-2-8162
U.S. Army Corps of Engineers (2013) *Incorporating Sea Level Change in Civil Works Programs.* ER 1100-2-8162. Washington, DC: U.S. Army Corps of Engineers.

ER 1105-2-100
U.S. Army Corps of Engineers (2000) *Planning Guidance Notebook.* ER 1105-2-100. Washington, DC: U.S. Army Corps of Engineers. http://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1105-2-100.pdf

ER 1110-2-8159
U.S. Army Corps of Engineers (1997) *Life Cycle Design and Performance*. ER 1110-2-8159. Washington, DC: U.S. Army Corps of Engineers. http://www.publications.usace.army.mil/Portals/76/Publications/EngineerRegulations/ER_1110-2-8159.pdf

EM 1110-2-1619
U.S. Army Corps of Engineers (1996) *Risk-Based Analysis for Flood Damage Reduction Studies.* EM 1110-2-1619. Washington, DC: U.S. Army Corps of Engineers.

EM 1110-2-6056
U.S. Army Corps of Engineers (2010) *Standards and Procedures for Referencing Project Elevation Grades to Nationwide Vertical Datums*. EM 1110-2-6056. Washington, DC: U.S. Army Corps of Engineers. http://140.194.76.129/publications/eng-manuals/em1110-2-6056/

USACE 2013
U.S. Army Corps of Engineers (2013) *Coastal Risk Reduction and Resilience*. CWTS 2013-3. Washington, DC: Directorate of Civil Works, U.S. Army Corps of Engineers. http://www.corpsclimate.us/docs/USACE_Coastal_Risk_Reduction_final_CWTS_2013-3.pdf

A-2. Related References.

a. Federal Government Publications.

Cowardin et al. 1979
Cowardin, L.M., V. Carter, F.C. Golet, and E.T. LaRoe (1979) *Classification of Wetlands and Deepwater Habitats of the United States*. Version 04DEC1998. Jamestown, ND: Northern Prairie Wildlife Research Center, Fish and Wildlife Service, U.S. Department of the Interior. http://www.npwrc.usgs.gov/resource/wetlands/classwet/index.htm

FEMA 2012
Federal Emergency Management Agency (2012) *Definitions of Base Flood Elevations (BFE).* Website accessed January 2013. http://www.fema.gov/national-flood-insurance-program/definitions

FGDC 2012
Federal Geographic Data Committee (2012) *Coastal and Marine Ecological Classification Standard.* FGDC-STD-018-2012. Standards Working Group, Federal Geographic Data Committee. http://www.csc.noaa.gov/digitalcoast/_/pdf/CMECS_Version%20_4_Final_for_FGDC.pdf

JPL 2013
Jet Propulsion Laboratory (2013) *GPS Time Series Interactive Website.* Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA. http://sideshow.jpl.nasa.gov/mbh/series.html

Moser et al. 1990
Moser, D., E. Stakhiv, and L. Vallianos (1990) *Risk-Cost Aspects of Sea Level Rise and Climate Change in the Evaluation of Coastal Protection Projects. Changing Climate and the Coast* (J.G. Titus, ed.). Washington, DC: Environmental Protection Agency.

NOAA 2000
National Oceanic and Atmospheric Agency (2000) *Tide and Current Glossary*. Silver Spring, MD: Center for Operational Oceanographic Products and Services, National Ocean Service, NOAA. http://tidesandcurrents.noaa.gov/publications/glossary2.pdf

NOAA 2010a
National Oceanic and Atmospheric Administration (2010a) *Technical Considerations for Use of Geospatial Data in Sea Level Change Mapping and Assessment.* NOAA Technical Report NOS 2010-01. Washington, DC: National Ocean Service, NOAA.

NOAA 2010b
National Oceanic and Atmospheric Administration (2010b) *Mean Sea Level Trends, San Diego, CA.* Silver Spring, MD: Center for Operational Oceanographic Products and Services, NOAA. http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=9410170

NOAA 2011
National Oceanic and Atmospheric Administration (2011) *Ocean and Coastal Resource Management. States and Territories Working With NOAA on Ocean and Coastal Management*. Website accessed July 2011. Washington, DC: National Ocean Service, NOAA. http://coastalmanagement.noaa.gov/mystate/welcome.html

NOAA 2012
National Oceanic and Atmospheric Administration (2012) *Laboratory for Satellite Altimetry / Sea Level Rise.* Website accessed December 2012. Silver Spring, MD: National Environmental Satellite, Data, and Information Service, NOAA. http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/

NRC 1985
National Research Council (1985) *Glaciers, Ice Sheets and Sea Level.* NRC Polar Research Board. Washington, DC: National Academy Press.

NRC 2009
National Research Council (2009) *Sustainable Critical Infrastructure Systems: A Framework for Meeting 21st Century Challenges, Report of a Workshop*. Washington, DC: National Academy Press.

Thieler and Hammar-Klose 1999
Thieler, E.R., and E.S. Hammar-Klose (1999) *National Assessment of Coastal Vulnerability to Sea-Level Rise, Preliminary Results for U.S Atlantic Coast.* Open-File Report 99-593. Reston, VA: U.S. Geological Survey. http://pubs.usgs.gov/of/of99-593/

Thieler and Hammer-Klose 2000a
Thieler, E.R., and E.S. Hammar-Klose (2000a) *National Assessment of Coastal Vulnerability to Future Sea-Level Rise: Preliminary Results for the U.S. Pacific Coast*. Open-File Report 00-178. Reston, VA: U.S. Geological Survey. http://pubs.usgs.gov/of/of00-178/

Thieler and Hammer-Klose 2000b
Thieler, E.R., and E.S. Hammar-Klose (2000) *National Assessment of Coastal Vulnerability to Future Sea-Level Rise: Preliminary Results for the U.S. Gulf of Mexico Coast*. Open-File Report 00-179. Reston, VA: U.S. Geological Survey. http://pubs.usgs.gov/of/of00-179/

U.S. Climate Change Science Program 2009
U.S Climate Change Science Program (2009) *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region* [J.G. Titus (Coordinating Lead Author), E.K. Anderson, D.R. Cahoon, S. Gill, R.E.Thieler, J.S.Williams (Lead Authors)]. Synthesis and Assessment Product 4.1. Washington, DC: U.S. Environmental Protection Agency. http://www.climatescience.gov/Library/sap/sap4-1/final-report/#finalreport

USEPA 2011
U.S. Environmental Protection Agency (2011) *Ecoregions of North America.* Website accessed July 2011. http://www.epa.gov/wed/pages/ecoregions/na_eco.htm

USGS 2012
U.S. Geological Survey (2012) *Coastal Classification Mapping Project.* Website, Coastal and Marine Geology Program, U.S. Geological Survey. http://coastal.er.usgs.gov/coastal-classification/

Zervas 2009
Zervas, C. (2009) *Sea Level Variations of the United States 1854–2006*. NOS CO-OPS 053. Silver Spring, MD: Center for Operational Oceanographic Products and Services, National Ocean Service, National Oceanic and Atmospheric Administration.

Zervas et al. 2013
Zervas, C., S.K. Gill, and W. Sweet (2013) *Estimating Vertical Land Motion from Long-Term Tide Gauge Records.* Technical Report. Silver Spring, MD: Center for Operational Oceanographic Products and Services, National Ocean Service, National Oceanic and Atmospheric Administration.

b. Other Publications.

Bird 2008
Bird, E. (2008) *Coastal Geomorphology, An Introduction*. Second edition. West Sussex, England: John Wiley and Sons.

Bray and Hooke 1997
Bray, M., and J. Hooke (1997) Prediction of soft-cliff retreat with accelerating sea-level rise. *Journal of Coastal Research* 13(2): 453–467.

Breaker and Ruzmaikin 2013
Breaker, L.C., and A. Ruzmaikin (2013) Estimating rates of acceleration based on the 157-year record of sea level from San Francisco, California, U.S.A. *Journal of Coastal Research* 29(1): 43–51. doi: http://dx.doi.org/10.2112/JCOASTRES-D-12-00048.1

Brown et al. 2011
Brown, C., W. Werick, W. Leger, and D. Fay (2011) A decision-analytic approach to managing climate risks: Application to the Upper Great Lakes. *Journal of the American Water Resources Association* 47(3): 524–534.

Bruun 1962
Bruun, P. (1962) Sea level rise as a cause of erosion. *Journal of the Waterways and Harbors Division, American Society of Civil Engineers* WW1(Feb. 1962): 117–133.

Bruun 1988
Bruun, P. (1988) The Bruun rule of erosion by sea-level rise: A discussion on large-scale two- and three-dimensional usages. *Journal of Coastal Research* 4(4): 627–648.

Burby 2006
Burby, R.J. (2006) Hurricane Katrina and the paradoxes of government disaster policy: Bringing about wise governmental decisions for hazardous areas. *The Annals of the American Academy of Political and Social Science* 604.1(2006): 171–191.

Chai et al. 2004
Chai, J.C., S. Shen, H. Zhu, and X. Zhang (2004) Land subsidence due to groundwater drawdown in Shanghai. *Geotechnique* 54.2(2004): 143–147.

Chow 1964.
Chow, V.T. (1964) *Handbook of Applied Hydrology: A Compendium of Water-Resources Technology*. New York: McGraw-Hill.

Cooper and Pilkey 1994.
Cooper, J.A.G., and O.H. Pilkey (1994) Sea level rise and shoreline retreat: Time to abandon the Bruun rule. *Global and Planetary Change* 43: 157–171.

Cooper et al. 2012
Cooper, H., Q. Chen, C. Fletcher, and M. Barbee (2012) Vulnerability assessment due to sea-level rise in Maui, Hawai'i using LiDAR remote sensing and GIS. *Climatic Change* 116(3–4): 547–563.

Davis et al. 2005
Davis, S.M., D.L. Childers, J.J. Lorenz, H.R. Wanless, and T.E. Hopkins (2005) A conceptual model of ecological interactions in the mangrove estuaries of the Florida Everglades. *Wetlands* 25(4): 832–842.

Dean 1991
Dean, R.G. (1991) Equilibrium beach profiles: Characteristics and applications. *Journal of Coastal Research* 7(1): 53–84.

Dean and Dalrymple 1991
Dean, R.G., and R.A. Dalrymple (1991) *Water Wave Mechanics for Engineers and Scientists.* Advanced Series on Ocean Engineering, Vol. 2. Singapore: World Scientific Publishing.
DEFRA 2009
Department for Environment, Food and Rural Affairs (2009) Appraisal of flood and coastal erosion risk management. London, United Kingdom: Department for Environment, Food and Rural Affairs.

Douglas 2001
Douglas, B.C. (2001) Sea level change in the era of the recording tide gauge. *International Geophysics* 75: 37–64.

Environment Agency 2009
Environment Agency (2009) *Thames Estuary 2100 Flood Risk Management Plan: Technical Report.* London, United Kingdom: Environment Agency.
Esteban et al. 2011

Esteban, M., H. Takagi, and T. Shibayama (2011) Sea level rise and the increase in rubble mound breakwater damage. Presented at *Ad-Hoc Expert Meeting on Climate Change Impacts and Adaptations: A Challenge for Global Ports*, 29–30 September, 2011, Geneva, Switzerland.

Everts 1985
Everts, C.H. (1985) Sea level rise effects on shoreline position. *Journal of Waterway, Port, Coastal and Ocean Engineering* 111(6): 985–999.

Flick et al. 2013

Flick, R., K. Knuuti, and S. Gill (2013) Matching mean sea level rise projections to local elevation datums. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 139(2): 142–146.

Glick et al. 2010
Glick, P., J. Clough, and B. Nunlay (2010) *Assessing the Vulnerability of Alaska's Coastal Habitats to Accelerating Sea-Level Rise using the SLAMM Model: A Case Study for Cook Inlet.* Reston, VA: National Wildlife Federation.

Grinsted et al. 2010
Grinsted, A., J. Moore, and S. Jevrejeva (2010) Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. *Climate Dynamics* 34: 461–472.

Hirsch 2011
Hirsch, R.M. (2011) A perspective on nonstationarity and water management. *Journal of the American Water Resources Association* 47(3): 436–446. doi: 10.1111/j.1752-1688.2011.00539

Holgate and Woodworth 2004
Holgate, S.J., and P.L. Woodworth (2004) Evidence for enhanced coastal sea level rise during the 1990s. *Geophysical Research Letters* 31: L07305. doi:10.1029/2004GL019626

Horton et al. 2008
Horton, R., C. Herweijer, C. Rosenzweig, J. Liu, V. Gornitz, and A.C. Ruane (2008) Sea level rise projections for current generation CGCMs based on the semi-empirical method. *Geophysical Research Letters* 35: L02715.

Huang et al. 2004
Huang, Zhenguo, Yongqiang Zong, and Weiqiang Zhang. Coastal inundation due to sea level rise in the Pearl River Delta, China. *Natural Hazards* 33.2: 247–264.

Hunter 2010
Hunter, J.R. (2010) Estimating sea-level extremes under conditions of uncertain sea-level rise. *Climatic Change* 99: 331–350. doi:10.1007/s10584-009-9671-6

IOC 1985
Intergovernmental Oceanographic Commission (1985) *Manual on Sea-Level Measurements and Interpretation. Volume 1* (T. Aarup, M. Merrifield, B. Perez, I. Vassie, and P. Woodworth, ed.). IOC Manuals and Guides No. 14, vol. I. Paris, France: Intergovernmental Oceanographic Commission.

IOC 2012
Intergovernmental Oceanographic Commission (2012) *Manual on Sea-Level Measurements and Interpretation. Volume 4—An Update to 2006* (T. Aarup, M. Merrifield, B. Perez, I. Vassie, and P. Woodworth, ed.). IOC Manuals and Guides No. 14, vol. IV. JCOMM Technical Report No. 31; WMO/TD. No. 1339. Paris, France: Intergovernmental Oceanographic Commission.

Jevrejeva et al. 2010
Jevrejeva, S., J.C. Moore, and A. Grinsted (2010) How will sea level respond to changes in natural and anthropogenic forcings by 2100? *Geophysical Research Letters* 37: L07703.

Katsman et al. 2011.
Katsman, C.A., A. Sterl, J.J. Beersma, H.W. Van den Brink, J.A. Church, W. Hazeleger, R.E. Kopp, D. Kroon, J. Kwadijk, R. Lammersen, J. Lowe, M. Oppenheimer, H.-P. Plag, J. Ridley, H. von Storch, D.G. Vaughan, P. Vellinga, L.L.A. Vermeersen, R.S.W. van de Wal, and R. Weisse (2011) Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta – The Netherlands as an example. *Climate Change* 109: 617–645. doi 10.1007/s10584-011-0037-5

Kiang et al. 2011
Kiang, J.E., J.R. Olsen, and R.M. Waskom (2011) Introduction to the featured collection on "Nonstationarity, Hydrologic Frequency Analysis, and Water Management." *Journal of the American Water Resources Association* 47(3): 433–435. doi: 10.1111/j.1752-1688.2011.00551

Knuuti 2002
Knuuti, K. (2002) Planning for sea level rise: U.S. Army Corps of Engineers policy. *Proceedings of Conference on Solutions to Coastal Disasters '02, San Diego, CA*, p. 549–560. Reston, VA: American Society of Civil Engineers.
Kondolf et al. 2002
Kondolf, G.M., H. Piégay, and N. Landon (2002) Channel response to increased and decreased bedload supply from land use change: Contrasts between two catchments. *Geomorphology* 45(1): 35–51.

Kriebel 2012
Kriebel, D. (2012) The need for a tidal flood stage to define existing and future sea level hazards. *Proceedings of Conference on Solutions to Coastal Disasters '11, Anchorage, AK*, p. 461–473. Reston, VA: American Society of Civil Engineers.

Larsen et al. 2003
Larsen, C.F., K.A. Echelmeyer, J.T. Freymueller, and R.J. Motyka (2003) Tide gauge records of uplift along the northern Pacific–North American Plate boundary, 1937–2001. *Journal of Geophysical Research* 108(B4): 2216.

Leuliette et al. 2004
Leuliette, E.W., R.S. Nerem, and G.T. Mitchum (2004) Calibration of TOPEX/Poseidon and Jason altimeter data to construct a continuous record of mean sea level change. *Marine Geodesy* 27(1–2**)**: 79–94.

Linham and Nicholls 2010
Linham, M.M., and R.J. Nicholls (2010) *Technologies for Climate Change Adaptation: Coastal Erosion and Flooding*. TNA Guidebook Series. Roskilde, Denmark: UNEP Riso Centre on Energy, Climate and Sustainable Development.

Ludwig et al. 2005

Ludwig, J.A., B.P. Wilcox, D.D. Breshears, D.J. Tongway, and A.C. Imeson (2005) Vegetation patches and runoff-erosion as interacting ecohydrological processes in semiarid landscapes. *Ecology* 86.2(2005): 288–297.

Milly et al. 2008
Milly, P.C.D, J. Betancourt, M. Falkenmark, R.M. Hirsch, Z.W. Kundzewicz, D.P. Lettenmaier, and R.J. Stouffer (2008) Stationarity is dead: Whither water management? *Science* 319(5863): 573.

Morris et al. 2002
Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, and D.R. Cahoon (2002) Responses of coastal wetlands to rising sea level. *Ecology* 83: 2869–2877.

Moser et al. 2008
Moser, D., M. Schultz, T. Bridges, and B. Harper (2008) Flood risk management and the U.S. Army Corps of Engineers Actions for Change. *Fourth International Symposium on Flood Defence, Toronto, Canada.*

Munoz-Perez et al. 1999
Munoz-Perez, J.J., L. Tejedor, and R. Medina (1999) Equilibrium beach profile model for reef-protected beaches. *Journal of Coastal Research* 15(4): 950–957.
Muto and Swenson 2005
Muto, T., and J.B. Swenson (2005) Large-scale fluvial grade as a nonequilibrium state in linked depositional systems: Theory and experiment. *Journal of Geophysical Research* 110.F3: F03002.

Nerem and Mitchum 2002
Nerem, R.S., and G.T. Mitchum (2002) Estimates of vertical crustal motion derived from differences of TOPEX/POSEIDON and tide gauge sea level measurements. *Geophysical Research Letters* 29(19): 1934.

Nicholls 2010
Nicholls, R.J. (2010) Impacts of and responses to sea-level rise. In *Understanding Sea-Level Rise and Variability* (J.A. Church, P.L. Woodworth, T. Aarup, and W.W. Wilson, ed.). P. 17–51. Wiley-Blackwell.

Nicholls 2011
Nicholls, R.J. (2011) Planning for the impacts of sea level rise. *Oceanography* 24(2): 144–157. doi:10.5670/oceanog.2011.34

Nicholls et al. 2011
Nicholls, R.J., N. Marinova, J.A. Lowe, S. Brown, P. Vellinga, D. de Gusmão, J. Hinkel, and R.S.J. Tol (2011) Sea-level rise and its possible impacts given a “beyond 4 degree world” in the twenty-first century. *Philosophical Transactions of the Royal Society A* 369: 161–181.

Nieuwenhuis and Schokking 1997

Nieuwenhuis, H.S., and F. Schokking (1997) Land subsidence in drained peat areas of the Province of Friesland, The Netherlands. *Quarterly Journal of Engineering Geology and Hydrogeology* 30.1: 37–48.

Obeysekera and Park 2013
Obeysekera, J., and J. Park (2013) Scenario-based projection of extreme sea levels. *Journal of Coastal Research* 29(1): 1–7.

Parker et al. 2004
Parker, G., Y. Akamatsu, T. Muto, and W. Dietrich (2004) Modeling the effect of rising sea level on river deltas and long profiles of rivers. *Proceedings, International Conference on Civil and Environmental Engineering (ICCEE-2004), Hiroshima University, Japan*, July 27–28, 2004, p. 1–10.

Pfeffer et al. 2008
Pfeffer, W.T., J.T. Harper, and S. O'Neel (2008) Kinematic constraints on glacier contributions to 21st-century sea-level rise. *Science* 321(5894) 1340–1343.

Pilkey et al. 1993
Pilkey, O.H., R.S. Young, S.R. Riggs, A.W.S. Smith, H. Wu, and W.D. Pilkey (1993) Concept of shoreface profile of equilibrium: A critical review. *Journal of Coastal Research* 9(1): 255–278.
Plate 2002
Plate, E.J. (2002) Flood risk and flood management. *Journal of Hydrology* 267.1: 2–11.

Rahmstorf 2007
Rahmstorf, S. (2007) A semi-empirical approach to projecting future sea level rise. *Science* 315(5810): 368–370.

Ranasinghe et al. 2012
Ranasinghe, R., D. Callaghan, and M.J.F. Stive (2012) Estimating coastal recessing due to sea level rise: Beyond the Bruun rule. *Climatic Change* 10(3–4): 561–574.

Ross et al. 1994
Ross, M.S., J.J. O'Brien, and L. da Silveira Lobo Sternberg (1994) Sea-level rise and the reduction in pine forests in the Florida Keys. *Ecological Applications* 1994: 144–156.

Rotzoll and Fletcher 2012
Rotzoll, K., and C.H. Fletcher (2012) Assessment of groundwater inundation as a consequence of sea-level rise. *Nature Climate Change* 11 November 2012. doi:10.1038/nclimate1725

Savonis 2011
Savonis, M.J. (2011) U.S. ports: Addressing the adaptation challenge. *Ad Hoc Expert Meeting on Climate Change Impacts and Adaptation: A Challenge for Global Ports*, 29–30 September 2011.

Sella et al. 2007
Sella, G.F., S. Stein, T.H. Dixon, M. Craymer, T.S. James, S. Mazzotti, and R.K. Dokka (2007) Observation of glacial isostatic adjustment in "stable" North America with GPS. *Geophysical Research Letters* 34: L02306.

Snay et al. 2007
Snay, R., M. Cline, W. Dillinger, R. Foote, S. Hilla, W. Kass, J. Ray, J. Rohde, G. Sella, and T. Soler (2007) Using global positioning system-derived crustal velocities to estimate rates of absolute sea level change from North American ride gauge records. *Journal of Geophysical Research* 112: B04409.

Steever et al. 1976
Steever, E.Z., R.S. Warren, and W.A. Niering (1976) Tidal energy subsidy and standing crop production of *Spartina alterniflora*. *Estuarine and Coastal Marine Science* 4: 473–478.

Stive and de Vriend 1995
Stive, M.J.F., and H.J. de Vriend (1995) Modeling shoreface profile evolution. *Marine Geology* 126: 235–248.

Stive et al. 1991
Stive, M.J.F., R.J. Nicholls, and H.J. de Vriend (1991) Sea-level rise and shore nourishment: A discussion. *Coastal Engineering* 16: 147–163.

Swart et al. 2004
Swart, R.J., P. Raskin, and J. Robinson (2004) The problem of the future: Sustainability science and scenario analysis. *Global Environmental Change* 14: 137–146.

Taniguchi et al. 2002
Taniguchi, M., W. Burnett, J. Cable, and J. Turner (2002) Investigation of submarine groundwater discharge. *Hydrological Processes* 16.11: 2115–2129.

Tebaldi et al. 2012
Tebaldi, C., B. Strauss, and C. Zervas (2012) Modelling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters* 7(1): 2012.

Titus et al. 1987
Titus, J.G., C. Kuo, M. Gibbs, T. LaRoche, M. Webb, and J. Waddell (1987) Greenhouse effect, sea level rise, and coastal drainage systems. *Journal of Water Resources Planning and Management* 113.2: 216–227.

Titus et al. 2009
Titus, J.G., D.E. Hudgens, D.L. Trescott, M. Craghan, W.H. Nuckols, C.H. Hershner, J.M. Kassakian, C.J. Linn, P.G. Merritt, T.M. McCue, J.F. O'Connell, J. Tanski, and J. Wang (2009) State and local governments plan for development of most land vulnerable to rising sea level along the U.S. Atlantic coast. *Environmental Research Letters* 4(October–December): 044008.

Vermeer and Rahmstorf 2009
Vermeer, M., and S. Rahmstorf (2009) Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences* 106(51): 21527–21532.

Webb and White 2010
Webb, J.W., and K.D. White (2010) Non-stationarity in water management: A USACE perspective. *Proceedings, Workshop on Nonstationarity, Hydrologic Frequency Analysis, and Water Management*, Boulder, CO, 13–15 Jan 2010. P. 16–19. http://www.cwi.colostate.edu/NonstationarityWorkshop/proceedings.shtml

Westerink et al. 2008
Westerink, J.J., R.A. Luettich, J.C. Feyen, J.H. Atkinson, C. Dawson, H.J. Roberts, M.D. Powell, J.P. Dunion, E.J. Kubatko, and H. Pourtaheri (2008) A basin-to channel-scale unstructured grid hurricane storm surge model applied to southern Louisiana. *Monthly Weather Review* 136.3: 833–864.

Whelan et al. 2009
Whelan, K.R.T., T.J.I. Smith, G.H. Anderson, and M.L. Ouellette (2009) Hurricane Wilma's impact on overall soil elevation and zones within the soil profile in a mangrove forest. *Wetlands* 29: 16 –23.

Wilkinson et al. 2009
Wilkinson, T., E. Wiken, J. Bezaury-Creel, T. Hourigan, T. Agardy, H. Herrmann, L. Janishevski, C. Madden, L. Morgan, and M. Padilla (2009) *Marine Ecoregions of North America*. Montreal, Canada: Commission for Environmental Cooperation. http://www.cec.org/Storage/83/7831_MarineEcoregions-web_en.pdf

Williams et al. 2009
Williams, S.J., B.T. Gutierrez, J.G. Titus, S.K. Gill, D.R. Cahoon, E.R. Thieler, K.E. Anderson, D. FitzGerald, V. Burkett, and J. Samenow (2009) Sea-level rise and its effects on the coast. Chapter 1. In *Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region* [J.G. Titus (Coordinating Lead Author), E.K. Anderson, D. Cahoon, S.K. Gill, R.E. Thieler, J.S. Williams (Lead Authors)]. U.S. Climate Change Program and Subcommittee on Global Change Research. Washington, DC: U.S. Environmental Protection Agency. http://www.climatescience.gov/Library/sap/sap4-1/final-report/default.htm

Willows and Connell 2003
Willows, R.I., and R.K. Connell (ed.) (2003) *Climate Adaptation: Risk, Uncertainty and Decision-Making*. UKCIP Technical Report. Oxford, United Kingdom: U.K. Climate Impacts Programme.

Woppelmann et al. 2007
Woppelmann, G., B.M. Miguezb, M.-N. Bouinc, and Z. Altamimic (2007) Geocentric sea-level trend estimates from GPS analyses at relevant tide gauges world-wide. *Global and Planetary Change* 57: 396–406.

Yen 1995
Yen, B.C. (1995) Hydraulics and effectiveness of levees for flood control. *U.S.–Italy Research Workshop on the Hydrometeorology, Impacts, and Management of Extreme Floods*, Perugia, Italy, November 1995.

Zeeman 1974
Zeeman, E.C. (1974) On the unstable behaviour of stock exchanges. *Journal of Mathematical Economics* 1.1: 39–49.

Zhang et al. 2004
Zhang, K., B.C. Douglas, and S.P. Leatherman (2004) Global warming and coastal erosion. *Climatic Change* 64: 41–58.

c. USACE Publications.

EM 1110-2-1100
U.S. Army Corps of Engineers (2005) *Coastal Engineering Manual*. EM 1110-2-1100. Washington, DC: U.S. Army Corps of Engineers.

EM 1110-2-1417
U.S. Army Corps of Engineers (1994) *Flood Runoff Analysis*. EM 1110-2-1417. Washington, DC: U.S. Army Corps of Engineers. http://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1417.pdf

Brinson 1993
Brinson, M.M. (1993) *A Hydrogeomorphic Classification for Wetlands.* Technical Report WRP-DE-4. Vicksburg, MS: Waterways Experiment Station, U.S. Army Corps of Engineers.

CERC 1985
U.S. Army Coastal Engineering Research Center (1985) *Estimating Irregular Wave Runup Heights on Rough Slopes, Computer Program: Wavrunup (MACE-14).* CETN-I-37. Vicksburg, MS: Coastal Engineering Research Center, Waterways Experiment Station, U.S. Army Corps of Engineers.

USACE 1983
U.S. Army Corps of Engineers (1983) *Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies*. Washington, DC: U.S Army Corps of Engineers.

USACE 1984
U.S. Army Corps of Engineers (1984) *Shore Protection Manual*. Fourth Edition. Vicksburg, MS: Coastal Engineering Research Center, Waterways Experiment Station, U.S. Army Corps of Engineers.

USACE 2009
U.S. Army Corps of Engineers (2009) *Extent of Resources at Risk—A Technical Review of Coastal Projects: Shore Protection, Navigation and Ecosystem Restoration for North Atlantic Division.* Brooklyn, NY: North Atlantic Division, U.S. Army Corps of Engineers.

USACE 2011a
U.S. Army Corps of Engineers (2011) *Central and Southern Florida Project, Comprehensive Everglades Restoration Plan, Biscayne Bay Coastal Wetlands, Integrated Project Implementation Report and Environmental Impact Statement*. Jacksonville District, U.S. Army Corps of Engineers and South Florida Water Management District.

USACE 2011b
U.S. Army Corps of Engineers (2011) *Design Elevation Report, Hurricane and Storm Damage Risk Reduction System.* Draft Report Version 4.0a. New Orleans, LA: New Orleans District, U.S. Army Corps of Engineers.

USACE 2011c
U.S. Army Corps of Engineers (2011) *Ecological forecasting tools and planning of ecosystem restoration projects*. Ecosystem Management and Restoration Research Program. RDC TN-EMRRP-EM-10. Vicksburg, MS: U.S. Army Research and Development Center, Environmental Laboratory. http://el.erdc.usace.army.mil/elpubs/pdf/em10.pdf

USACE 2012
U.S. Army Corps of Engineers (2012) *Application of Risk Management and Uncertainty Concepts and Methods for Ecosystem Restoration: Principles and Best Practice*. EBA Technical Notes Collection. ERDC TN-EMRRP-EBA-15. Vicksburg, Mississippi: U.S. Army Engineer Research and Development Center, Environmental Laboratory.
http://el.erdc.usace.army.mil/elpubs/pdf/eba15.pdf

USACE 2013
U.S. Army Corps of Engineers (2013) *Coastal Risk Reduction and Resilience*. CWTS 2013-3. Washington, DC: Directorate of Civil Works, U.S. Army Corps of Engineers.

Yoe 2002
Yoe, C.E. (2002) *Trade-off Analysis Planning and Procedure Guidelines*. IWR 02-R-2. Alexandria, VA: Institute for Water Resources, U.S. Army Corps of Engineers.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B

Data Requirements and Development of Sea Level Change Curves

B-1. What is Sea Level Change (SLC)? The following discussion on general background on SLC is included here to provide scientific context supplementing Chapter 2 and ER 1100-2-8162. The discussion is modified from NOAA Technical Report NOS 2010-01, *Technical Considerations for Use of Geospatial Data in Sea Level Change Mapping and Assessment* (NOAA 2010a); however, many other publications provide a similar discussion (Church et al. 2007, NRC 2012).

a. Global and Relative SLC. The level of the sea observed along the coast changes in response to a wide variety of astronomical, meteorological, climatological, geophysical, and oceanographic forcing mechanisms. From the highest-frequency wind waves and sea swell to tsunamis and local seiches; to the daily tides; to monthly, seasonal, and annual variations; to decadal and multi-decadal variations; and finally, to changes over hundreds of millions of years, sea level is constantly changing at any given location.

(1) Time Scale. For the purposes of this document, the time scales of concern with respect to SLC include the monthly through the multi-decadal time frames. Multi-decadal change in sea level is often described as indicated by long-term sea level trends or by trends over shorter time periods (such as monthly sea level anomalies), both of which are discussed in this document. SLC exhibits geospatial and temporal variations and can rise or fall relative to the land surface, depending on location and time scale. Therefore, this document focuses on SLC, rather than sea level rise, which is a specific type of SLC. In addition, there is a subtle but significant distinction between global sea level change and relative sea level change (Williams et al. 2009).

(2) Global Sea Level Change. Global sea level, also sometimes referred to as global mean sea level, is the average height of all the world's oceans. Global sea level rise is a specific type of global SLC that climate models are forecasting will occur at an accelerated rate and is the topic of much of the discussion in this document. Global (eustatic) sea level change is often caused by the global change in the volume of water in the world's oceans in response to three climatological processes: 1) ocean mass change associated with long-term forcing of the ice ages ultimately caused by small variations in the orbit of the earth around the sun; 2) density changes related to total salinity; and, most recently, 3) changes in the heat content of the world's oceans, which recent literature suggests may be accelerating due to global warming. Global SLC can also be caused by basin changes, through such processes as seafloor spreading.

(3) Relative Sea Level Change. Relative (local) SLC is the local change in sea level relative to the elevation of the land at a specific point on the coast. Relative SLC is a combination of global, regional, and local sea level changes caused by estuarine and shelf hydrodynamics, regional oceanographic circulation patterns (often caused by changes in regional atmospheric patterns), hydrologic cycles (river flow), and local and/or regional vertical land motion (subsidence or uplift). Thus, relative SLC is variable along the coast. Relative sea level rise is a specific type of SLC that affects many applications, since the contribution to the local

relative rate of rise from global sea level rise is expected to increase. Some areas, as discussed later in this appendix, are experiencing relative sea level fall, which can also have ecological and societal impacts. Some localized areas exhibit a more dramatic relative SLC trend than is generally observed globally unless data are filtered to account for local geophysical anomalies.

b. Geologic History of Sea Level. Figure B-1 shows large variations in global mean sea level elevation over the last 400,000 years resulting from four natural glacial and interglacial cycles. Global mean sea level was approximately 4–6 m higher than present during the last interglacial warm period 125,000 years ago and 120 m lower than present during the last ice age, approximately 21,000 years ago (CCSP 2009). Figure B-2 illustrates the rise in global mean sea level at variable rates over the last 18,000 years as the earth moved from a glacial period to the present interglacial warm period. The rise was rapid but highly variable, slowing about 3,000 years ago. Recent acceleration is not noticeable at this scale.

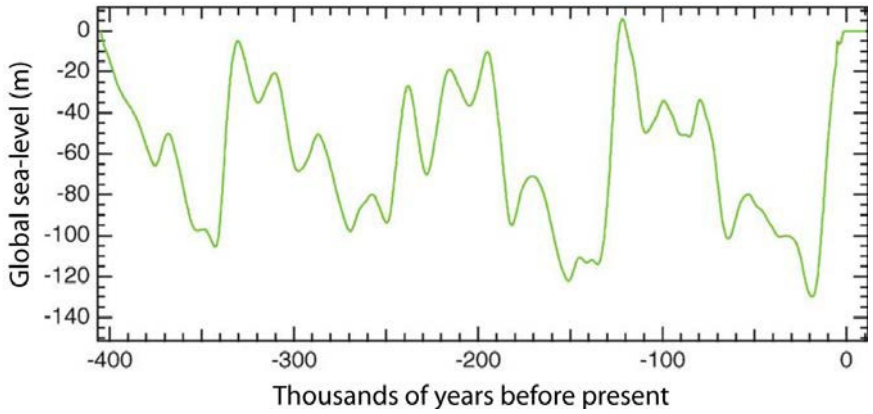


Figure B-1. Global sea level change from 400,000 years ago to the present. (From Williams et al. 2009.)

c. Present-Day Global Sea Level. Figure B-3, modified from the Intergovernmental Panel on Climate Change's 2007 report (IPCC 2007) by Williams et al. (2009), shows annual averages of global mean sea level change in millimeters (mm). The red curve shows sea level variation from tide gauge observations since 1870 [updated from Church and White (2006)], the blue curve displays adjusted tide gauge data from Holgate and Woodworth (2004), and the black curve is based on satellite observations from Leuliette et al. (2004). The red and blue curves represent deviations from their averages for 1961–1990, and the black curve is a deviation from the average of the red curve for 1993–2001. Vertical error bars show 90% confidence intervals for the data points. The estimated trend over the past century, based on analyses of tide gauge records around the globe, is 1.7–1.8 mm/yr.

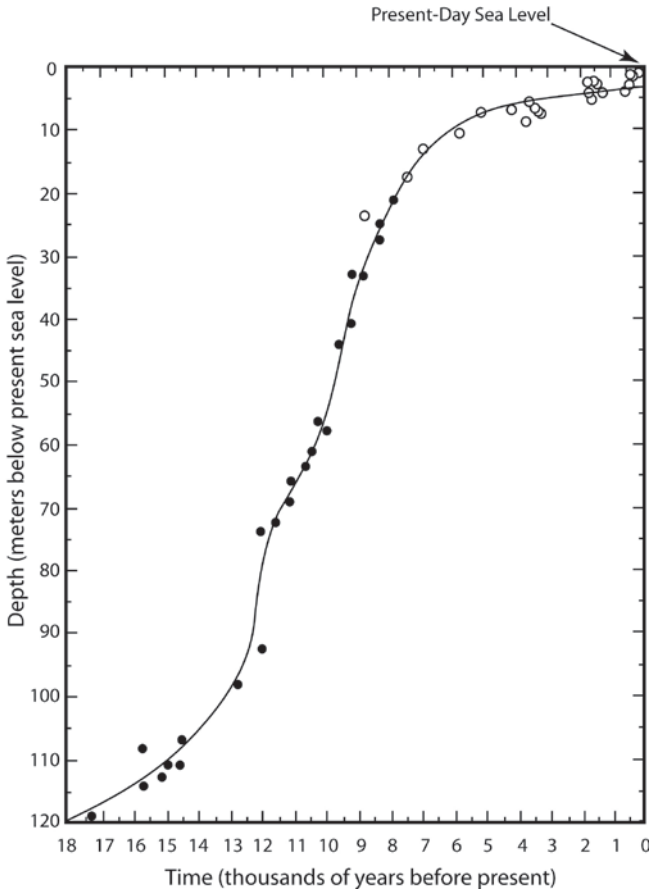


Figure B-2. Rise in global mean sea level over the last 18,000 years. (From Williams et al. 2009.)

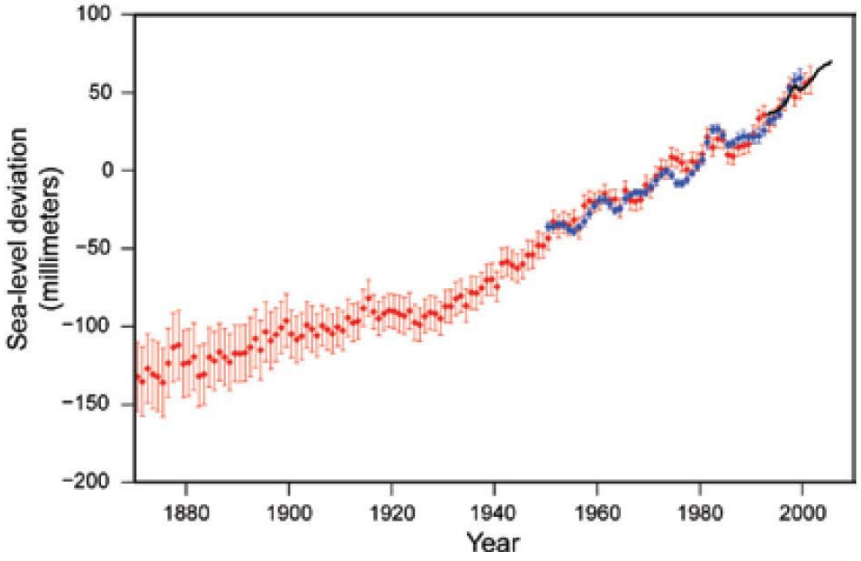


Figure B-3. Global mean sea level change since 1860. [From Williams et al. 2009 (modified from IPCC 2007).]

d. Global Mean Sea Level over the Period of Record from Satellite Altimetry. Figure B-4 shows an estimate of the present trend in global sea level rise based on a series of overlapping satellite altimeter missions performed since 1992, capturing a rate of 2.8 mm/yr for the global oceans (http://ibis.grdl.noaa.gov/SAT/SLC/index.php). This relatively short period of record is not sufficient to determine a sea level change trend.

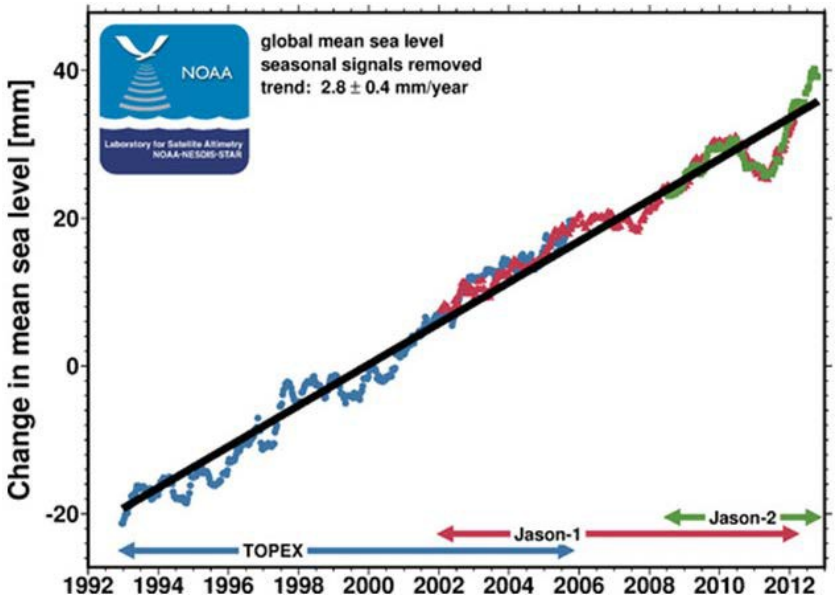


Figure B-4. Estimated rate of global sea level rise since 1993 using satellite altimeter data. (From NOAA 2012.)

e. Geospatial Variability. Figure B-5 illustrates the significant geospatial variability of sea level trends around the world (http://ibis.grdl.noaa.gov/SAT/SLC/index.php). Although the composite global trend in sea level change is an average increase of 3.0 mm/yr from 1993 to the present, in Figure B-5 some areas show variations from an increase of over 10 mm/yr to a decrease of over 10 mm/yr. It is important to understand this regional variability in the global signal when estimating local and regional rates. These regional patterns and the limited duration of the time series may reflect decadal variability rather than long-term trends. Note, for instance, the obvious geographic pattern similar to that observed during normal to La Niña conditions.

B-2. Computation of Sea Level Trends from Tide Gauge Data. Relative sea level trends are computed by NOAA-NOS from carefully compiled observations at long-term tide stations. Monthly mean sea level values are computed from the observed hourly heights over each calendar month.

a. Time Series Analysis. Time series of monthly mean sea levels are created, quality controlled, and referenced to a documented reference datum for the entire time series. The monthly data can also be used to obtain the average seasonal cycle for each station represented as 12 mean values. The residual time series after the trend has been removed contains valuable information about the correlation of the interannual variability between stations, which is better

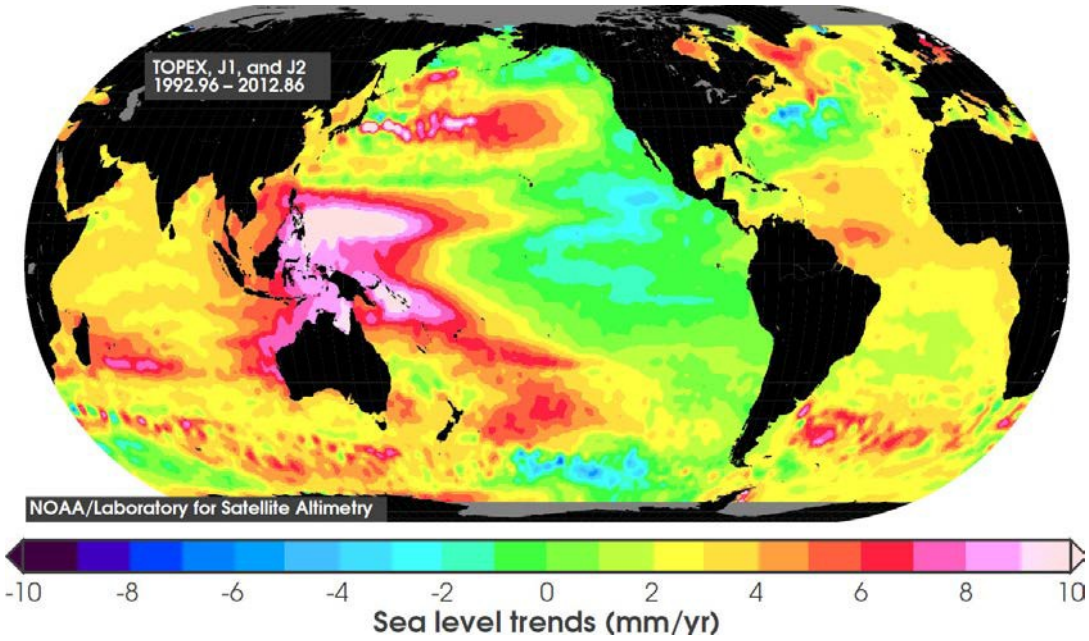


Figure B-5. Regional rates of sea level change between 1993 and present from overlapping satellite altimeter missions. **(**From NOAA 2010b.)

defined by a monthly residual series than by an annual residual series. Trends derived from monthly mean sea level (MSL) data also have smaller standard errors, as was shown in Zervas (2009). The NOAA sea level trends are computed using the methodology found in Zervas (2009). The least-squares solution incorporates knowledge of the average seasonal cycle. A simple least-squares linear regression gives an accurate MSL trend but can substantially underestimate the standard error or uncertainty of that trend. The reason is that, for sea level data, the residual time series is serially auto-correlated even after the average seasonal cycle is removed. Each month is partially correlated with the value of the previous month and the value of the following month. There are actually fewer independent points contributing to the standard error of a linear regression, which assumes a series of independent data. Therefore, following Zervas (2009), the monthly MSL data are characterized as an auto-regressive process of order 1. This is the recommended treatment for computing relative sea level trends from long-term monthly MSL data from tide gauge observations.

b. Long-Term Trends.

(1) Figure B-6 shows the monthly MSL for San Diego, California, after removal of the signal due to the regular seasonal fluctuations caused by coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The long-term linear trend is also shown, including its 95% confidence interval. The plotted values are relative to MSL for the most recent National Tidal Datum Epoch (NTDE) time period (1983–2001).

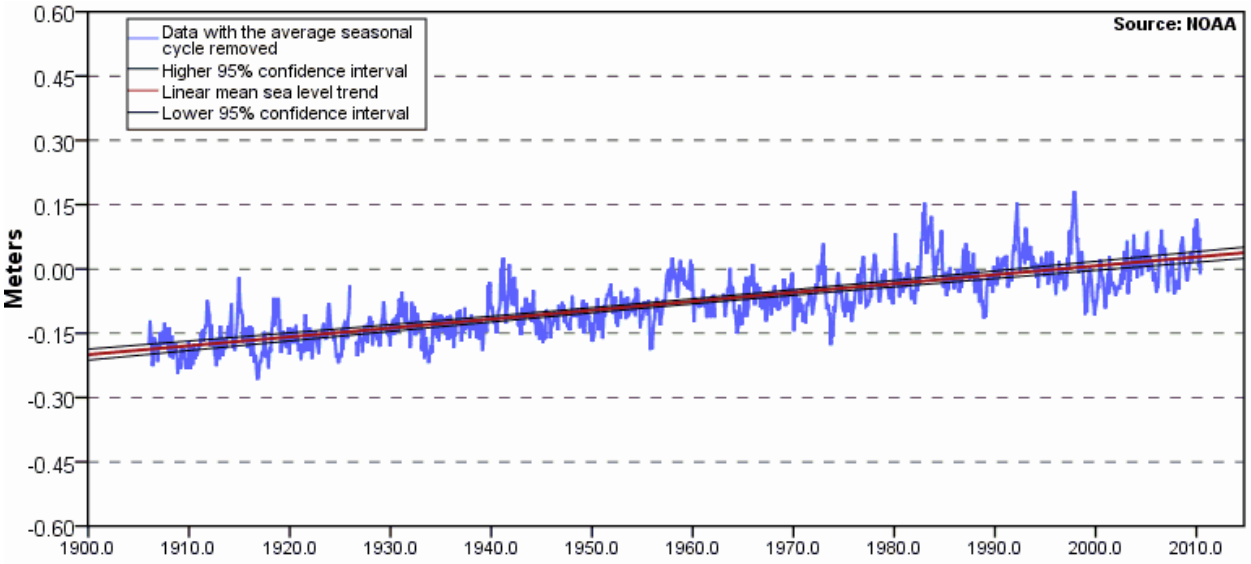


Figure B-6. Relative mean sea level trend for San Diego, CA. The mean sea level trend is 2.06 mm/yr with a 95% confidence interval of ±0.20 mm/yr based on monthly mean sea level data from 1906–2006, which is equivalent to a change of 0.68ft (0.2m) in 100 years. (From NOAA Sea Levels Online 2010; http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=9410170.)

(2) Changes in MSL, either rise or fall, have been computed at 128 long-term water level stations using a minimum span of 30 years of observations at each location. These measurements have been averaged by month by NOAA to remove the effect of high-frequency phenomena, such as waves and tides, to compute an accurate linear sea level trend. The trend analysis has also been extended to a network of global tide stations including 114 additional non-NOAA stations. Estimates represent a combination of regional sea level change as well as local land movement (either uplift or subsidence). Figure B-7 presents data from NOAA tide gauges, from which the following general conclusions can be drawn (NOAA 2012):

(a) Most U.S. tide stations experienced a rise in local MSL during the 20th century, with several isolated regions, such as southeast Alaska, experiencing a drop in local MSL.

(b) Most of the Atlantic and Pacific coasts of the lower contiguous 48 states have had sea level rise trends between 0 and +0.3 meters per century (green symbols on Figure B-7).

(c) The highest rates of local MSL rise in the U.S. have occurred along the Gulf Coast in the Mississippi River delta region at 0.9–1.2 meters per century (red symbols), with significant rises in Texas and the mid-Atlantic (0.3–0.6 meters per century).

(d) Some stations in Alaska exhibit a trend toward decreasing local MSL. Sea level is falling relative to the land quite rapidly (>10 mm/yr) in the upper portions of glacial fjords in Southeast Alaska (e.g., Sitka and Juneau, Glacier Bay) because of local land vertical rebound after recent and ongoing loss of the weight of the land glaciers. In many other portions of

Alaska, such as Cook Inlet, relative sea level is falling (at lower rates) due to ongoing vertical land motion associated with regional tectonic movement. The 1964 earthquake was a manifestation of this tectonic activity, and vertical land deformation continues after that event.

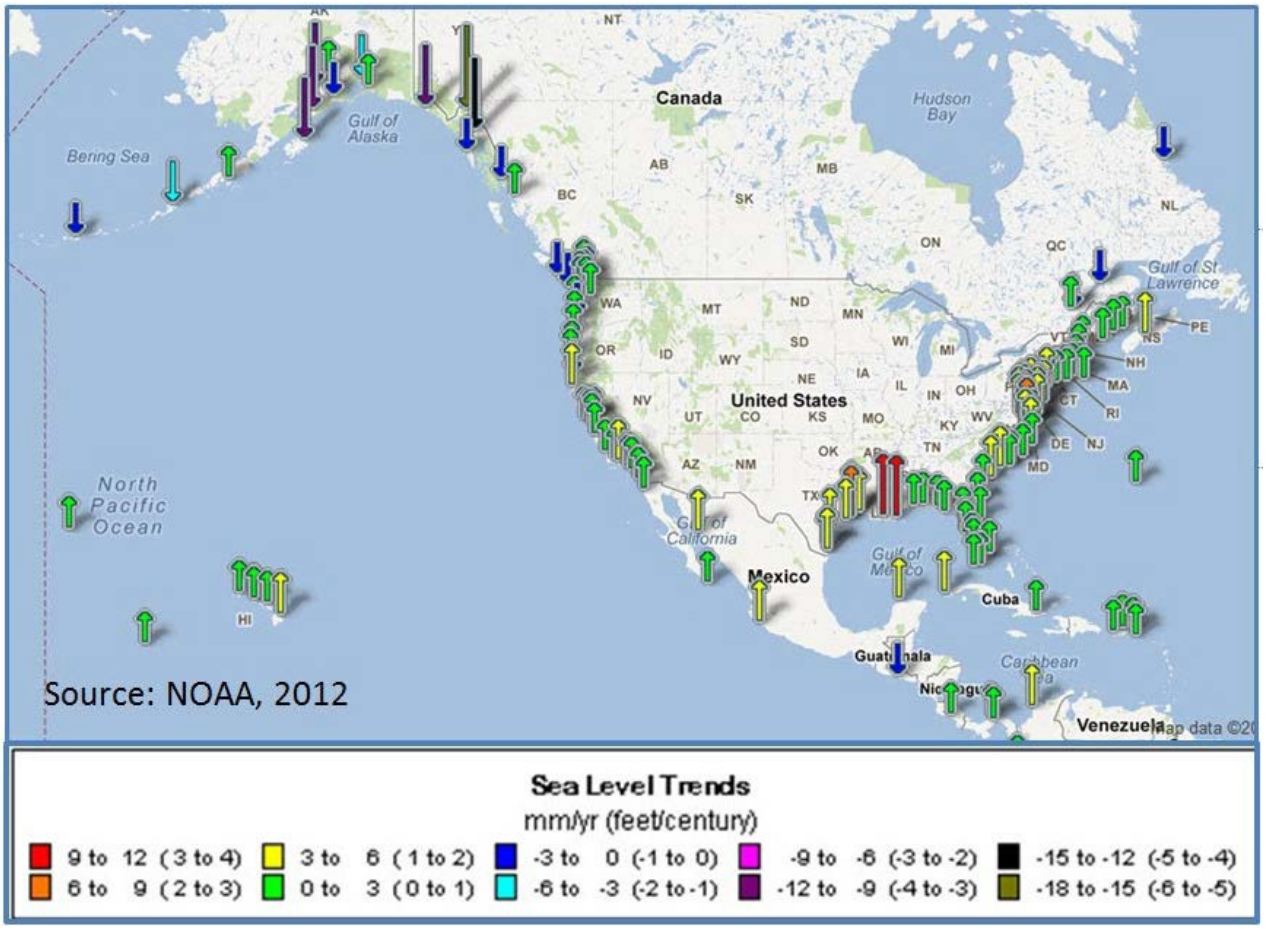


Figure B-7. Mean sea level trends for U.S. tide stations (NOAA 2011). See http://tidesandcurrents.noaa.gov/sltrends/slrmap.html for updated information.

(3) Discrete shifts in sea level data or changes in relative sea level trends due to earthquakes are monitored by NOAA at their tidal gauges, and trends are recomputed from data after a known significant earthquake event (such as the 1964 Alaska earthquake). Trends are not computed from pre- and post-event data. Post-event data analyses and surveys from the tide gauges to local benchmarks and geodetic bench marks are used to estimate vertical movement. Data from nearby CORS are also now being used to estimate local vertical land motion to help monitor the magnitude of the effect of earthquake events on sea level data.

c. Recommended Period of Record.

(1) Record Length. Each calculated linear trend has an associated 95% confidence interval that depends primarily on the period of record for each station. A derived inverse power

relationship indicates that 50–60 years of data are required to obtain a trend with a 95% confidence interval of ±0.5 mm/yr. This dependence on record length is caused by the interannual variability in the observations, and as a result, tide gauges with periods of record of less than 40 years are not recommended for determining SLC.

(2) Trends in Standard Error. Figure B-8 is a plot of the relationship between the period of record and the standard error of the trend for selected U.S. tide gauges. The standard error does not decrease to a reasonable level until approximately the 40- or 50-year period of record (Zervas 2009). These data indicate that record lengths shorter than 40 years could have significant uncertainty compared to their potential numerical trend values of a few millimeters per year. The figure qualitatively illustrates the asymptotic nature of increasing record length vs. decreasing standard error of the trend estimate, indicating that the standard error of the trend estimate can be large for tide stations with shorter records compared to those with longer records. Figure B-9 (Zervas 2009) shows the MSL trend 95% confidence interval versus the year range of data, with actual data and a least-squares regression line. The 95% confidence interval from the least-squares fitted line reduces to less than 1 mm/year once at least 40 years of gauge data are available. Figures B-8 and B-9 thus support the suggestion that a tide station should have at least 40 years of data before being used to estimate a local MSL trend, particularly when such a trend will be extrapolated into the future for use as a minimum baseline for projected future change in local MSL. For project planning and design supporting the entire project life cycle, the actual standard error of the estimate should be calculated for each tide gauge data trend analysis, and the estimates in Figures B-8 and B-9 should not be used as the sole supporting data.

d. Confidence Limits. Magnitude and confidence limits (based on standard error of the estimate) of trends for Atlantic coast, Gulf of Mexico, and tropical NOS tide gauges based on Zervas (2009) are provided by NOAA at http://tidesandcurrents.noaa.gov/sltrends/slrmap.html.

(1) Effect of Record Length on Confidence Limits. The effect of record length on confidence limits can be demonstrated by Galveston Pier 21 and Galveston Pleasure Pier. These gauges are located approximately one mile apart, with Pleasure Pier on the ocean side and Pier 21 on the navigation waterway side of Galveston Island. The Pier 21 gauge was established in 1908 and Pleasure Pier gauge in 1957, so Pier 21 has approximately 103 years of record and Pleasure Pier approximately 54 years. The confidence limits on Pier 21 are significantly narrower than for Pleasure Pier (Figure B-10).

(2) Confidence Limits for Pacific Coast. Confidence limits are not as uniform for many sites along the U.S. Pacific coast as for the Atlantic and tropical tide gauges (Figure B-11). Because of this, estimating historical SLC may be problematic and will require engineering judgment on a case-by-case basis and, to be robust, should take advantage of interdisciplinary and interagency subject matter expertise. It may be possible, depending on tide gauge location and proximity to nearby stations with longer records, to use the longer record trend as a proxy, providing the two records are well correlated for the concurrent period of record.

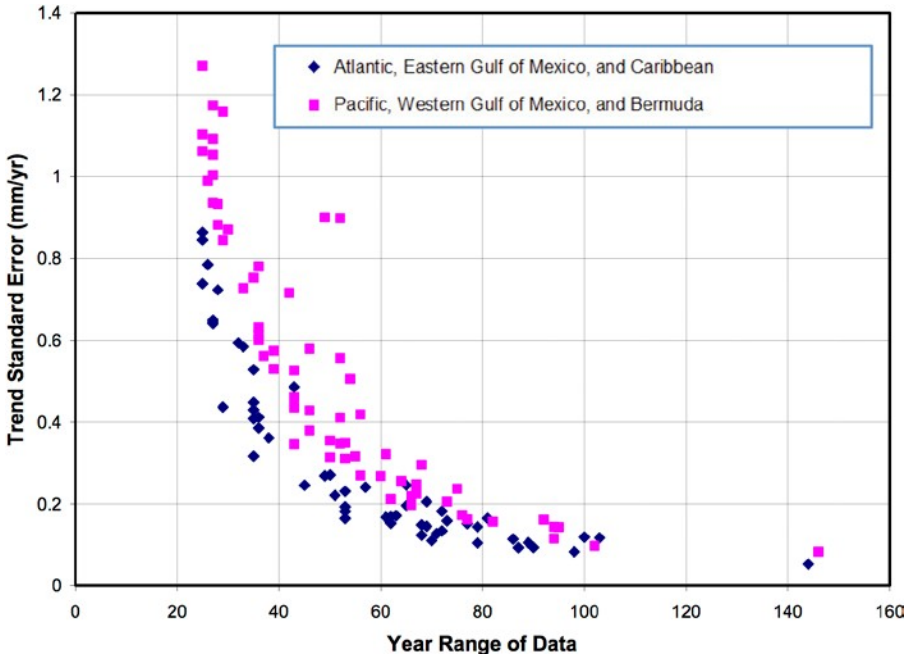


Figure B-8. Standard error of linear trend of SLC vs. period of record for selected U.S. tide stations. (From Zervas 2009.)

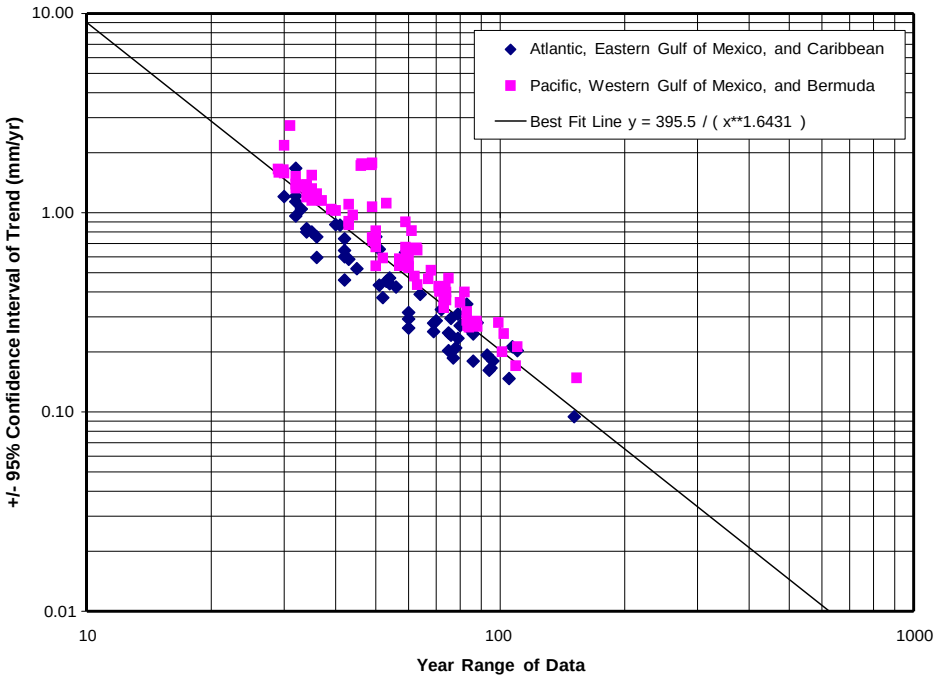


Figure B-9. ± 95% confidence interval of linear MSL trends (mm/yr) vs. year range of data. The least-squares fitted line is also shown. (From Zervas 2009.)

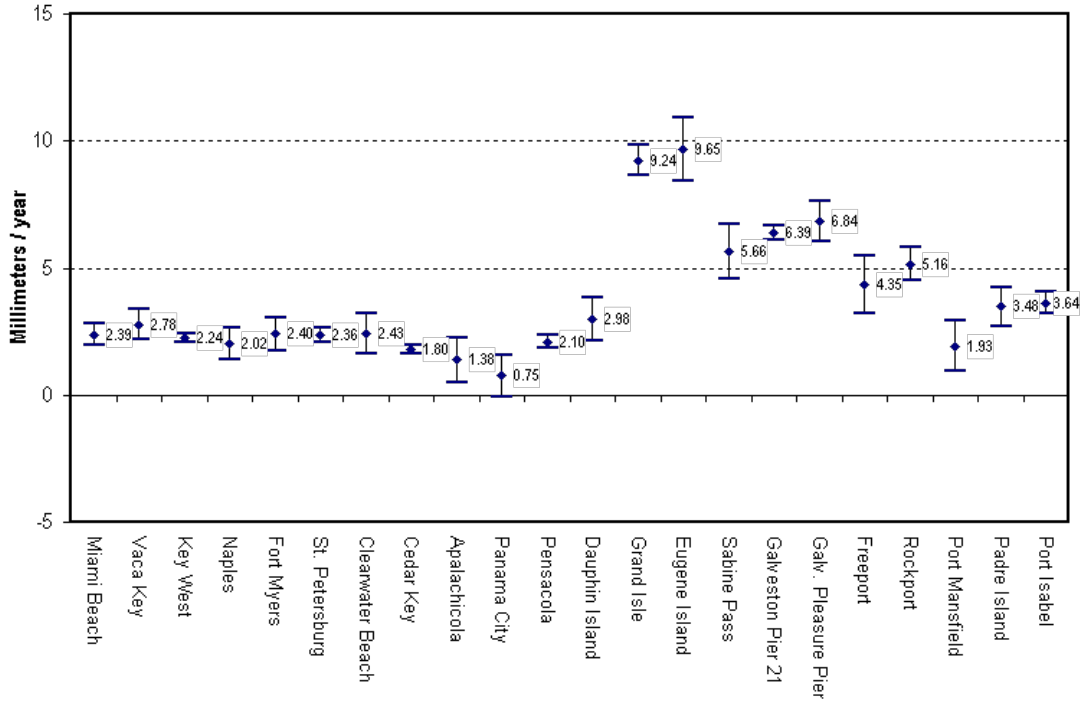


Figure B-10. Magnitude and confidence limits of trends for Florida Keys and Gulf of Mexico coast NOS tide gauges. (From Zervas 2009.)

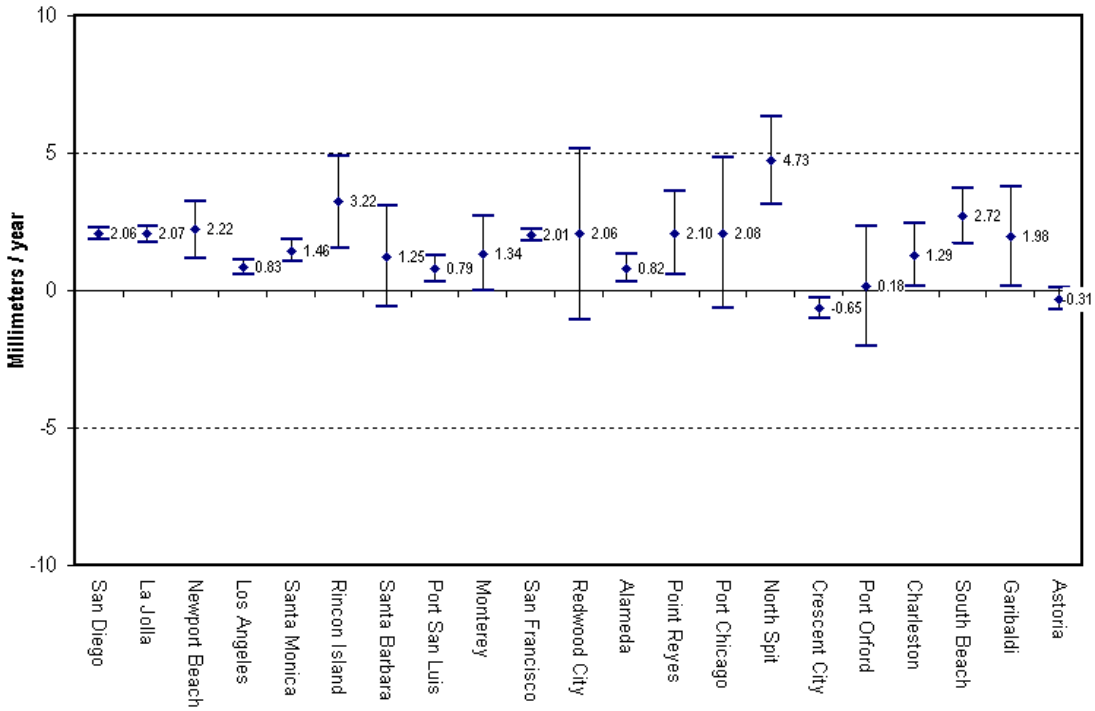


Figure B-11. Magnitude and confidence limits of trends for southern Pacific coast NOS tide gauges. (From Zervas 2009.)

B-3. Regional Sea Level Change. Figures B-10 and B-11 provide a sense of the regional variability of relative sea level trends around the coast. The graphical display of the data shows significant regional correlation of sea level trends, but in some instances the wide confidence limits also limit that interpretation. In many regions, a large component of the relative sea level trend can be due to vertical land motion, from either land subsidence, tectonic activity, or land isostatic rebound and deformation. (This is discussed further in Section B-4). The areas of maximum vertical land motion can generally be regionally described. For instance, in the coastal Louisiana and Texas region and the southeast Alaska region, the vertical land motion component dominates the trend. Plots showing the magnitudes and confidence limits of trends for other regions of the U.S. coastline can be found in Zervas (2009).

a. Satellite Altimetry. The graphical products from the satellite altimeter missions also demonstrate the regional variability of SLC. Figure B-4 depicts the global rates of SLC since 1993 for the entire footprint of the satellite orbits (60°N to 60°S). Note that although the average for the entire globe is approximate 3.0 mm/yr, there is significant regional variability, with some areas showing neutral or even negative sea level trends. This is the case for much of the West Coast and Gulf of Alaska for the U.S., for instance. Although the satellite altimeter average global rate is often used to suggest recent changes in rates of global sea level rise, the actual local or regional rate may be much different, and this relatively short period of record is not sufficient to determine a sea level change trend.

b. Local Analysis Required. The above discussion explains why the methodology for estimating future impacts being recommended in this ETL relies on a local analysis of the present sea level trend coupled with sea level rise scenarios based on climate models, rather than just using a common global rate for the last century of 1.7–1.8 mm/yr.

B-4. Estimating Local Vertical Land Motion from Tide Gauge Records. Vertical land motion (VLM) must be accounted for when applying regional and local sea level scenarios (NOAA 2012). VLM measurements are one of the primary adjustments needed to locally calibrate scenario projections of global sea level rise. This section documents a methodology that can be used to estimate the VLM at NOAA tide stations by performing an oceanographic analysis of the long-term data sets (Zervas et al. 2013). The methodology presented here involves the decomposition of the observed relative mean sea level data and their computed trends. It is recognized that the long-term sea level time series observed at tide stations contains a component due to oceanography and a component due to VLM. The oceanographic signal is not completely described by a simple global sea level trend estimate.

a. Methodology

(1) Purpose of the Method. The methodology provides estimates of local VLM at tide stations with 30–60 years of data that are more accurate than just simply subtracting the estimated global sea level trend of 1.7 mm/yr from the observed relative mean sea level trend. Relative sea level trends calculated from shorter data periods are more likely to be affected by anomalously high or low oceanographic levels at the beginning or end of their series. By removing the regional oceanographic variability as calculated based on longer-period stations, both more accurate and more precise estimates of land motion are possible at shorter-period stations.

(2) Sea Level Variations. Long-term tide gauge records provide information on relative sea level variations. This is because they measure sea level relative to local land elevations through repeat leveling surveys from the tide gauge reference zeros to local tidal benchmark networks. Over time, sea level variations are thus tracked relative to a fixed station datum maintained by the benchmark network. The sea level variations contained in the long-term tide gauge records contain components that vary in frequency (e.g., from storm surge to decadal scale) and that vary spatially. Some common influences include tidal variations, local hydrodynamic variability, dynamical changes in regional and coastal oceanographic processes, climate-related global sea level variations, and local and regional VLM (NOAA 2010b). The regional and coastal oceanographic processes are often in response to regional changes in atmospheric forcing and variations in decadal oscillations (ENSO, NAO, etc.). The sea level trends that NOAA derives from these data sets are relative sea level trends (Zervas 2009).

(3) Use of Long-Term Tide Gauge Records. In research on global sea level rise, long-term tide gauge records have been a primary source of information for estimating 20th century sea level trends (i.e., Church and White 2011). To do this, researchers carefully select only the longest, high-quality tide gauge records. In addition, only tide gauges located in open coastal areas with relatively "stable" land motion are chosen.

(4) Vertical Global Glacial Isostatic Adjustment. These records are then adjusted for vertical global glacial isostatic adjustment (GIA) using GIA models (Douglas 2001). Using these techniques, the research community has calculated that the rate for global sea level rise for the last century is 1.7 mm/yr (Bindoff et al. 2007). GIA models, however, provide only the broadest-scale resolution of VLM and do not have enough resolution to provide information at local scales (Sella et al. 2007). Local processes associated with tectonics, volcanism, sediment compaction, and subsurface mineral and water extraction are often of significance and generally not accounted for in the GIA models. For the purposes of engineering design and planning for sea level rise in a practical sense, VLM has been estimated by simply subtracting the best-estimate global rates of sea level rise from the local trend observed at a tide gauge (NRC 1987).

(5) Direct Measurements. Emerging technology to directly measure VLM is in the form of networks of Continuously Operating Reference Systems (CORS). At locations where these high-accuracy GPS receivers can be co-located with tide gauges, VLM can be more precisely determined and taken into account for estimating global sea level change (Snay et al. 2007, Woppelmann et al. 2007, JPL 2013). However, these CORS networks are a recent phenomenon, and long-term records are only starting to be accumulated. Co-location at tide gauges is proceeding very slowly. In the absence of direct measurement, it is possible to decompose the tide gauge records to provide an estimate of local VLM.

(6) Other Methods. Other methodologies for estimating VLM include comparing satellite altimeter data with simultaneous tide gauge data (Nerem and Mitchum 2002) and using repeat static GPS bench mark surveys at tide stations over time.

b. Analysis. The linear trends in relative mean sea level (NOAA sea level trends) are computed from the observations using the procedures found in Zervas (2009). These are the published NOAA trends also shown at http://tidesandcurrents.noaa.gov/sltrends. Figure B-12 is

an example for Boston, MA. Oceanographic residuals are obtained from each station time series by subtracting the relative NOAA sea level trend and the average annual signal in mean sea level (Zervas 2009). This procedure was developed after reviewing an approach by Larsen et al. (2003) to construct a common mode oceanographic signal or an "oceanographic correction."

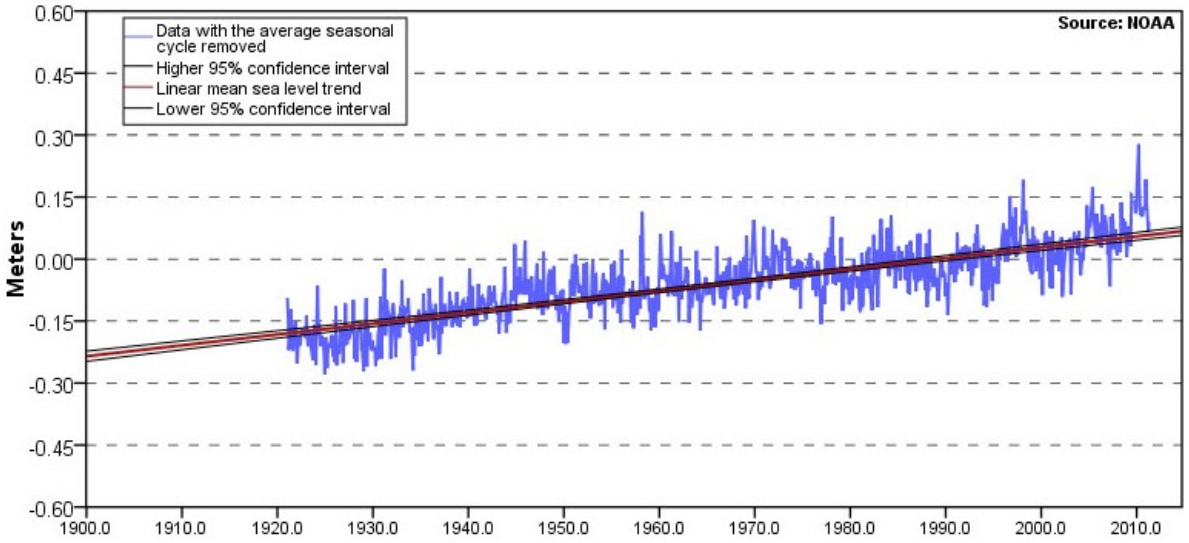


Figure B-12. Monthly mean sea level time series at Boston, MA, with the average seasonal signal removed and computed trend indicated. The mean sea level trend is 2.63 mm/yr, with a 95% confidence interval of ±0.18 mm/yr based on monthly mean sea level data from 1921 to 2006, which is equivalent to a change of 0.86ft (0.3m) in 100 years.

(1) Average Oceanic Residual Time Series. An average oceanographic residual time series was constructed for each region by averaging the residuals from the set of tide stations in each region. The oceanographic residuals are obtained from each of these station time series by de-trending them with the derived relative NOAA sea level trend and removing each station's individual seasonal cycle simultaneously. Conceptually,

$$O_{res} = MMSL_{obs} - MSL_{seasonal} - RSLR \qquad \text{(B-1)}$$

where $MMSL_{obs}$ = observed monthly mean sea level
$MSL_{seasonal}$ = average seasonal cycle in MSL
RSLR = relative sea level trend
O_{res} = oceanographic residual.

The U.S. coast was divided into 11 distinct geographic regions after performing a correlation analysis among the stations. These regions are:

- Gulf of Maine
- Mid-Atlantic Bight
- South Atlantic Bight

- Eastern Gulf of Mexico
- Western Gulf of Mexico
- Puerto Rico and Virgin Islands
- Hawaii
- Southern and Central California
- Northern California, Oregon, and Washington
- Southeastern Alaska
- Southern Alaska and Aleutian Islands.

(2) Example of Average Regional Oceanographic Signal. Figure B-13 is an example of the average regional oceanographic signal constructed from tide stations in the Gulf of Maine. The acknowledged 20th century global sea level trend of 1.7 mm/yr was added to each of the regional oceanographic residuals. This time series represents an estimate of the sea level response to a full spectrum of oceanographic forcings within the data series as well as global sea level rise.

$$O_{response} = O_{reg\ ave} + GSLR \qquad \text{(B-2)}$$

where $O_{response}$ = total regional sea level response
$O_{reg\ ave}$ = average regional oceanographic residuals
GSLR = rate of global sea level rise for last century (1.7 mm/yr).

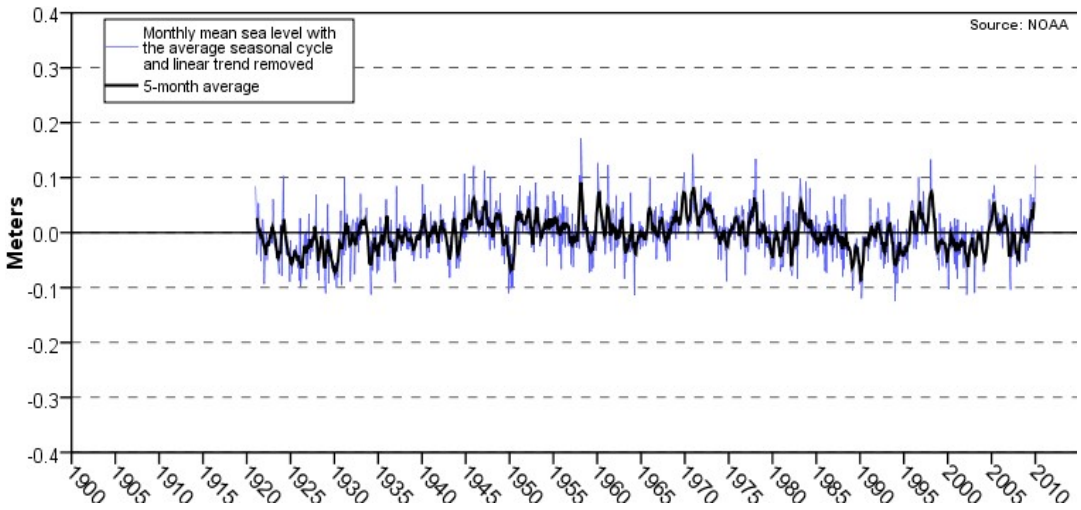


Figure B-13. Regional oceanographic residual using an average of the data from Eastport, ME, to Boston, MA.

As the last step, this regional oceanographic signal was subtracted from each original monthly mean sea level time series used to compute each individual NOAA sea level trend (with the average annual signal removed), and a linear trend was fit to the resultant data, as shown in Figure B-14 for Boston.

$$VLM_{series} = (MMSL_{obs} - MSL_{seasonal}) - O_{response} \quad \text{(B-3)}$$

The linear trend of this final time series should be a good approximation of any VLM taking place at the station, assuming that this process detected and removed the oceanographic signal appropriately.

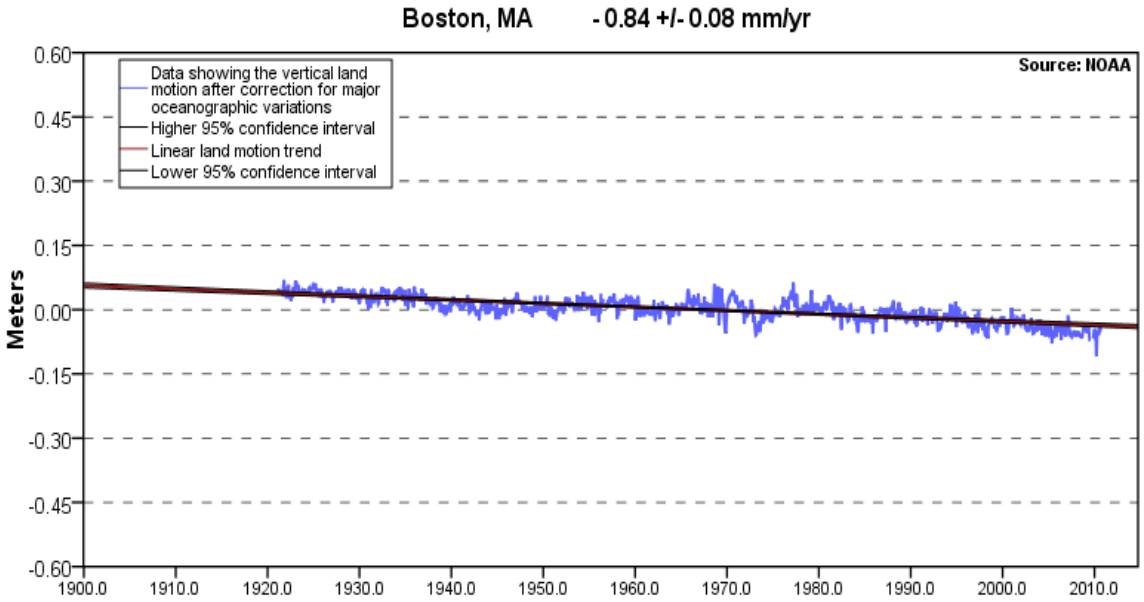


Figure B-14. Estimated vertical land motion at Boston, MA.

B-5. Climate Change Scenarios for Sea Level Rise and the Underlying Equations.

a. 1987 NRC Report. As discussed in Section 2-5 of this ETL, the equations adopted for use in this ETL have their roots in the original equations found in the NRC *Responding to Changes in Sea Level* document (NRC 1987). NRC (1987) performed a detailed assessment of peer-reviewed research and data analyses at the time (up through 1986), including the results of several NRC reports, most notably a study by the Polar Research Board (NRC 1985).

(1) Potential Acceleration. Based on their assessment, NRC (1987) recommended that feasibility studies for coastal projects consider the high probability of accelerating global mean sea level rise and provided three scenarios for eustatic sea level rise to the year 2100: rises of 0.5, 1.0, and 1.5 m. These scenario numbers were well within the bounds of the highest and lowest estimates based on the research at the time. They understood that the time-varying form of eustatic sea level rise from their present time of 1987 up to 2100 would most likely not be a linear function, and they adopted a curved form that would be consistent with anticipated future sea levels based on the latest research. NRC (1987) described these three scenarios using the following equation:

$$E(t) = 0.0012t + bt^2 \quad \text{(B-4)}$$

in which t represents years, starting in 1986, b is a constant, and E(t) is the eustatic sea level change, in meters, as a function of t. Each scenario used a different value for the coefficient b (2.8E-5 m/yr^2 for 0.5 m; 6.6E-5 m/yr^2 for 1.0 m; and 1.05E-4 m/yr^2 for 1.5 m).

(2) Updating Projections. The NRC committee recommended that "projections be updated approximately every decade to incorporate additional data." At the time the NRC report was prepared, the estimate of global mean sea level change was approximately 1.2 mm/year. Using the current estimate of 1.7 mm/year for GMSL change, as presented by the IPCC (2007), results in Equation B-4 being modified to:

$$E(t) = 0.0017t + bt^2 \quad \text{(B-5)}$$

Adjusting the equation to include the historic global mean sea level change rate of 1.7 mm/year results in updated values for the variable b of 2.36E-5 for modified NRC Curve I, 6.20E-5 for modified NRC Curve II, and 1.005E-4 for modified NRC Curve III.

b. USACE Guidance. USACE first issued planning guidance to take into account sea level change in 1986 in the form of a Headquarters memo. This memo provided the policy on technical considerations required for relative sea level change in the design of coastal flood control and erosion projects. This early guidance noted the difficulty of projecting future sea levels because of the complexity of the physical processes involved, and it required planners to account for historical changes in sea level. In 2000, the USACE *Planning Guidance Notebook* (ER 1105-2-100) required planners to consider the historical rate of change plus a higher range of sea level change that could include accelerated rates of change caused by warming temperatures and accelerated ice melt. The higher rate was set as the NRC 1987 high curve, Curve III. In 2009, USACE released transitory policy and guidance for all Civil Works programs that was eventually finalized in ER 1100-2-8162. This policy and guidance, developed with assistance from scientists at NOAA's National Ocean Service and the U.S. Geological Survey, required that low (extrapolation of current tide gauge record), intermediate (NRC Curve I), and high (NRC Curve III) SLC scenarios be considered. Adjusting Equation B-5 to include the historic GMSL change rate of 1.7 mm/year and the start date of 1992 [which corresponds to the midpoint of the current National Tidal Datum Epoch (NTDE) of 1983–2001], instead of 1986 (the start date for Equation B-4), results in updated values for the variable b being equal to 2.71E-5 for modified NRC Curve I, 7.00E-5 for modified NRC Curve II (not used in the USACE analysis but provided here for completeness), and 1.13E-4 for modified NRC Curve III. Manipulating Equation B-5 to account for the fact that it was developed for eustatic sea level rise starting in 1992, while projects will actually be constructed at some date after 1992, results in Equation B-6:

$$E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2) \quad \text{(B-6)}$$

where t_1 is the time between the project's construction date and 1992 and t_2 is the time between a future date at which one wants an estimate for sea level change and 1992 (or $t_2 = t_1$ + number of years after construction). For example, if a designer wants to know the projected eustatic sea level rise at the end of a project's period of analysis, and the project is to have a 100-year life and is to be constructed in 2013, $t_1 = 2013 - 1992 = 21$ and $t_2 = 2113 - 1992 = 121$.

c. Formulation and Evaluation Using Low, Intermediate, and High Rates of SLC. This ETL directs the formulation and evaluation of alternatives using low, intermediate, and high rates of future sea level change for both with- and without-project conditions, consistent with ER 1100-2-8162. At the beginning of the project, the without-project condition is assessed using the low, intermediate, and high SLC curves. Figure B-15 illustrates the comparison of the three sea level rise curves for a USACE project area in La Jolla, California. How those curves are evaluated within the alternative formulation and evaluation will depend on the strategic decision context of the project and the assessment of project area vulnerability.

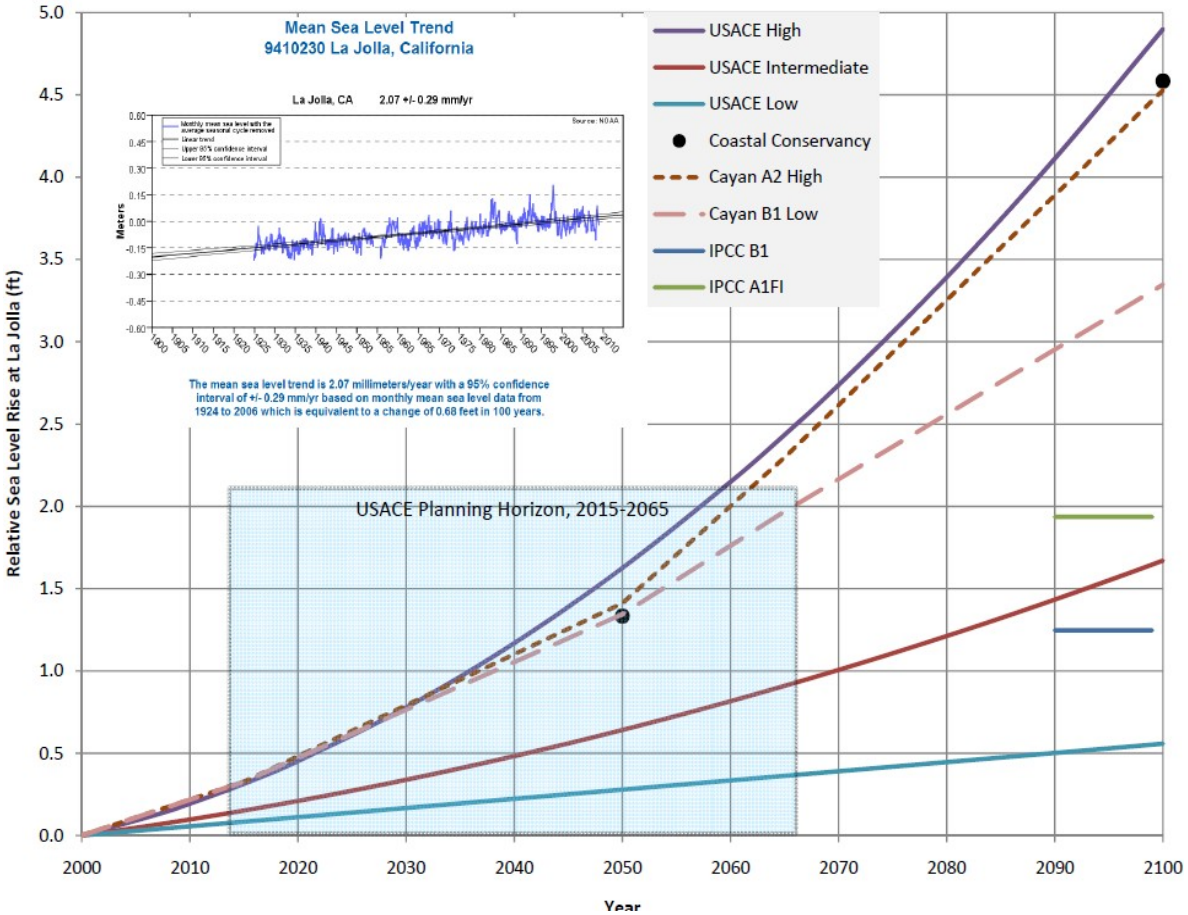


Figure B-15. Comparison of the three sea level rise curves for a USACE project in La Jolla, California.

(1) Low Scenario. The lowest (blue) curve in Figure B-15 is the extrapolation of the historical trend obtained from the local NOAA tidal gauge (data shown in the inset box). This curve is primarily controlled by regional sea level change projection and land uplift or subsidence.

(2) Intermediate Scenario. The red intermediate curve in Figure B-15 is estimated using the modified 1987 National Research Council (NRC) Curve I and Equations B-5 and B-6. These values are added to the local rate of vertical land movement as discussed in Section B-4. The

blue and green markers that bound this line indicate the low and high estimated from the 2007 IPCC Special Report on Emissions Scenarios (SRES), which contained a subset of six of the IPCC (2007) projections.

(3) High Scenario. The purple line in Figure B-15 provides the modified NRC Curve 3, representative of the high curve and the upper bound and given by Equations B-5 and B-6. Those values are added to the local rate of vertical land movement as discussed. This "high" rate exceeds the upper bounds of IPCC estimates from 2001, 2007, and 2013 to accommodate the potentially rapid loss of ice from Antarctica and Greenland, but it is within the range of peer-reviewed articles released since that time (Chapter 2, Figure 2).

d. Other Sea Level Scenarios. There is no prohibition against using other scenarios in addition to the low, intermediate, and high scenarios. For example, Parris et al. (2012) provides eustatic sea level rise scenarios developed in preparation for the National Climate Assessment, termed "NOAA scenarios." The lower two curves are the same, while the USACE high curve lies between the NOAA intermediate high and high curves. In a recent multi-agency effort facilitated by the U.S. Global Change Research Group (USGCRP), NOAA, FEMA, and USACE developed a sea level rise tool to assist in planning for future risks during Hurricane Sandy recovery efforts in the Northeast (http://www.globalchange.gov/what-we-do/assessment/coastal-resilience-resources). As part of this effort, the USACE sea level rise calculator tool was modified to include the equations used for the NOAA scenarios (http://www.corpsclimate.us/Sandy/) and allow for comparisons between them. Figure B-16 is an example comparison of the NRC and these NOAA scenario curves.

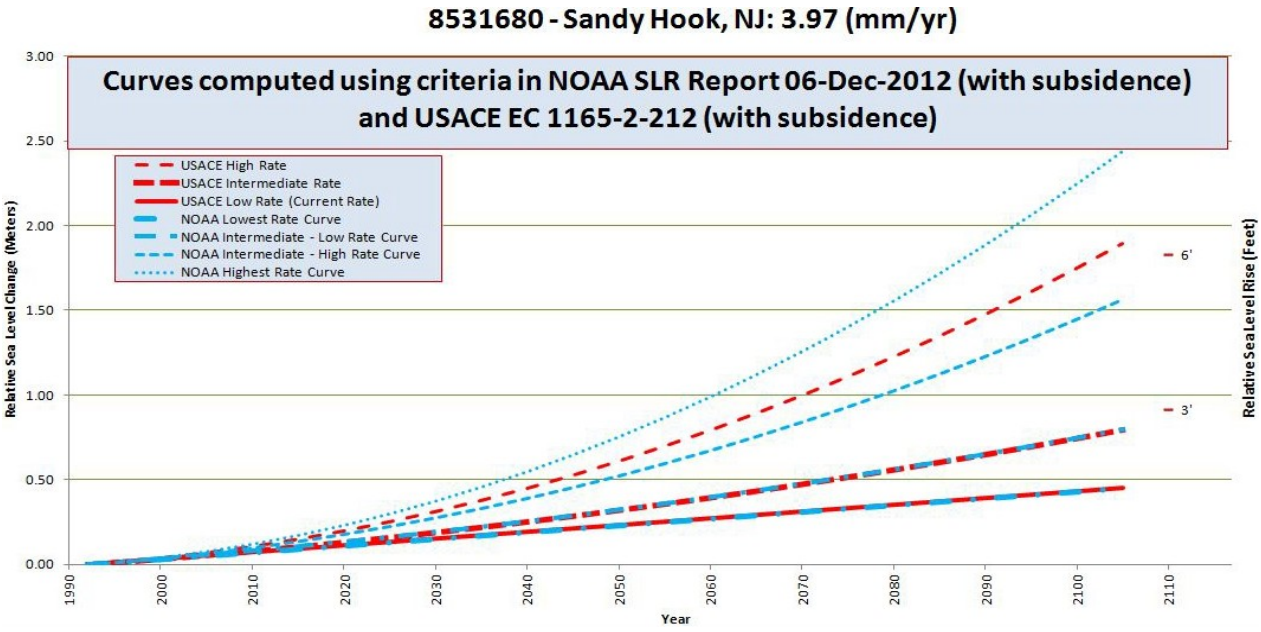


Figure B-16. Graphical comparison of the NRC and NCA sea level rise scenario curves (NRC I and NCA Intermediate Low curves are the same) using the USACE sea level rise calculator (http://www.corpsclimate.us/Sandy/curvesNJNY2_detailed_USACE.asp).

B-6. Projecting Extreme Water Levels and Frequency of Loading Events Related to Sea Level Change.

a. Exceedance Probabilities. Extremely high or low water levels at coastal locations are an important public concern and a factor in coastal hazard assessment, navigational safety, and ecosystem management. Exceedance probability is the likelihood that water levels will exceed a given elevation based on a statistical analysis of historic values. The Extreme Water Levels Product (http://tidesandcurrents.noaa.gov/est/) provides annual and monthly exceedance probability statistics for selected NOAA water level stations with at least 30 years of data. When used in conjunction with real-time station data, exceedance probability statistics can be used to evaluate current conditions and determine when a rare event is occurring. This information may also be instrumental in planning for the possibility of dangerously high or low water events on a local level. Because these statistics are station specific, their use for evaluating surrounding areas may be limited.

(1) Comparison to FEMA Base Flood Elevations. The extreme levels measured by the NOAA tide gauges during storms are called storm tides, which are a combination of the astronomical tide, the storm surge, and the wave setup caused by breaking waves. They do not include wave runup (the movement of water up a slope). Therefore, the 1% annual exceedance probability levels shown on the NOAA website do not necessarily correspond to the base flood elevations (BFE) defined by the Federal Emergency Management Administration (FEMA), which are the basis for the National Flood Insurance Program (FEMA 2012). Comparisons between NOAA and FEMA data can only accurately be made at the NOAA gauge locations. One reason for this is that the NOAA data are point data and the FEMA data are from a model grid. Also, wave setup is highly dependent on the location of interest; if a gauge is in a location where there is no wave breaking, there will be no wave setup, whereas FEMA's data are typically reported at the shoreline, where there is almost always wave breaking and a wave setup component. The 1% annual exceedance probability levels more closely correspond to FEMA's still water flood elevations (SWEL), defined as "the surface of the water resulting from astronomical tides, storm surge and freshwater inputs, but excluding wave setup contributions. In deep water this level approximates the midpoint of the wave height. In shallow water it is nearer to the trough than the crest."[4] The peak levels from tsunamis, which cause high-frequency fluctuations at some locations, have not been included in this statistical analysis because of their infrequency during the periods of historic record.

(2) Exceedance Probability Stick Diagram. Figure B-17 is an example of a NOAA exceedance probability stick diagram for Astoria, Oregon. High and low annual exceedance probability levels are shown relative to the tidal datums and the geodetic North American Vertical Datum (NAVD88). The levels are in meters relative to the 1983–2001 mean sea level datum established by CO-OPS. On average, the 1% level (red) will be exceeded in only one year per century, the 10% level (orange) will be exceeded in ten years per century, and the 50% level (green) will be exceeded in 50 years per century. The 99% level (blue) will be exceeded in all but one year per century, although it could be exceeded more than once in other years. The level of confidence in the exceedance probability decreases with longer return periods.

[4] See http://www.fema.gov/media-library-data/840f98e4cb236997e2bc6771f04c9dcb/Atlantic+Ocean+and+Gulf+of+Mexico+Coastal+Guidelines+Update.pdf

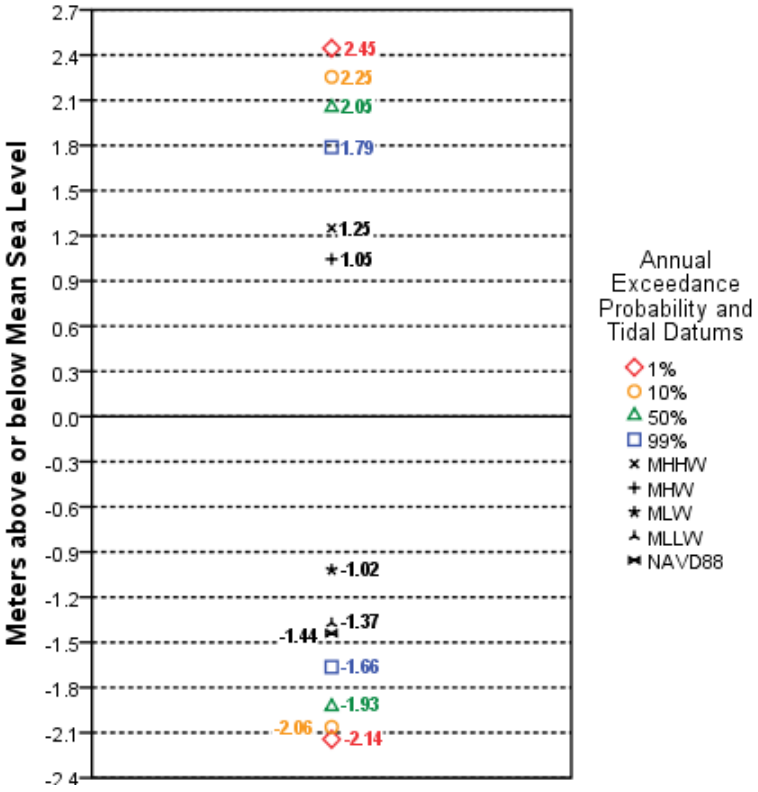


Figure B-17. Stick diagram of exceedance probability levels for Astoria, OR. (http://tidesandcurrents.noaa.gov/est/stickdiagram.shtml?stnid=9439040.)

(3) Annual Exceedance Probability. Annual exceedance probabilities (AEP) are provided by NOAA CO-OPS (http://tidesandcurrents.noaa.gov/est/index.shtml). The annual exceedance probability curves with 95% confidence intervals shown in Figure B-18 indicate the highest and lowest water levels as a function of return period in years. (NOAA provides a similar plot for the lowest water levels.) The dots indicate the annual highest water levels after the mean sea level trend was removed, which were used to calculate the curve. The levels are in meters relative to the mean higher high water (MHHW) established by CO-OPS (1 ft = 0.3 m). The position of the rightmost dot indicates the number of years of data used in the calculation.

(4) Analysis. The NOAA extreme water level product shown in Figures B-17 and B-18 is based on an analysis of the observed times series. The statistics thus should be used as an estimate of present conditions and do not take into account any future change in the rate of sea level change or any specific sea level rise scenario. Figure B-19 illustrates the concept of projecting future extreme water level excursions, using knowledge of the present trends and exceedance probabilities as a baseline and then adding a low and high estimate of future sea level change. The figure is intended to illustrate the potential future change in extreme low and high water levels with respect to the current elevation of those values. This is a first-level, conceptual screening tool for identifying minimum impacts and is not intended to replace a detailed engineering analysis. AEPs are provided by NOAA CO-OPS (http://tidesandcurrents.noaa.gov/est/index.shtml). Figure B-19 does not include extreme sudden changes, such as rapid subsidence due to an earthquake, that may be appropriate at some sites.

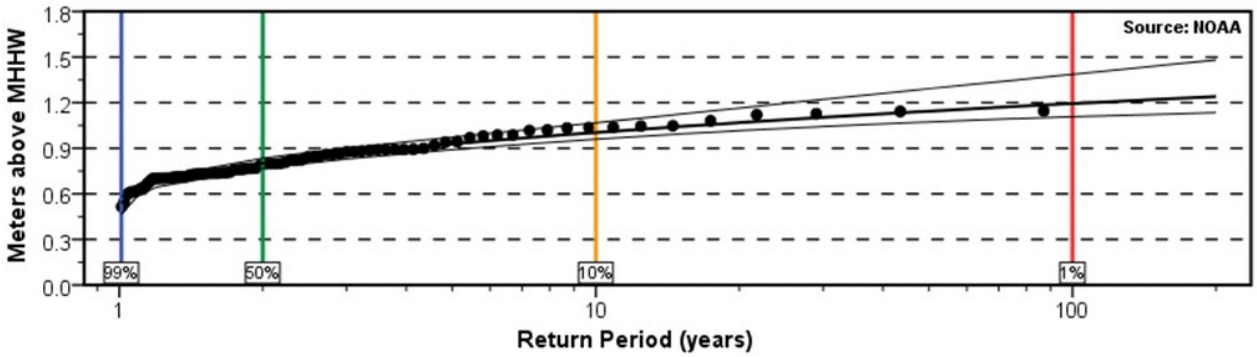
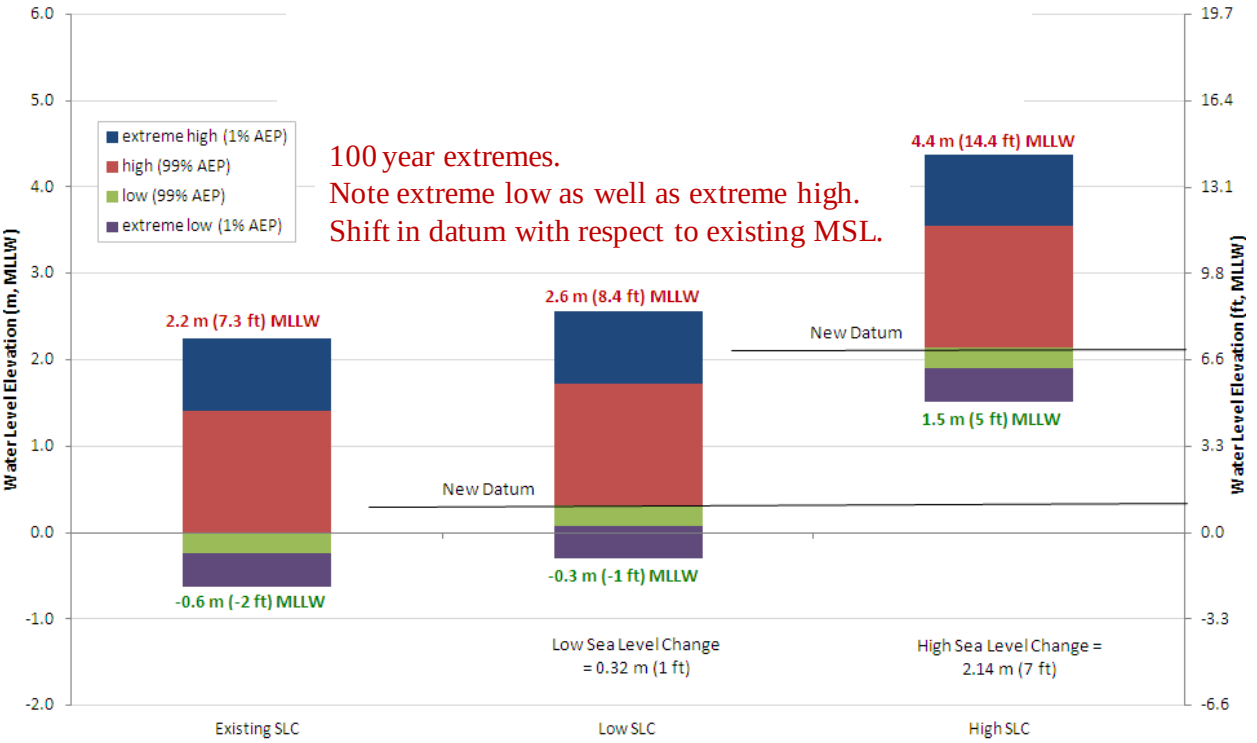


Figure B-18. Annual exceedance probability curve for Astoria, OR.
(http://tidesandcurrents.noaa.gov/est/curves.shtml?stnid=9439040.)



Notes:
(1) By 2110 NOAA will have updated the tidal datum 19-year epoch updates to keep pace. These plots as intended to show the adjustment relative to present day MLLW (1983-2001 NTDE).
(2) The extreme water level elevations shown do not include open coast extreme storm surge or wave run-up.
(3) Sea Level Change values are predicted 100-year value + one uncertainty to provide a conservative estimate of SLC for each scenario.
(4) Annual Exceedance Probabilites (AEP) are provided by NOAA CO-OPS (http://tidesandcurrents.noaa.gov/est/index.shtml)

Figure B-19. Example of projected extreme water level excursions to 2100
for Nantucket Island, MA.

(5) Datum Shifts. Shifts in datum should be considered in projecting future conditions. For example, in Figure B-19, the low SLC estimate shifts the datum approximately 1ft (0.3m), while the high SLC estimate shifts the datum more than 6.6ft (2m). These plots are intended to

show the adjustment relative to present-day mean lower low water (MLLW) for the NOAA National Tidal Datum Epoch (NTDE) 1983–2001.

(6) Low and High Water Levels. Extremes of low and high water levels should be considered, because they may represent the controlling loading case. For example, ecosystem, water supply, and drainage projects will be impacted by a shift in the normal and extreme low water levels. Extreme lows would also be important, for example, for a project where performance is connected to gravity flow canal or drainage systems. As seen in Figure B-19, the change from the existing condition at the project site can be significant.

b. Defining Future Vulnerability. As discussed in Section 2-6, defining future project area vulnerability involves assessing the potential increased frequency of water level events or loading conditions as future storm tides reach higher elevations than past storms and do so more frequently, impacting both flooding and structural loading. The response of each project area to changes in the magnitude and frequency of loading events will depend on the type of project as well as the vulnerability of the project area. Figure B-19 represents a first level of analysis for estimating the change in frequency of a given condition at a project site and is not intended to take the place of a rigorous engineering analysis. Future storm damages may occur to geographic areas not previously impacted by elevated sea levels. This topic has been the source of several recent research efforts, and several methodologies and approaches have been developed to provide future estimates.

(1) Figure B-20 and B-21 illustrate extreme event analysis for an application at Annapolis, Maryland, using an analysis technique developed by Kriebel (2012). Historical storm tides are superimposed in the future on a new MSL line shown by the black line representative of one of the sea level rise scenarios. Key elements of this empirical approach are the identification of a vulnerable flood threshold and the increases in the frequency of extreme events relevant to that threshold. How each project area and range of alternatives responds to the magnitude and frequency of loading event changes will depend on the type of project as well as the level of vulnerability of the project area.

(2) Figure B-20 plots the historical record of monthly mean sea level and the monthly highest observed tides and is the source data for the analysis. An empirical fit to the cumulative distribution (CDF) of the detrended monthly extremes was performed. Only long-term tide gauges with more than 50 years of record have been used for these analyses along with exceedence probabilities up to 50-year return level. Thus, the empirical CDF was not used to extrapolate to events more severe than the historical data record. The methodology uses the scenarios described in Section B-5 and assumes that future storms are statistically the same, relative to the mean sea level trend, as past storms (e.g., stationary). Changes in future storm climatology are not considered. Figure B-21 is an example result for Annapolis, MD.

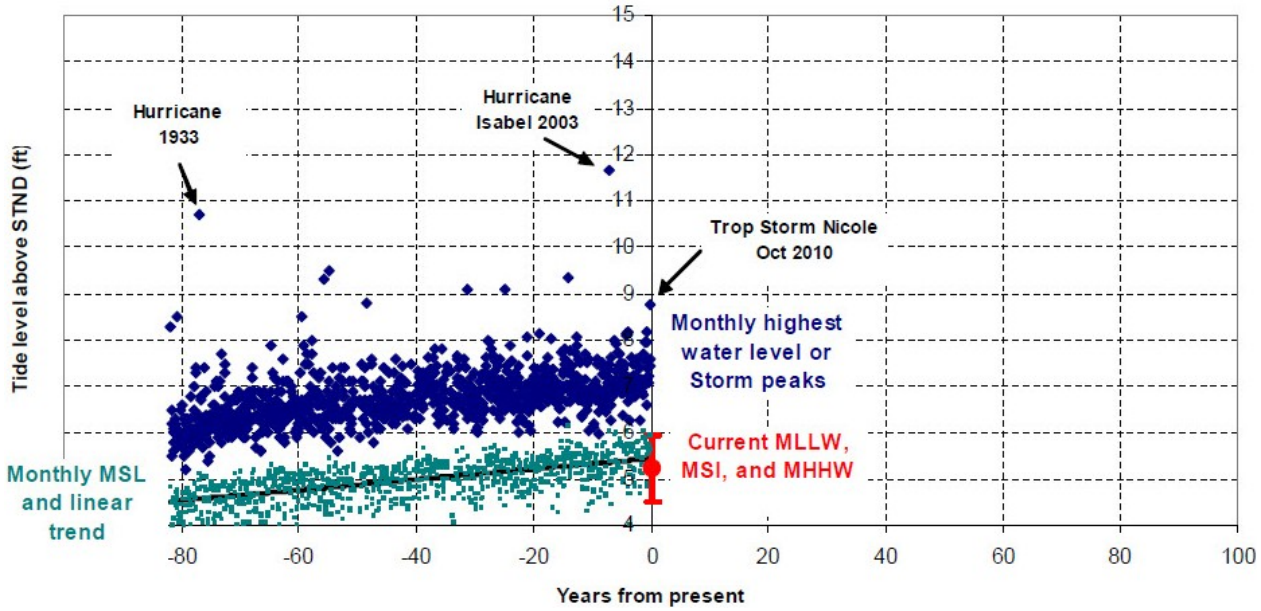


Figure B-20. Observed monthly MSL and monthly extreme data for Annapolis, MD, with observed trend.

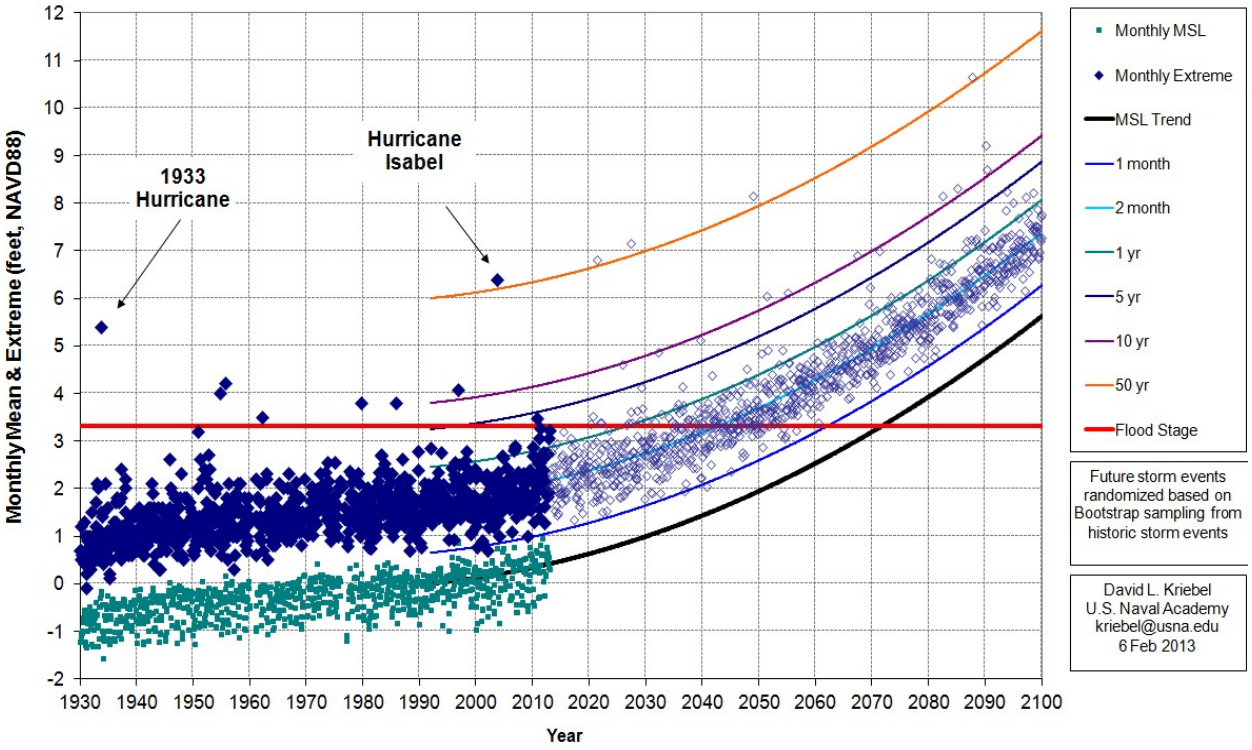


Figure B-21. Future vulnerability to sea level rise (high case) at Annapolis, MD, showing the relationship to local threshold elevations and flood recurrence intervals. (From Kriebel 2012.)

(3) In practice, using the empirical approach or fitting a Generalized Extreme Value (GEV) or similar extreme value distribution such as Generalized Pareto Distribution (GPD) to the entire data sample is recommended. The empirical CDF only works for storms within the range of historical data and has limited application for more severe events where extrapolation to events more severe than the historical storms is required. GEV and GPD analyses have the ability to extrapolate to lower probability than the data record and are preferred for extrapolation to storms more severe than those in the existing data record.

(4) Tebaldi et al. (2012) used a GPD approach to combine information from historical tide gauge records of water level with estimates of future global sea level rise in order to analyze current local trends and storm surge return levels and then project changes in future return levels and periods. Obeysekera and Park (2013) developed a methodology based on the synthesis of extreme value statistics with sea level rise scenarios using a GEV approach that allows for combinations of linear or nonlinear local and global sea level rise components. The methodology also can accommodate for the nonstationary evolution of sea level extremes. Hunter (2010) developed a simple method of determining a future sea level rise allowance that bases future allowances on estimates of the expected frequency of exceedance rather than on the probability of at least one exceedance. Like others, the methodology is based on the projected rise in mean sea level and its uncertainty and on the variability of observed extremes. The methodology assumes that the statistics of extremes relative to mean sea level are unchanged and then preserves the frequency of flooding events under projections of global mean sea level rise.

B-7. Comprehensive Evaluation of Projects with Respect to SLC Database Development. A valuable data resource developed by USACE regarding SLC can be found at www.corpsclimate.us/ccaceslcurves.cfm. This project provides a tool that uses the approaches and the sea level rise scenarios described in this guidance to estimate future sea levels based on user-specified inputs, including a drop-down menu of NOAA tide gauges. The calculator provides graphs and tables of results, as well as links to a more detailed spreadsheet.

APPENDIX C

Navigation Projects

C-1. General Approach and Background. The role of the USACE's navigation mission is to provide safe, reliable, and efficient waterborne transportation systems (channels, harbors, and waterways) for the movement of commerce, national security needs, and recreation. USACE accomplishes this mission through a combination of capital improvements and the operation and maintenance (O&M) of existing projects. Capital improvement activities include the planning, design, and construction of new navigation projects. These activities are performed for the navigation of shallow-draft (equal to or less than 14ft/4.3m draft) and deep-draft (greater than 14ft/4.3m draft) vessels on inland waterways, harbors, ports, and channels. The potential impacts of sea level change (SLC) on navigation structures and the possible adaptations that can be developed to counteract these impacts must be considered in all USACE studies and projects located in tidally influenced waters. This guidance does not address navigation studies and projects that are not subject to tidally influenced waters.

a. Federal Responsibilities. Federally authorized general navigation features (GNFs) include entrance channels, access channels, turning basins, and coastal structures (e.g., jetties or breakwaters) designed to provide safe transit, mooring, and berthing within the project area. Harbors are places that offer vessels shelter from weather. A harbor is also a port if it provides facilities for loading or unloading cargo or passengers. Waterways are routes used by vessels. Their primary function is to facilitate the movement of vessels, and they may simply connect bodies of deep or shallow water or they may be parts of riverine or coastal waterway systems. Also included are dredged material disposal areas (except those for the inland navigation system, the Atlantic Intracoastal Waterway, and the Gulf Intracoastal Waterway) and sediment basins. Special Navigation Programs include removal of wrecks and obstructions, snagging and clearing for navigation, drift and debris removal, bridge replacement or modification, and mitigation of project-induced damage to adjacent shorelines (under Section 111 of the Continuing Authorities Program). Shoreline protection and stabilization project elements may be needed to maintain navigation projects. GNFs are cost shared with the non-Federal project sponsor based on the authorized project depth.

b. Non-Federal Responsibilities. Associated non-Federal features include berthing areas, seawalls, bulkheads, port infrastructure, and transportation links, as well as other elements required to realize benefits claimed for the project. The cost of these navigation project elements is a 100% non-Federal responsibility. Table C-1 lists Federal or non-Federal GNFs at risk from SLC. It is important to recognize that each navigation project relies on all of its associated features to be functional and therefore for benefits to be realized.

Table C-1. Federal and non-Federal navigation project features at risk from sea level change.

Federal	Non-Federal
Structures Locks Breakwaters Jetties Groins Revetments Wave absorbers Disposal areas	Waterside Berthing areas Docks Wharfs Bulkheads Seawalls Dolphins
Channels Entrance channels Access channels Turning basins	Landside Storage areas Warehouses Roads Utilities Bridges

C-2. Key Concepts and Screening Process.

a. General. To determine the best course of action for addressing potential SLC impacts on navigation projects, it is essential to identify key questions to be answered. On a project-by-project basis, it will be necessary to identify which elements of a project may be sensitive to SLC. This will include consideration of both the Federally authorized general navigation features and the non-Federal infrastructure. This will require an inventory of channels, structures, operations, and an understanding and summary of overall project performance. Some useful questions include:

- What elements of the navigation project may be sensitive to SLC?
- What types of impacts could occur (structures, operations, performance)?
- What coastal or estuarine processes may be impacted?
- What level of analysis is merited given the expected impacts?
- What would be expected to happen without planning and designing for SLC?
- Is there a need for additional or secondary structures to improve the long-term stability of the project (spur groins, backshore protection, etc.)?
- Is there a need for changes to the channel dimensions (depth, width, etc.)? Will those changes impact adjacent structures or navigation processes?
- Which parts of the navigation project might be adaptable? Which parts would not be?
- How might adaptive management be applied to the project?
- How might maintenance requirements change over time?
- What monitoring activities will be required and at what times?
- Will changes in project authorization language be required?
- What do the USACE field offices need to do differently to address SLC impacts?
- Will an increase in the frequency of damaging events transition the project into a rehabilitation or reauthorization scenario?

- How might operational effectiveness or windows be altered and will that impact project benefits or safety over time?

Specific tasks that each project team should address include the following:

- Consider design and performance categories that may be affected.
- Develop a plan to conduct sensitivity analysis using three SLC curves.
- Determine if SLC would have a cumulative effect with other climate change factors (e.g., storm intensity, storm surge, precipitation).
- Identify tipping points for stability or project performance.
- Identify the potential range of SLC responses (structure response, wave transmission, shoreline/infrastructure damage, channel shoaling and maintenance).
- Assess potential impacts over 25-, 50-, and 100-year planning horizons over three SLC rate scenarios.

b. Key Concepts. Key concepts associated with the assessment of SLC impacts on navigation project are important because they will lead to the identification of potential solutions to the threat. Because the potential impacts of SLC on a navigation project will vary from project to project, the level of analysis warranted will also vary. As described in the main text, planning strategies to be considered include anticipatory, adaptive, and reactive. Which parts of the navigation project might be adaptable? How might the concept of adaptive management be applied to the project? If the project feature is not adaptable to SLC, will an anticipatory or reactive strategy be effective? Since there will always be residual risks associated with any recommended plan, it will be important to identify these risks and quantify their impact.

c. Scaled Analysis and Decision Making. The main text of this ETL suggests a tiered analysis for determining the consequences of potential SLC (Figure 9). Each tier represents a decision point that will dictate the level of detail and appropriate methods that are needed for subsequent tiers.

(1) Tier 1 – Establish a Strategic Design Context. This initial screening level assesses whether there is potential for significant or catastrophic consequences to life safety, property, critical infrastructure, and/or ecosystems. This initial phase determines the appropriate scale of analyses for incorporating SLC into Tier 2. In addition to the evaluation outlined in Figure 9, for a navigation project, some questions that can be asked at this stage include:

- What magnitude of both Federal and non-Federal infrastructure may be impacted?
- Does the non-Federal infrastructure (commercial, transportation, power, etc.) have areas of vulnerability that may result in impacts to realized benefits for the project?
- Have other Federal mission areas (specifically Coast Guard) and life safety issues been identified?
- Do decisions made with regard to the navigation project influence community decisions or larger regional systems?

(2) Tier 2 – Project Area Exposure and Vulnerability to SLC. The description of the future without-project (FWOP) condition is the foundation for subsequent plan formulation. In Tier 2,

the incorporation of SLC scenarios adds another dimension to the without-project description since there are three potential futures as defined by the three different SLC curves. In addition, loading and exposure variables may change through the project's life cycle. Specific questions for navigation project at this tier include:

- Does the 100-year, high-rate curve expand the potentially impacted project area into locations that will require additional protection and/or upgrades to project features (Federal or non-Federal) that already exist? For locations experiencing relative sea level fall (e.g., Alaska), evaluate the low rate at the 100-year time horizon.
- Is it expected that either the function or the operation of the project could change under potential future conditions (i.e., operational or access windows, adjustments for clearance or vessel movement)?
- Are support systems within the project itself expected to be adaptable to changed conditions or increased flooding due to overtopping of structures?
- What are the expected failure and/or damage modes for the navigation project features and surrounding area?
- How might storm surge, storm intensity, and storm frequency combine with SLC to modify stability, performance, and operational conditions at the project?

(3) Tier 3 – Alternative Development, Evaluation, and Adaptability. Tier 3 involves formulating and evaluating measures directed at the identified problems. SLC may be only one of the considerations for alternative development. Key questions for navigation projects in Tier 3 include:

- How might both Federal and non-Federal structures fail or be damaged under higher sea levels combined with larger and more frequent extreme wave heights?
- Are there thresholds with respect to stability and project performance that would transition a navigation project into a required structural or operational action?
- Are there modifications or actions that should be made now to prepare for possible future actions or to ensure that the project is adaptable?
- Have projected long-term maintenance issues connected with both infrastructure and channel maintenance been identified and are these project features sustainable into the future?

C-3. Discussion of Principles. In the context of this ETL, principles are those concepts that are commonly accepted to be true and that underpin assessments of the effects of SLC on USACE projects. Issues are matters specific to each principle that should be considered in order to properly address the effects of SLC. Issues cannot necessarily be solved with a single answer or method. Methods encompass tools ranging from first-level screening to higher-level modeling (i.e., rules of thumb to complex computational models) available to address each of the issues. Table C-2 summarizes principles, issues, and methods for the navigation mission area. Table C-3 lists some of the physical processes of navigation projects that are sensitive to SLC.

Table C-2. Principles, issues, and methods for incorporating SLC in planning in the navigation mission area.

	Principles	Issues	Methods
Coastal and Hydrodynamic Forces and Processes	Navigation projects located along the open coast or back bays are typically exposed to the direct impacts of the coastal environment. SLC will result in changes to incident loading parameters as well as to cumulative effects of multiple parameters. Coastal processes related to navigation project performance will be impacted.	Changes to the coastal forces and processes should be assessed based on their ability to modify either the stability or the performance of a navigation project. Direct SLC impacts to wave height and storm surge should be evaluated in addition to the secondary impacts those parameters have on important coastal processes such as wave transmission, wave runup and overtopping, harbor resonance, and other performance-related processes.	At the lowest level, rules of thumb and simple equations can be used to assess the changes in basic parameters such as wave height to a change in water level. At the higher design and analysis levels, numerical and physical modeling capabilities are available to quantify changes in incident wave energy under various SLC scenarios. Typical parameters to be assessed include transformed wave height, transmitted wave height (incident, overtopping, diffracted), wave runup and overtopping, storm surge, harbor resonance, etc.
Morphological Response	Relative SLC will result in morphology responses within and adjacent to ocean and bayside navigation projects that may affect feature stability as well as project performance. SLC has the potential to modify the coastal processes affecting navigation channel stability and disposal site dispersiveness.	Potential morphology responses associated with SLC include shoreline change (advance or retreat), narrowing and lowering of the beach berm, dune recession, bluff erosion, potential of jetty flanking (e.g., separation from shore), and changes to ebb and flood tidal shoals. Increased shoaling may result from SLC-induced modification of coastal processes and any adjacent beach renourishment projects. Increased scour at structure foundations can result from higher incident wave heights, sea level fall, or channel modifications in response to SLC. The operation and response of open water or upland disposal sites may be modified based on increased/decreased forces.	Some morphological responses, such as foundation scour, can be assessed using simple equations as well as the projection of increased loading parameters. Hydrodynamic modeling can be conducted to predict modifications to project area forcing. Sediment transport modeling can be conducted to identify possible changes in transport pathways and magnitude. Attempts are to be made to predict increased shoaling due to SLC and any adjacent beach renourishment projects, and appropriate life-cycle dredging costs should be reflected in plan formulation.

	Principles	Issues	Methods
Infrastructure Vulnerability or Biological Response (Ecosystems)	SLC has the potential to change the design loading and key processes relative to navigation features (structures, channels, disposal sites) and adjacent features (e.g., beach renourishment projects for coastal risk reduction) as well as non-Federal project features over the project life cycle. Stability may be affected by SLC-induced changes to the forces that act on a feature, which might reduce the life of the feature or increase its maintenance requirement.	The potential changes in loading to each structure within the navigation project should be evaluated. Tipping points and thresholds that may result in destabilization of the structure should be identified. Structure characteristics that may need to be modified (larger, higher, longer) to sustain project performance should be identified. The maintenance of authorized depths in navigation channels should be assessed in conjunction with their implications for modifications to channel dimensions and layout, required changes to structures, and new dredging work and maintenance.	Projected changes in design criteria based on increased loading should be calculated. Adequate geotechnical investigations to characterize in situ material to be encountered under sea level fall should be addressed. Adequate clearance (both horizontal and vertical) from Federal and non-Federal navigation features would have to be provided. Adequate bridge clearance must be incorporated to accommodate sea level rise. Bulkheads, seawalls, revetments, berthing areas, drainage systems, transportation links, and other port infrastructure vulnerable to inundation must be designed to accommodate various SLC scenarios. Changes in rates of damage to existing or projected structures should be calculated.
Human Response	SLC will, at some water level threshold, cause human responses. Some human responses to SLC may have a strong influence on the future behavior of navigation project sponsors and stakeholders. Anthropogenic responses must therefore be accounted for when determining future without-project and with-project conditions.	What are the thresholds and tipping points for human responses to SLC? What are the expected human responses? What are the economic thresholds past which responses are not sustainable? Will any human responses influence future morphological, structural, or operational evolution?	Analysis should include site-specific historical human responses to threatened navigation infrastructure and the economic sustainability of future response costs in the presence of SLC (economic thresholds). Relevant existing regulations and laws that might limit future responses (e.g., resource agencies' reluctance to permit general navigation feature modifications) should be reviewed. Any potential limitations to local stakeholder actions that could impact the assumed benefits or continued effective operation of the navigation project should be identified.

	Principles	Issues	Methods
Project Feature or System Response	Individual project features (revetments, jetties, breakwaters, channels, etc.) may require modification over the project life cycle to maintain stability and function. Project features should be assessed both in plan view as well as in cross section in terms of their stability and performance. Long-term maintenance required to maintain function should be addressed. Project operation and performance may be impacted on a routine basis.	The frequency and volume of wave transmission (overtopping, transmission, diffraction) and wave surge and the associated impacts to port and harbor operations may increase over time, resulting in impacts to operation and a decrease in throughput. Under sea level rise, wave heights will increase over time, and the increasing design loads may ultimately result in structural failure and impacts to port facilities. Under sea level fall, available channel depths will be impacted, and structure foundations will be exposed to increased wave scour, resulting in structural failure.	Various types of structures can be analyzed for stability using tools ranging from basic equations to physical or numerical modeling. Overall project operational conditions can be assessed using a range of numerical model types to calculate wave conditions, wave and surge runup, and harbor/port response. Engineering and economic models can be used to estimate harbor/port operational and maintenance procedures over the project life cycle. Critical thresholds can be identified as well as plans for adaptation throughout the project life.

Table C-3. Primary physical processes sensitive to SLC associated with navigation projects.

Process	Impact
Wave attack	Wave run-up and overtopping Wave transformation Depth-limited wave Wave and storm surge Rubblemound damage rate Increased ship wake impacts
Inundation	Wave run-up and overtopping Wave and storm surge
Short- and long-term erosion	Wave run-up and overtopping Depth-limited wave Wave and storm surge Shoreline change rates (storm event, seasonal, long term)
Inland waterways and drainage hydraulics	Canal and drainage system profiles
Harbor, basin, and channel hydrodynamics	Harbor resonance Vessel excursion and movement Wave transmission (diffraction, overtopping, permeability) Water quality circulation characteristics
Morphological change and shoaling	Foundation scour Adjacent shoreline change Disposal site dispersiveness Sediment transport and deposition (subaqueous and subaerial) Subsidence and uplift
Water quality changes (surface and ground)	Salinity Circulation Mixing of ocean, estuarine, and river water
Management practices	Catchment management Dredging Dredged material placement site capacity Groundwater or fluid withdrawal Shoreline stabilization measures

a. Coastal Forces and Processes.

(1) The nature of navigation projects makes them unique relative to other USACE Civil Works project types in the assessment of SLC. Navigation projects are generally located along the open coast and are typically exposed to the direct impacts of the coastal environment. Coastal navigation structures such as breakwaters, groins, revetments, and seawalls are usually necessary to ensure safe transit and berthing at ports and harbors. SLC will result in changes to individual loading parameters as well as cumulative effects of multiple parameters. In addition, coastal processes related to navigation project performance, such as wave overtopping, wave transmission, and harbor resonance, may be impacted. Table C-3 shows some of the primary coastal processes that may be altered by SLC. These include potential changes in wave attack, project area inundation, interior drainage hydraulics, and hydrodynamics related to both harbors and channels.

(2) The changes to the coastal forces and processes should be assessed based on their ability to modify either the stability or the performance of a navigation project. At the lowest level, rules of thumb and simple equations can be utilized to assess the changes in basic parameters such as wave height or a change in water level. At the higher design and analysis levels, numerical and physical modeling capabilities are available to quantify changes in incident wave energy under various SLC scenarios. Both direct impacts and secondary and cumulative impacts resulting from multiple parameter changes will need to be assessed.

b. Morphological Response.

(1) Relative SLC will result in morphological responses within and adjacent to navigation projects. Potential morphological responses associated with SLC include shoreline or riverbank change (advance or retreat), narrowing and lowering of the beach berm, dune recession, bluff erosion, foundation scour, and changes to ebb and flood tidal shoals. In Table C-3, morphological changes fall under the broad process categories of Short- and long-term erosion and Morphological change and shoaling.

(2) A project's morphological responses to SLC can affect the long-term stability of the project's features and performance, as well as the required operations and maintenance. Project-related issues also include the possibility that dredged material placement sites (submerged and sub-aerial) will experience a change in capacity. Methods used to describe morphological responses due to SLC should be carefully selected to determine first-order impacts to project feature stability, project performance, or project maintenance.

(3) The morphological responses can be both natural and project-induced. Project-induced changes will need to be separated out to determine liability in accordance with the principles of Section 111 of the Continuing Authorities Program. Sediment pathways, and ultimately sediment budgets, can be impacted by SLC.

(4) Sea level fall will create different morphological considerations than sea level rise. Where vertical land movement combined with sea level rise results in a net negative response, physical and operational changes to the project will need to be assessed. This may impact the provision of authorized depth, project shoaling and maintenance, and the operation of dredged material disposal sites.

c. Infrastructure Vulnerability to Sea Level Change.

(1) Infrastructure vulnerability should be assessed from both the structural and the project performance standpoints. Changing water levels combined with the potential for increased frequency and magnitude of storm events (waves and surge) will increase the impact on Federal structures (jetties, breakwaters, revetments, and groins) and non-Federal structures (berthing areas, bulkheads, seawalls, and infrastructure) and the project vicinity (drainage and transportation links) over the project's life cycle. The broad process categories in Table C-3 related to infrastructure vulnerability include Wave attack, Inundation, Short- and long-term erosion, Morphological change and shoaling, and Management practices.

(2) A navigation project infrastructure's vulnerability to SLC should be evaluated in cross section and project layout. A feature's stability may be affected by SLC-induced changes to the forces that act on it, which might reduce the life of the feature or increase its maintenance requirement. Recommended improvements to project features or the addition of secondary structures to address either stability or performance should be included in the analysis. In some cases, measures taken now to allow adaptation in the future should be addressed. Such measures could range from land acquisition for future building to the design of a structure's cross section or layout to facilitate future adaptation.

(3) The maintenance of authorized depths in navigation channels should be assessed in conjunction with its implications for modifications to channel dimensions and layout, required changes to structures, and new dredging work and maintenance.

(4) Port infrastructure will generally only be impacted under a sea level rise scenario. If the sea level falls, the port infrastructure will essentially be elevated farther and farther from harm's way; however, port operations could be affected, particularly offloading and onloading clearances. If the sea level rises, clearances may be reduced for bridges or other port facilities.

(5) Bulkheads, seawalls, revetments, berthing areas, drainage systems, transportation links, and other port infrastructure vulnerable to inundation must be analyzed under a sea level rise scenario. Non-Federal navigation project sponsors will be responsible for ensuring the longevity and performance of such features so that the benefits claimed for the project can be realized.

(6) Navigation structures are typically constructed in layers of stone, with the inner layers providing foundation and porosity requirements while the outer (armor) layer ensures stability against incident wave energy. Sea level rise will be an issue for navigation structures because it changes loading, runup, and overtopping and results in changes in navigability. As sea level rises, structures that encounter depth-limited waves will be exposed to ever-increasing wave heights. This will increase loading over time, with its associated increases in runup and overtopping.

(a) One consequence of increasing design loads on navigation structures is the threat of structural failure. Another consequence is that the frequency of wave overtopping and its associated impact on port and harbor operations may increase over time, resulting in a decrease in throughput. Navigability may also be an issue because larger waves may impact channels, basins, wharfs, docks, and moorings.

(b) Structure stability and foundation issues are to be considered under both sea level rise and sea level fall scenarios. If sea levels rise, wave heights will increase and structures may be underdesigned for the increased loading. If sea levels fall, foundations of structures will be exposed to increased wave scour, which could result in instability. Other potential issues for structures if sea levels rise include (but are not limited to) the need for higher crest elevations, wider crest widths, and larger footprints. If increased overtopping over time is not acceptable, then increasing the crest elevation of a structure may be warranted. If a structure is designed to accommodate an adaptive management strategy, its crest width may need to be widened during initial construction to allow future modifications. Each of these adaptations would increase the project's footprint.

(c) The shape and length of navigation structures may also need to be adjusted because SLC may affect both flanking at the root and wave sheltering within the basin. In project areas exposed to significant sediment transport regimes, increases in sand transmission through structures will also need to be evaluated.

(7) Navigation channels are characterized by their depth, width, and length. SLC has the potential to modify the coastal processes affecting navigation channel stability, resulting in increased waves, currents, and shoaling.

(a) Navigation projects are sensitive to sea level fall, as authorized depths would be in jeopardy immediately following each dredging cycle. Decreasing navigation depths would also result in the need for "new work" dredging. This new work dredging could push the channel bottom into differing subsurface strata, requiring specialty dredging. This would involve lengthening the entrance channel out to the design depth contour. Channel width would not be affected in this case, but channel side slopes would cut farther and farther into the channel banks over the project's life cycle. Adequate clearance from adjacent Federal and non-Federal navigation features would have to be provided.

(b) If sea levels rise, channel depths will increase (assuming the absence of shoaling). For projects where shoaling is an ongoing and active process, maintenance dredging requirements would be partially offset by the rising sea level. The potential for new work dredging throughout a project's life will require that adequate geotechnical investigations be accomplished in support of plan formulation. As mentioned above, under a sea level rise scenario, the impacts on navigability caused by potential increases in wave energy need to be assessed.

(c) Another issue specific to sea level rise would be the decreasing clearance at fixed span bridges. Other impacts of SLC on navigation channels that will be more difficult to quantify include (but are not limited to) increased shoaling volumes, redistribution of shoaling locations, and changes to current velocity and direction. With respect to the operation of port facilities, SLR may alter the operational windows or limits for cargo handling, and the positions of ships relative to the fixed facilities may change. Other drivers warranting detailed consideration of SLC impacts include concerns for channel stability, alignment, and performance.

d. Human Response to SLC.

(1) For navigation projects, the human response relative to SLC will be a combination of the reactions of port and non-Federal sponsors to increased exposure as well as to any operational modifications required in response to changing conditions within the navigation project. Broad process categories in Table C-3 related to the human response with respect to navigation projects include wave attack; inundation; harbor, basin, and channel hydrodynamics; and management practices.

(2) The reactions of port and non-Federal sponsors to increased exposure of the non-Federal facilities will help in assessing and quantifying the extent to which benefits can be realized at the project, as well as in determining if additional modifications to the Federal project will be required. In some cases, improvements and modifications to the non-Federal structures

and system can reduce damages and impacts to project operation. In other cases, modifications to the Federal structures will be necessary, changes in operation will be required, or, in more extreme cases, abandonment of some facilities may be necessary. It will be important to assess the reasonable range of non-Federal sponsor and user responses to the changes in exposure and conditions at the project. Historical human and institutional responses at the project or in the region may provide some information on what can be expected in the future. Relevant existing regulations and laws that might limit future responses should be reviewed and evaluated. Any potential limitations to local stakeholder actions that could impact the assumed benefits or continued effective operation of the navigation project should be identified.

e. Project and System Response to SLC. Each navigation project feature (both Federal and non-Federal) should be methodically assessed to determine the stability and performance response to SLC. After each individual feature is assessed, the larger project operation and sustainability should be analyzed. All of the process categories noted in Table C-3 can be related back to the project and system response in some manner. Potential morphology and systems impacts of SLC will be challenging to identify and quantify, but an effort should be made to envision the threats and consequences of these concerns. The results from the overall assessment should include individual project feature modification recommendations, maintenance requirements, new feature recommendations, and any potential impacts to project and port operations that may influence damages, life safety, or benefits. The identification of important thresholds, in terms of both structure stability and project operation, is important to help determine key decision points in the project's life cycle. Some of the categories requiring assessments are summarized below.

(1) Increased Project Costs. Project costs have the potential to increase over the project life due to the impacts of SLC.

(a) Realistic costs for channel and structure construction, as well as operation and maintenance, must be captured in all project phases.

(b) Project cost could increase significantly due to SLC under all three decision-making strategies (anticipatory, adaptive, and reactive).

(c) Under an anticipatory strategy, additional costs attributable to SLC will be realized during initial construction. If SLC requirements to ensure channel and structure stability throughout the project life are deferred into the future (under an adaptive or reactive strategy), the resultant cost increases must be included in the initial feasibility analysis. Likewise, non-Federal costs for providing the necessary port infrastructure for the realization of the project benefits being claimed must be quantified. The additional costs for making ports and harbors "sea level proof" must also be included in the initial feasibility analysis.

(2) Navigation Project Outputs. Outputs from navigation projects include the transportation of goods and services, safe mooring, safe access to open water, adequate depths and basin dimensions, safe refuge from storms, and recreation opportunities. USACE places a high value on most of these outputs, with a low priority given to the recreational benefits. SLC poses significant risks to these outputs.

(a) Efficient, Effective and Safe Transportation of Commercial Goods and Services. Facilitation of the efficient transit of commercial goods and services is a primary navigation project. This resource adds value to local, state, and Federal interests. Any interruption would necessitate the use of more expensive modes of transport and ultimately an increase in the cost of commodities. Project features will have to keep the impacts of SLC in check throughout the project life. This is a high priority for USACE.

(b) Safe Mooring. Safe mooring of vessels is required to facilitate offloading of cargo, crew, and passengers. Safe mooring also implies keeping wave dissipation at berthing areas below required thresholds. Potential SLC creates the need to design navigation structures that will stay below these thresholds throughout the project life. This is a high priority for USACE.

(c) Safe Access to Open Water. Safe access to open water requires that entrance channel dimensions be provided as authorized and that wave attenuation be below threshold levels throughout the project life. Sea level proofing will be needed for associated general navigation features. This is a high priority for USACE.

(d) Adequate Navigation Depths and Basin Dimensions. Establishing and maintaining authorized depths and basin dimensions are examples of actions required if navigation projects are to accrue the benefits claimed. The impacts of SLC on these project features will depend on whether sea level is rising or falling at a project location. Therefore, impacts will have to be assessed on a project-by-project basis. This is a high priority for USACE.

(e) Harbor of Refuge. Many Federally authorized navigation projects not only provide the other resources mentioned, but they are also critical harbors of refuge for local and transient vessels. SLC will not have an impact on the need for such facilities, but it will be necessary to keep these facilities open and functioning over the project life. This is a high priority for USACE.

(f) Recreation. SLC impacts on recreational outputs will not determine the ultimate fate of general navigation features at Federally authorized ports and harbors. Recreation is a low-priority output of Federally authorized navigation projects.

(3) Systems Impacts. A navigation project is a system of many individual components. SLC has the potential to impact many components of the system, resulting in significant cumulative impacts. In the case of navigation projects, there is the potential for far-reaching system impacts that should be investigated in the context of SLC. Economic impacts could occur on local, state, regional, national, and international scales if port and harbor operations are constrained. Food security issues on local and regional scales would result if SLC caused a long-term interruption of services. Public safety and public health issues could also arise under certain SLC scenarios. If the larger system aspects are considered, decision makers should have adequate lead time to react to the potential system-wide threats posed by the process. Engineering and economic models can be utilized to estimate harbor and port operational and maintenance procedures over the project life cycle.

C-4. Approach to Analysis and Planning Process.

a. Strategic Decision Context for Navigation Projects. Prior to the vulnerability analysis, a general assessment of the strategic importance of the project should be conducted. The size and cost of the project, as well as the potential for significant modifications in the project area, should be determined. The size and operation of the project should provide a general picture of the possible economic magnitude of non-performance consequences. Other issues such as life safety potential and environmental concerns should be enumerated. Finally, the role of the project within the community and the region should be assessed to help determine to what extent non-performance of the port might impact the larger region. Additional elements of this first tier can be found in Figure 9 in the main text of this ETL.

b. Qualitative Assessment of Potential Sea Level Change Impacts on Resources within the Project Area. Tier 2 of Figure 9 outlines an approach to determining the project area's vulnerability and level of exposure. One of the first steps in this approach, subsequent to defining a first estimate of vertical and horizontal extent of potential SLC impacts, is to identify the project area resources that may be impacted. Table C-4 provides a qualitative matrix of critical resource considerations for navigation studies and projects. The density of the resource is quantified as either high, medium, low, or none present. Notes are provided for each resource to clarify the extent of the concern for each critical resource. The last column in the matrix is a qualitative assessment of the risk that SLC is expected to pose to the resource (utilizing the same classification scheme as for Density of Resource). As indicated in the table, the density of navigation structures is high, with an associated high potential of being impacted by SLC. The density of navigation channels is listed as high, but the risk posed from SLC will depend on whether the sea level rises or falls. A similar table should be displayed in all navigation project decision documents as a first look at the potential impacts from SLC. More detailed analyses and assessments of risk would be expected to be developed as the study progresses. Figure C-1 illustrates a typical project layout that might be used in conjunction with the qualitative matrix. This example also shows graduated levels of impact for different SLR values, as well as the locations of the resources that are likely to be impacted.

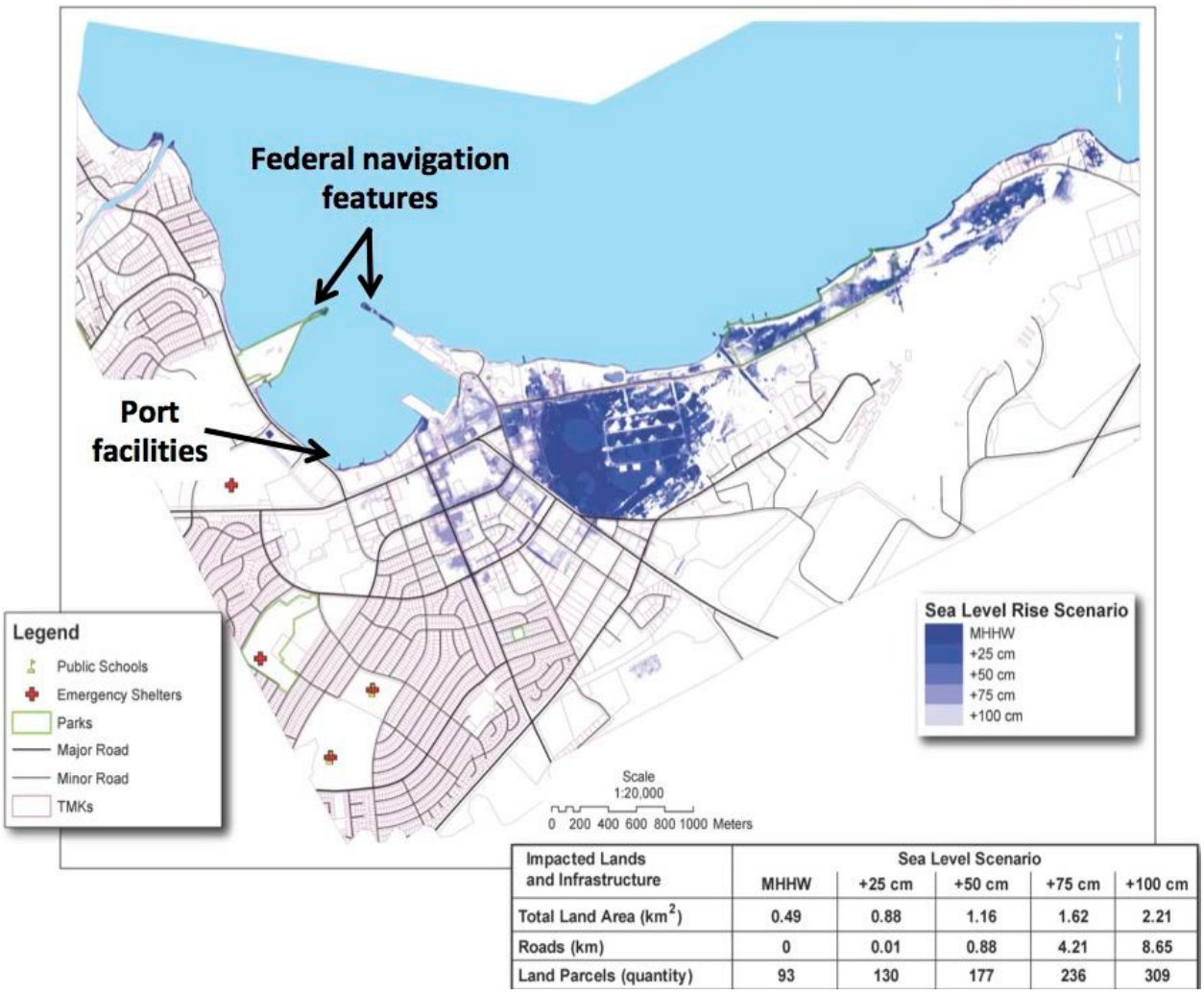
c. Stability and Performance Functions for Navigation Projects. Whether a new project is being designed or an existing project is being evaluated, a navigation project will need to be assessed for both stability and performance under the projected range of water levels in addition to the cumulative effects on other parameters that a change in water level would induce. The stability and performance of different navigation project features may vary by project, but all of the functions can be related to basic design relationships. Some examples are given below.

(1) Project Stability. These assessments should evaluate short- and long-term stability as well as maintenance requirements. Both will inform the timeline of necessary actions, the potential magnitude of impacts, and the life-cycle project costs. Below is a list of potential SLC-influenced loading scenarios that could affect project stability and required maintenance.

Table C-4. Qualitative matrix for navigation projects, showing critical resources, expected density of the resource, relevant notes, and the relative risk to the project posed by SLC.

Critical resources in study area	Density of resource*	Relevant notes	Risk from SLC*
Length and type of primary Federal navigation structures	3	The length and type of navigation structure will determine stability and maintenance impacts (age, last maintained).	3
Length and type of secondary Federal navigation structures (groins, spur jetties, dikes, etc.)	2	The length and type of navigation structure will determine stability and maintenance impacts (age, last maintained).	2
Length and type of Federal shoreline protection structures	1	The length and type of shoreline protection structure will determine stability and maintenance impacts (age, last maintained).	2
Channel length and authorized depth, mooring areas and basins	3	Sea level rise may impact this favorably; sea level fall may require adjustments to authorized lengths and depths. Harbor and entrance resonance and performance issues may arise (length, area).	1
Dredged material management sites	1	Sites may become more or less dispersive and/or have changes in capacity (number, area).	1
Port facilities (bulkheads, wharves, docks, piers, etc.)	3	Performance of existing Federal structures under modified ocean conditions will result in increased magnitude and frequency of impacts to associated project features (length, type, seasons of use).	3
Commercial infrastructure	3	Performance of existing Federal structures under modified ocean conditions will result in increased magnitude and frequency of impacts to associated project features (type, value).	2
Transportation infrastructure (roads, rail, etc.)	2	Impacts to transportation infrastructure can impact benefits realized (length, type).	2
Utilities, drainage systems, communication	2	Connectivity and support systems may be affected resulting in decreased project benefits (length, type).	2
Coast Guard presence	2	Potential operational impacts. Harbor of refuge?	2
Environmental and habitat areas	1	Assessment of any environmental systems in project area (type, sensitivity).	1

*3 = high, 2 = medium, 1 = low, X = none present.



Impacted Lands and Infrastructure	Sea Level Scenario				
	MHHW	+25 cm	+50 cm	+75 cm	+100 cm
Total Land Area (km^2)	0.49	0.88	1.16	1.62	2.21
Roads (km)	0	0.01	0.88	4.21	8.65
Land Parcels (quantity)	93	130	177	236	309

Figure C-1. Example layout of a navigation project with impacted features and areas noted. (From Cooper et al. 2012.)

(a) Extreme loading on cross section components. The impacts and mode of failure resulting from extreme loading on the structure cross section will vary depending on the structure type (i.e., flexible or rigid, rock or concrete). Various elements of the cross section design can be affected, including armor unit size, crest elevation, crest width, side slopes, and toe protection. Maintenance and adaptation options will vary with the degree of sensitivity.

(b) Extreme focused loading areas in project layout, shore tie-in connections, or structure head features (wave height, water level, wave runup and overtopping). Increased water levels and greater wave heights can modify both the zone of impact and the degree of impact on critical areas of a project. Instability in these areas can result in greater project instability and deterioration, which can result in both additional maintenance requirements and impacts on project performance.

(c) Extreme loading on adjacent interior shoreline, harbor, and port facility structures (structure damage, flooding, inundation, undermining, and erosion). Since the purpose of the project is to provide access and support for port operations, impacts to interior structure stability and/or operations due to lack of access from inundation or erosion can result in expensive or unacceptable operational disruptions.

(d) Extreme and annual loading relevant to sediment transport processes that can impact adjacent shoreline, estuarine areas, morphology change, backshore stability, and structure foundation. The navigation project performance relies on the stability of the structures and the accessibility of the navigation channels and port areas. Changes in sediment transport processes have the potential to modify bathymetry such that structures can be directly undermined or damaged. Also, incident wave height can be modified, resulting in increased loading of the structures. Adjacent shoreline and backshore stability may also play a role in overall project stability.

(2) Project Performance. Some of the project performance categories will be covered under the project stability section (i.e., damages due to transmitted waves, etc.). Other performance categories that need to be assessed will be directly related to how the project performs its navigation function. This can involve channel and harbor conditions, routine maintenance activities, and windows of time available for operation.

(a) Average and extreme wave and current conditions that can affect windows and conditions of operation (entrance and access channels). Changes in water level magnitude (with resultant increases in wave heights and currents), in addition to a potential for increased frequency of energetic conditions, may result in necessary changes to channel navigability as well as operational windows within the port facility.

(b) Duration of time for a given water level elevation relevant to bridge clearance, channel depth/access limitations, and port offloading operations. There may be some vertical controls within a navigation project or port that will modify the allowable operation of the project. Bridge clearance may be a concern with respect to sea level rise. Authorized channel depth may be a concern with respect to sea level fall. Port offloading operations may rely on land-based infrastructure and equipment for which a change in water level will impact efficiency.

(c) Wave transmission due to increased depth-limited waves, increased frequency of defined events, overtopping of structures, and transmission through entrance channel. With an increase in water level, wave transmission to interior port areas may increase (in both magnitude and frequency) due to a variety of processes: structure permeability, structure overtopping, diffraction around structures, and transmission through channels.

(d) Changes in harbor processes that could impact port operations (resonance, wave reflection, currents, current velocities, water level frequency and duration curves, etc.). In some cases, SLC-driven changes in water depth will have follow-on effects that can disrupt harbor or port operations. Harbor resonance is typically evaluated as a function of basin dimensions and basin depth and has the potential to migrate into an unacceptable condition with SLC. Interior currents may also be impacted but most likely to a lesser degree.

(e) Average sediment transport processes that can impact the volume and frequency of dredging. Changes in channel and harbor maintenance dredging may result from altered hydrodynamics.

(f) Environmental impacts (salinity, habitat change, inundation zones, tidal prism changes). An examination of the larger project area may identify specific environmental impacts that result from SLC at the project, most likely driven by tidal prism changes and changes in inundation zones. In some cases, migration of the habitat type is feasible. In others, there may be irretrievable changes. See Appendix F for more information on SLC impacts to ecosystems.

d. Other Design and Maintenance Considerations. The following are general considerations for the development of navigation structures during the initial planning phase. SLC scenarios could potentially influence the ultimate type, shape, and configuration of coastal navigation structures to ensure effective and efficient project performance.

(1) Type. If significant design and performance changes are expected due to SLC, more thought may need to be given to the type of structure recommended and whether it is designed to be adaptable over the long term or whether it is capable of performing adequately under predicted SLC scenarios.

(2) Adaptability. Some structure types are more adaptable than others. In areas where SLC is expected to be relevant or significant over the long term, more consideration to an adaptable structure may be appropriate. For example, overlays cannot be placed on top of many types of concrete armor units (such as tri-bars and Core-Locs) to increase crest height or repair side slopes. However, additional stone can be placed on top of rubblemound structures as an adaptive measure in response to sea level rise.

(3) Shape. SLC will not have a significant influence on the shape of a navigation structure other than the possible need to extend tie-backs under a scenario in which the sea level rises.

(4) Location. The locations of navigation structures may need to be modified based on the functions they provide. Structure location may need to be re-evaluated under SLC scenarios in which water depths will increase over the life of the project. This appears to be one characteristic that may not be very adaptable to SLC over the project life cycle.

(5) Length. Jetty and breakwater lengths are based on the extent of protected areas needed to define a project. Lengths may be modified in response to changes in water depth under various SLC scenarios. Jetty length can be easily adapted; however, structure modifications can be prohibitively costly. A series of breakwaters may function differently as lengths and gap widths are modified. It will be important to quantify the increased cost of incorporating additional structure length upfront versus deferring action to the O&M phase of a project.

(6) Crest Elevation. The crest elevation of a structure is a function of the design still water level as well as the design wave height. The crest elevation of a rubblemound structure can be raised, but sufficient crest width must be available to ensure that future maintenance activities are not precluded by the original design. It is important to remember that overlays on top of some types of concrete armor units are not recommended. If raising the crest elevation of a

structure is deferred to the O&M phase, a suitable armor layer type must be chosen for initial construction. A vertical-faced navigation structure's crest height may be more difficult to modify than that of a sloped structure.

(7) Transmissibility. Since core material is typically impermeable, its elevation regulates the amount of sediment that can transfer through a navigation structure. Under sea level rise, increased sediment transmissibility may negatively impact operations of a navigation project over the project's life cycle. Therefore, the core elevation may need to be increased at the time of construction to address transmissibility issues in the case of sea level rise in a sediment-rich environment.

(8) Foundation requirements. A navigation structure's foundation will experience varied amounts of wave energy over the project's life cycle for every SLC scenario. In the case of sea level rise, wave energy incident to the foundation will decrease with increased depth. The opposite will be the case under sea level fall; as sea level decreases, plunging breakers may began to impinge on the toe of a structure, with wave impacts and turbulence undoubtedly increasing over time. It will be important to address such anticipated changing forces during the planning phase.

(9) Design Wave Considerations. Design wave characteristics, including height, period, and frequency of occurrence, will vary depending on which SLC scenario is under consideration. Model studies addressing structure stability, project function, and/or hydrodynamic circulation under various SLC scenarios would be helpful in addressing potential concerns.

(10) Economic Considerations. The impacts of SLC on project costs are to be quantified in the planning phase for inclusion into plan formulation. If an anticipatory implementation strategy is considered, the cost to address SLC will be included in initial construction. If deferred until later in the project's life cycle, these costs must be accounted for as O&M requirements. In any case, realistic projections of potential SLC cost impacts must be included in the planning processes to ensure that projects are economically justified and able to provide the benefits claimed. SLC impacts may necessitate modifications or additions to coastal navigation structures and may increase the volume and frequency of dredging and/or mitigation for impacts to adjacent shorelines. Increased associated costs may include initial construction, future structural or operational adaptations, addition of secondary structures, maintenance dredging, vessel and infrastructure damages, and shoreline and backshore damages. It is essential to determine if SLC impacts are to be addressed during initial construction or deferred until later in the project's life cycle.

(11) Environmental Considerations. Environmental impacts could include factors such as salinity changes, habitat changes, increased flooding, riverine changes, and gravity flow drainage changes. Impacts on mitigation costs due to changes to the project's footprint must be quantified.

(12) Site Considerations. General site characteristics to be considered under various SLC scenarios include the extent of available fast land adjacent to the project, the local and regional coastal processes, the local and regional sediment budgets, and the overall geomorphologic

setting of alternative sites. For new projects, it may be necessary to obtain additional easements for future needs.

(13) Topographic Considerations. Plan formulation must include enough of the upland to accommodate anticipated SLC. Topography may be expected to change in response to SLC, particularly for barrier islands and the foredune configuration, as well as potential focus areas in the vicinity of structures. Bathymetry, in terms of actual depth, could also become either deeper or shallower, depending on whether the relative change is positive or negative. A project's long-term stability, considering expected changes in topography and bathymetry in response to SLC, must be incorporated into the selected plan. In the case of sea level rise, the project site must be able to accommodate the potential landward migration of navigation structure footprints. As sea level rises, structure tie-backs may need to be extended landward to resist flanking.

(14) Local and Regional Considerations. Local processes, particularly riverine and estuarine, may be expected to change, including coastal processes, riverine processes, salinity, hydrodynamics, flooding, groundwater flow, and others. The impact of these changes may or may not have direct implications for navigation structures. There is a chance that these types of site considerations can be discounted early in the planning process, thereby simplifying the requisite analysis. Impacts on upland drainage under a sea level rise scenario could have major implications for project site selection and associated non-Federal project feature development. Similarly, if adjacent beaches are vulnerable to breaching, a new inlet could capture tidal prism from a navigation project, impacting hydrodynamics.

(15) Geologic Considerations. Geology is an important parameter in identifying a suitable site for a navigation project, but it is not a stand-alone consideration in the context of SLC. If a site is an acceptable location in a geologic sense, the fact that the sea level may rise or fall over the life of a proposed navigation project may not preclude its suitability.

e. Tipping Points and Thresholds. Tipping points and thresholds within the project area will inform the study team on the best strategy to apply to the project as well as the best timing of that strategy. As discussed in the main text, an anticipatory, adaptive, or reactive strategy can be employed. For example, recommended future adaptations to address either stability or performance issues could include modifications to the cross section and length of structures (and channels) or the addition of secondary structures. Under the appropriate strategy, the performance modes of the project features can be inventoried.

(1) Important Factors. Variables impacted by climate change and SLC in terms of project feature stability and performance are to be identified. The tipping points where the alternative or project feature no longer provides the desired level of protection should be identified. These tipping points will occur at different times along the SLC scenario curves. Figure C-2 shows an adaptive strategy for addressing SLR where the tipping point for a navigation structure's stability is correlated to an "unacceptable wave height." Working backwards from the "action point" at which time a structural modification would be required, there must be enough lead time for planning, funding, and constructing the modification. Prior to the start of "lead time," in-progress review of wave data and periodic inspection of the structure will be required to verify the threat and schedule accordingly. Prudent timing of actions will prevent the loss of structure functionality, unwanted consequences, and the loss of associated project benefits.

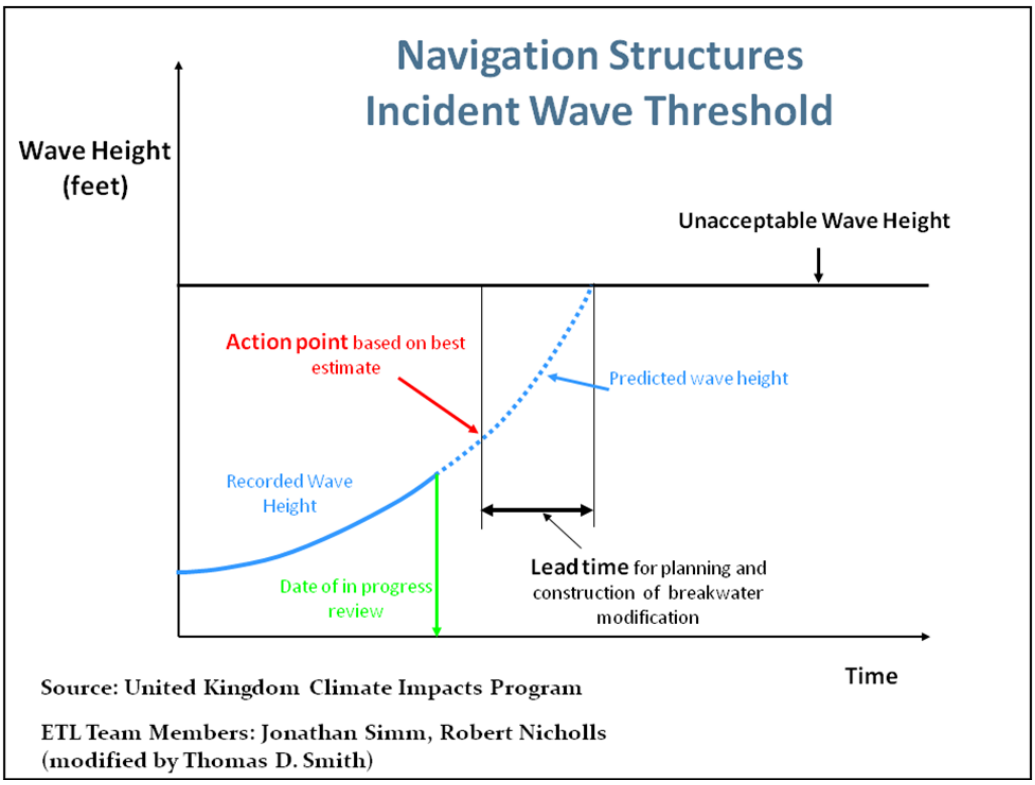


Figure C-2. Activities required under an adaptive strategy to prevent reaching a tipping point at which wave height becomes unacceptable.

(2) Temporal Changes. SLC will induce tipping points for various processes at different times within the project's life cycle. If wave heights increase due to sea level rise over time, then there may be a corresponding increase in overtopping at navigation structures. This approach can also be used when evaluating a project performance category. With respect to operations at port and harbor facilities, the impacts of SLC may increase in intensity and frequency over time. Take, for example, the navigation structure overtopping threshold shown in Figure C-3 at which point operations within the facility would be negatively impacted. As the sea level rises, this threshold would be exceeded at an ever-increasing frequency, and its magnitude would also continue to increase over time. Left unresolved, these impacts would result in the loss of operational time at the facility and associated unrealized project benefits. The value at which overtopping would become unacceptable could be identified initially based on engineering judgment. Monitoring and verification of wave height and overtopping would enable "real-time" assessment of the mounting threat.

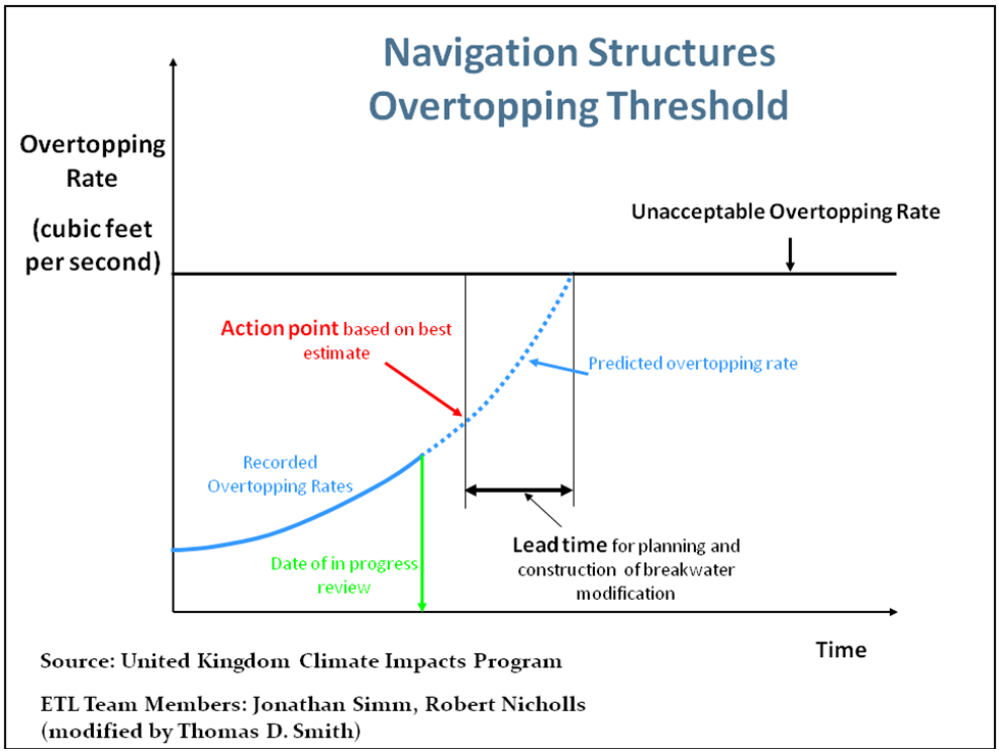


Figure C-3. Tipping point diagram for navigation structure overtopping threshold under a sea level rise scenario.

(3) Example. To illustrate potential impacts of SLC, the increase in intensity and frequency of return period storm tides at the U.S. Naval Academy Engineering Building (Kriebel 2012) is shown in Figure C-4, which displays 80 years of maximum water elevations projected out an additional 80 years from the present for a specific SLR scenario for storm tides with different return periods (1 month through 50 years). As shown in the figure, the frequency at which the building is flooded and the intensity of flooding increase over time. The figure also shows how the building was flooded once every 10 years 75 years ago and will be flooded 12 times per year 75 years in the future. This exemplifies one of the many dramatic consequences that will have to be dealt with to keep up with SLC.

(4) Depth. Channel depth may reach a tipping point under a sea level fall (SLF) scenario. A similar adaptive strategy may be effective, as in the wave height and overtopping example above. Figure C-5 shows how depth may decrease to the point where a channel no longer provides the authorized depth. Monitoring will be the key to verifying that the threat is real and identifying the appropriate lead time to ensure that new work dredging can be accomplished prior to a reduction in service. Adequate geotechnical investigations will be required to quantify the consequences of having to conduct new work dredging to maintain the authorized depth. Under an SLF scenario, it may be necessary to provide “over depth dredging” to ensure that the channel is not above the project depth soon after construction.

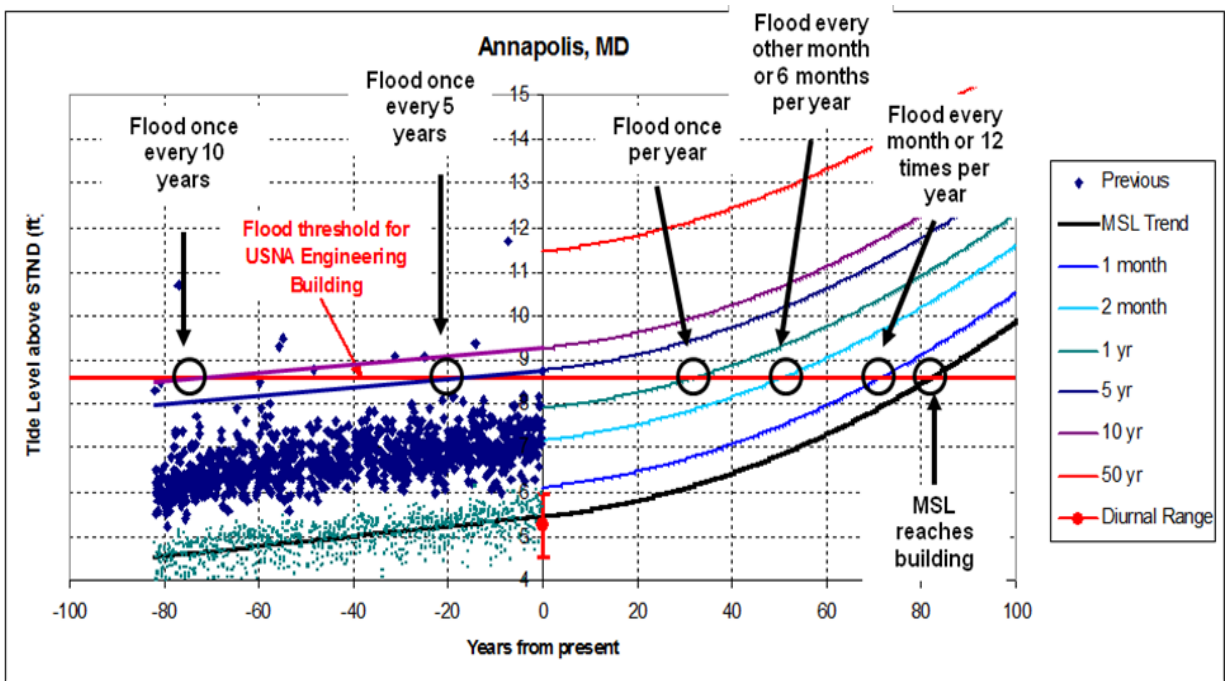


Figure C-4. Interpretation of projected SLR results and average frequency of flooding at the U.S. Naval Academy Engineering Building. (From Kriebel 2012.)

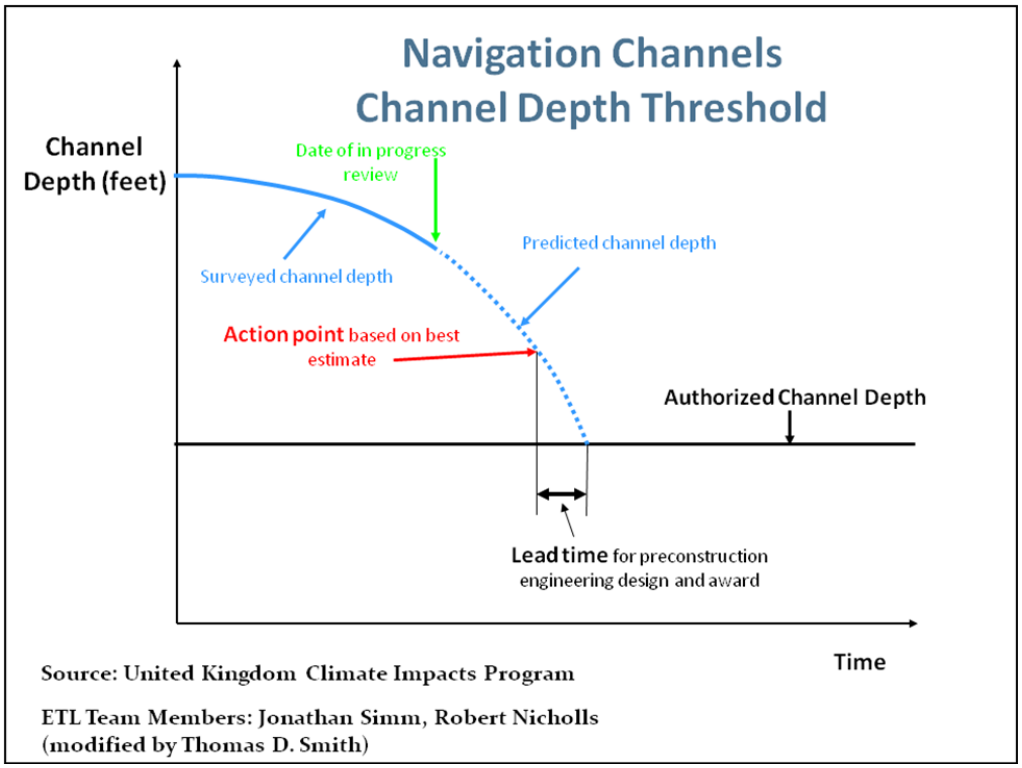


Figure C-5. Tipping point diagram for authorized channel depth under a sea level fall scenario.

(5) Breakwaters.

(a) Esteban et al. (2011) investigated the potential SLC impacts on rubblemound structures. The information provided in this section illustrates the types of structural stability issues that may impact resilient structure design as well as potential maintenance impacts in the future. Figure C-6 shows the average increase in breakwater cross section for the various sea level rise scenarios shown as evaluated by Esteban et al. (2011). The scenarios used in this evaluation (0.15–1.35 m) do not necessarily correspond to those recommended in this ETL, but the comparative differences are informative. To produce this figure, the results at various depths for the different significant wave heights (H_s) and peak wave periods (T_p) were averaged. The results appear counterintuitive, as there are significant differences in the required armor stone necessary for different rates of sea level rise. Figure C-7 shows the required weight of armor stone for Scenario 2, compared with a control scenario where there is no SLR. The figure indicates the effects that sea level has on different values of water depth (h) for a slope (theta) of 1:40 and an H_s of 9.0 m, showing how (especially for the lower values of h) the requirements in armor stone will increase substantially as H_b increases and hence higher waves will reach the structure. The effect is far more severe for Scenario 4, as shown in Figure C-8. Coastal structure foundations may also be impacted by increased wave energy over time in a sea level fall (SLF) scenario. Structure toe and foundation issues could ultimately result in slope failure and significant structural damage.

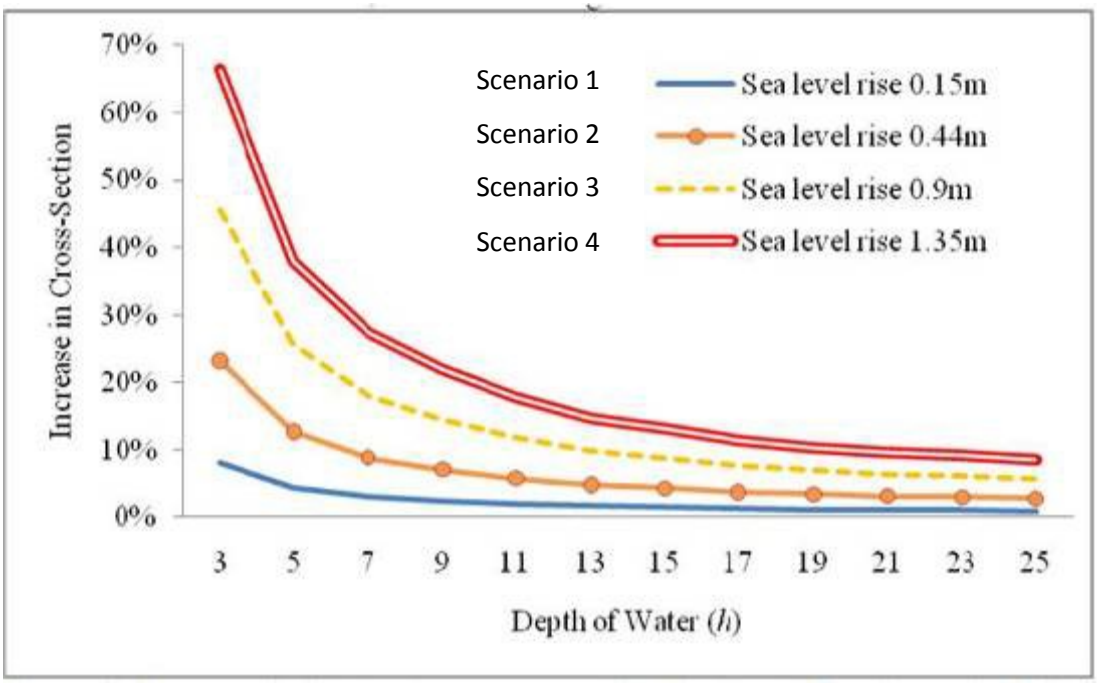


Figure C-6. Increase in breakwater cross section for various sea level rise scenarios. The percent increase in cross section is greater for shallower water depths because the ratio of potential sea level rise to total design water depth is greater along the left side of the figure. (From Esteban et al. 2011.)

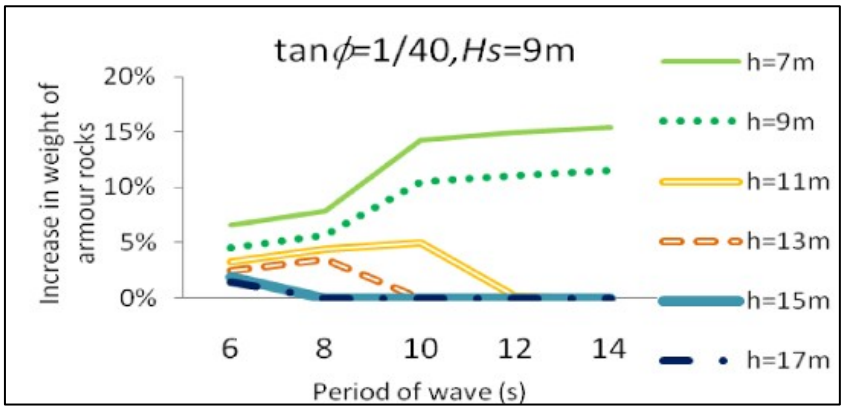


Figure C-7. Increase in the required weight of armor stone for Scenario 2, compared with no SLR. (From Esteban et al. 2011.)

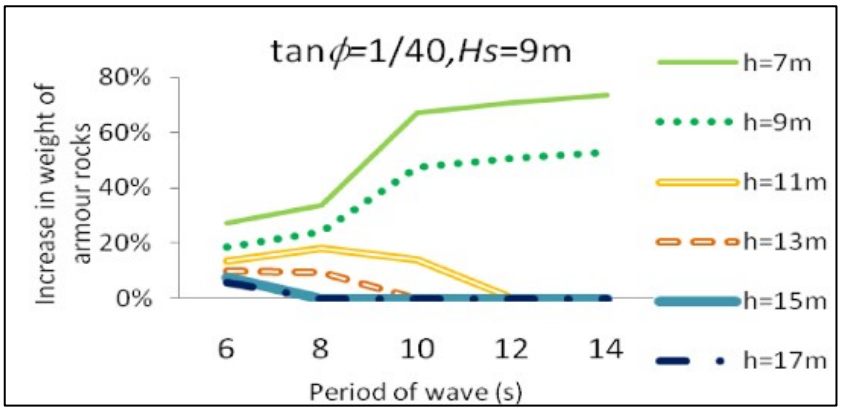


Figure C-8. Increase in the required weight of armor stone for Scenario 4, compared with no SLR. (From Esteban et al. 2011.)

(b) The effect of an increase in required armor stone weight is greater for the case of the sections with lower h, as an increase in sea level will also increase H_b. On the other hand, for the deeper sections, H_b is less likely to be affected, and hence the armor stone requirements will not change substantially or at all, as shown in Figures C-7 and C-8. Thus, for the deeper sections, the most important effect is the increase in h, which will require the breakwater crest to increase in elevation to minimize overtopping. Nevertheless, averaging the results for various ranges of T_p and H_s to make Figure C-6 will obviously result in the loss of some degree in accuracy, as can be seen from Figure C-9 and Figure C-10. The values shown in both of these figures are averaged values of the increase in armor stone and cross-sectional area required for a variety of H_s and h, though in this case each point shown is the average of the five computed values of T_p for each H_s. Figure C-9 thus shows how, for the case of the deeper structures, averaging all the values of H_s does not induce a significant deviation in the production of Figure C-10, though this deviation from the average will increase for the shallower sections. For the case of the armor stone, the deviation is more significant, though in this case it should also be understood that most of the likely increase in cost will come from increasing the height of the breakwater as a consequence of greater overtopping and not because of the need for larger armor stone. In fact,

most of the increase in breakwater cost comes from the enlargement of the cross-sectional area of the core and underlayers of the breakwater that results from increasing the height of the structure. This typically represents between 22% and 34% of the area of any one section, as shown in Figure C-10.

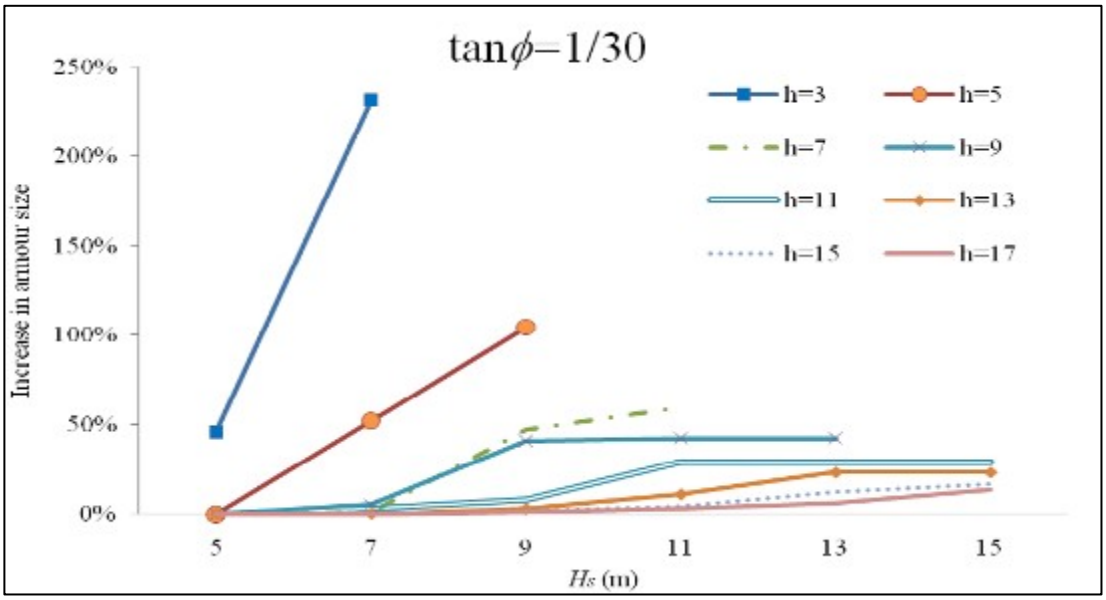


Figure C-9. Increase in armor stone size for Scenario 4 for a variety of H_s values. (From Esteban et al. 2011.)

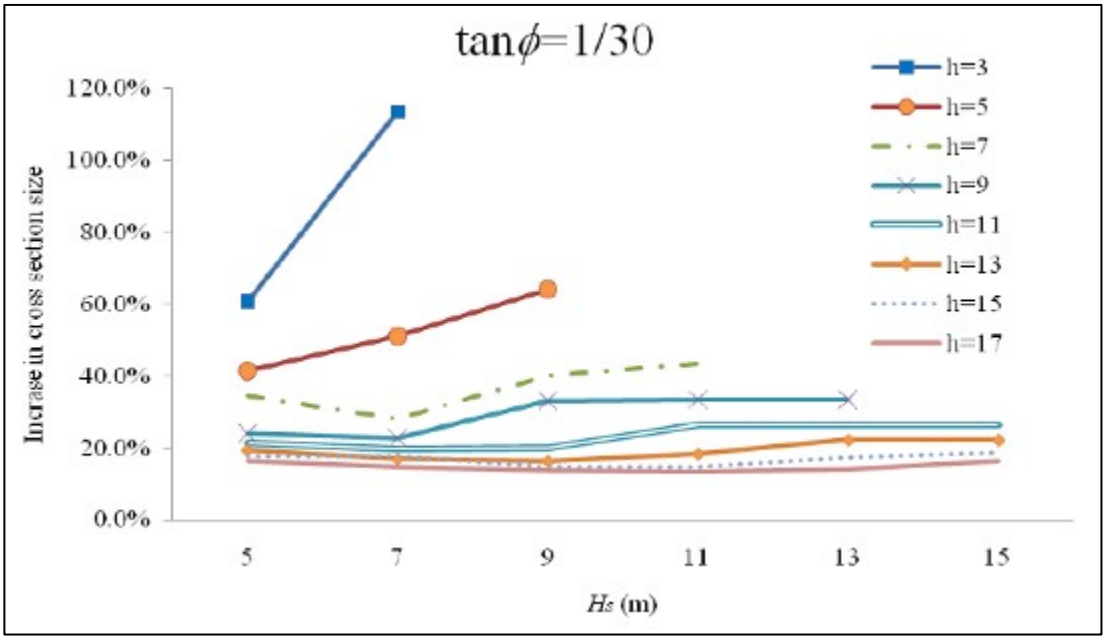


Figure C-10. Increase in cross section of structure for Scenario 4 for a variety of H_s values. (From Esteban et al. 2011.)

(6) Life-Cycle Changes. In some cases, project features may change over the life cycle. For example, a channel that is authorized for "best water" [e.g., does not have a defined footprint; under this designation, the U.S. Coast Guard (or similar agency) moves the channel markers as necessary to identify the navigation fairway where the deepest water exists] may require maintenance dredging to keep pace with shoaling induced by SLC. Figure C-11 illustrates a case where channel markers are periodically relocated during the project life cycle to align with "best water." The threshold where marker relocation will no longer ensure safe navigation due to shoaling must be identified early. This will provide enough lead time to dredge the channel prior to the onset of negative impacts from SLC. As shown in the figure, maintenance dredging is to be required with a sea level rise of 2.0ft (0.6m). This would occur at year 50 for the high curve and year 100 for the intermediate curve.

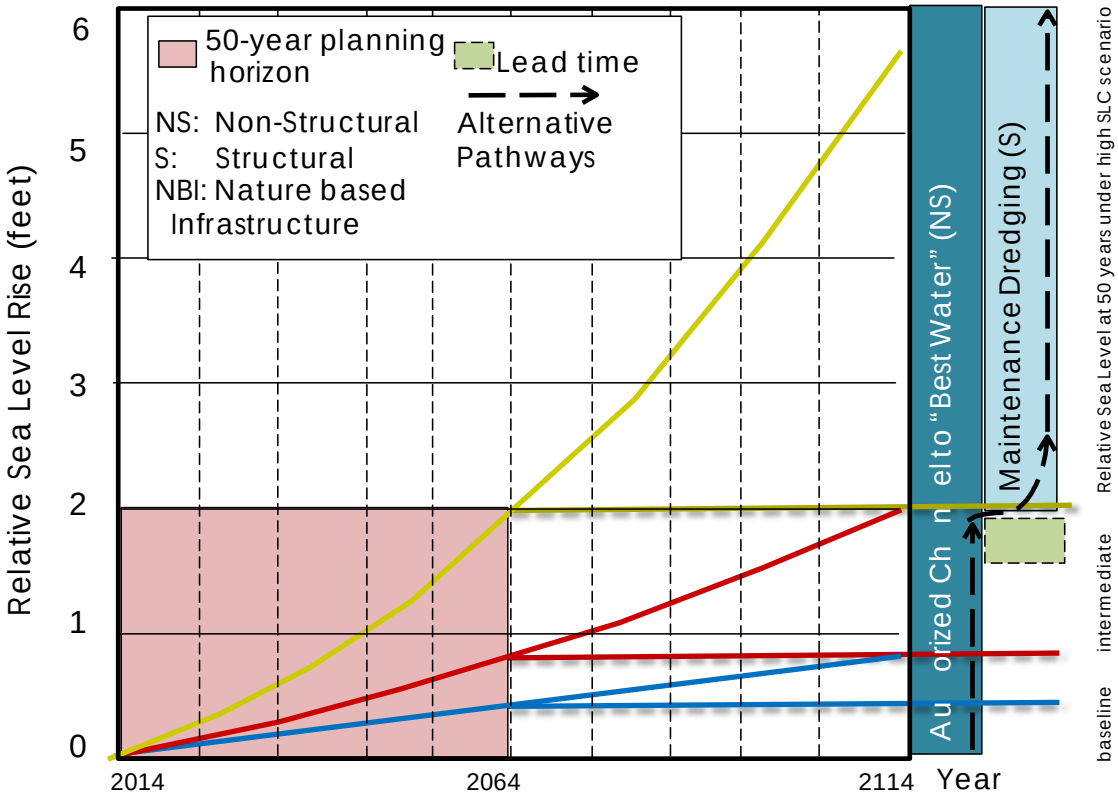


Figure C-11. Transition of a project feature over the life cycle from "best water" to maintenance dredging for the three USACE SLC planning curves (blue is low, red is intermediate, and yellow is high-rate curve).

f. Level of Analysis (Methods, Tools, and Models). Methods, tools, and models are currently available to quantify SLC impacts on USACE's navigation mission at all project phases. Modeling levels of complexity can be categorized as low, medium, and high. Low-complexity models are those that can be applied with generic inputs to characterize the project area; medium-level models may require the acquisition of site-specific data, while high-complexity models are those that require detailed site data, setup, and a high-speed computer

infrastructure. Key questions to be answered concerning the appropriate level of modeling required for a particular study or project to address SLC include but are not limited to the following:

- What level of complexity is required to quantify the impacts of SLC on a specific study or project?
- What authority is the project being investigated under? C.A.P. Section 107 and General Investigation (GI) navigation studies will require different levels of modeling in accordance with guidance and project implementation costs. Section 107 navigation studies may be able to be accomplished using analytical tools and models. GI navigation studies may require models with more powerful functionality and stability characteristics.
- What data sets are required to run the models, and are the data currently available? It will be important to inventory data requirements and gaps to capture the total cost of each modeling effort.
- What is the accuracy and uncertainty of each method?
- What computer resources are required to run each model?
- What study phases does the method or model support?
- Is the method or model common practice or still under development?
- Are there other issues besides navigation concerns that need to be addressed?

  – Environmental issues (salinity, water quality) may require models such as SMS, CH3D, ADH, PTM, or CE-QUAL.
  – Adjacent beach integrity and adjacent beach nourishment could be investigated with GENESIS, GENCADE, BEACH-FX, or SBEACH.
  – Groundwater issues with salinity contaminants might need to be modeled with SMS, GMS, GSSHA, or WASH123D.

Figure C-12 summarizes the different levels of analysis that may be considered depending on the project type and degree of sensitivity to SLC.

(1) The Coastal Engineering Design and Analysis System (CEDAS) suite of tools and models is particularly well suited for rapid analysis of potential impacts. CEDAS can be used to determine waves at structures, overtopping rate, transmission through structures, and navigation constraints by vessel type. It is also an appropriate screening-level tool to determine whether or not more detailed assessment is required.

(2) If medium-level models are required to investigate processes such as wave–structure interactions, the phase-averaging models contained in the Coastal Modeling System (CMS-Wave and CMS-Flow) can provide rigorous assessments. Phase-resolving models such as Bouss2D and Bouss3D are able to resolve wave-by-wave transformation of energy through, around, and over coastal structures. ADCIRC and STWAVE can be coupled to model wave- and tide-induced water circulation and sediment transport. Other helpful medium-level models include the Particle Tracking Module, the FATE models (short and long term), and CH3D.

(3) Highly complex models required for evaluating certain three-dimensional and environmental processes (salinity, turbidity, water quality, etc.) include ADH and CE-QUAL. CADET, ANKUDINOV, and SQUAT can be used to evaluate ship motions and vessel response.

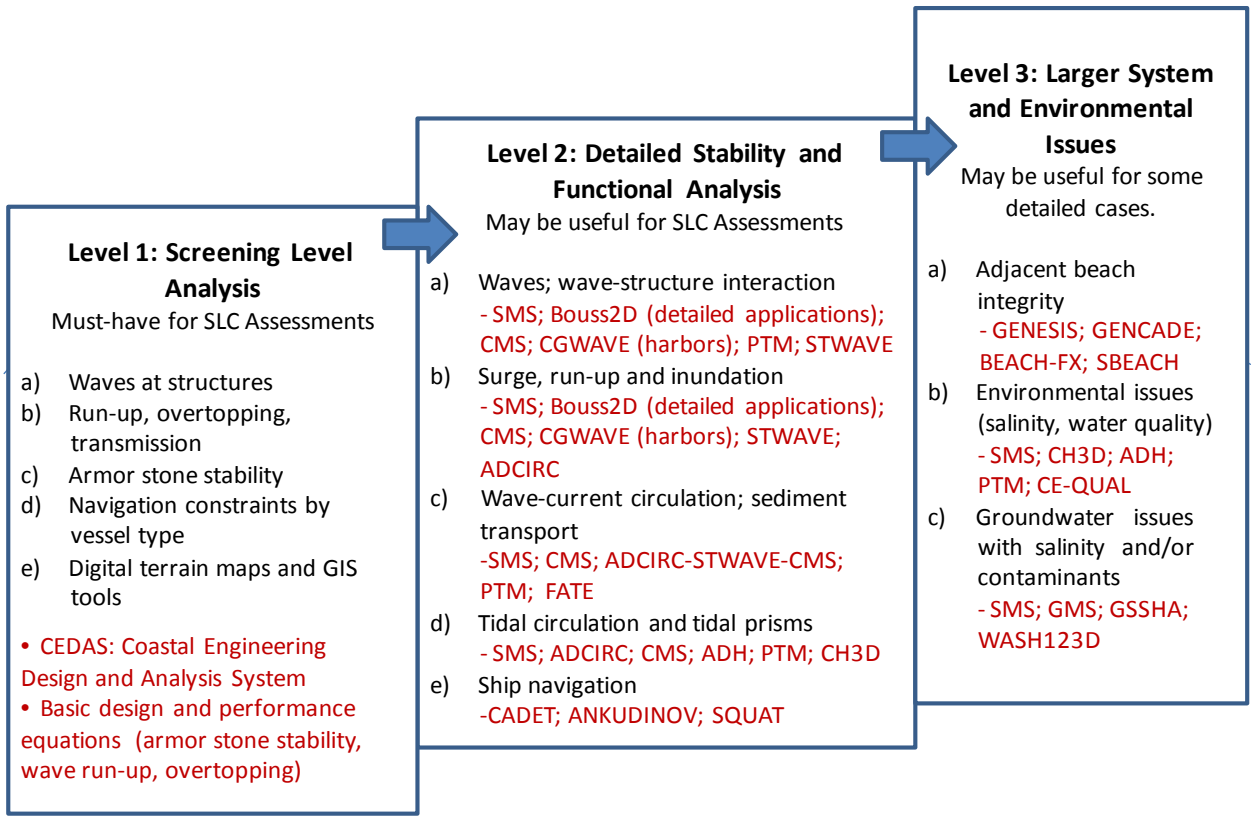


Figure C-12. Graduated levels of USACE analysis tools and modeling techniques.

g. Potential Adaptation Approaches for Navigation Projects. Figure 5 of this ETL displays adaptation options by mission area and stage of development in the project area. Navigation projects are typically located in already developed areas. Their mission requires that they be located in close proximity to the water. For that reason, retreat is not typically an option for this type of project. Adaptation options for navigation projects will typically be some combination of the accommodate or protect options. For these types of projects, it will be important to be able to quantify the expected costs and impacts in terms of both maintenance and reduced project performance if actions are not taken to address SLC. Quantifying impacts to non-Federal portions of the navigation project will help to define impacts to assumed benefits for the project. Table 1 of the main text provides a summary of some of the potential adaptation options by project type and mission area. Note that an alternative plan may consist of a combination of adaptation approaches that crosses boundaries from protect to accommodate to retreat.

C-5. Example Application.

a. To illustrate how the impacts of potential SLC are to be investigated under the USACE navigation mission, the following example describes the design of a jetty at Barber Point Harbor on the island of Oahu, Hawaii. The 375-foot-long jetty was designed to reduce cross currents in the entrance channel, and it incorporated consideration of two distinct structure reaches (trunk and root) and an armor layer comprising either rock or concrete armor units.

b. Figures C-13 and C-14 show plan and cross-section views of the proposed jetty (as designed without consideration for SLC), respectively. Armor stone weight was based on the Hudson equation:

$$W = \frac{w_r H^3}{K_d (S_r - 1)^3 \cot \theta}$$

where W = design weight of armor (lb)
w_r = unit weight of armor unit (pcf)
S_r = specific gravity of armor unit
H = design wave height
K_d = stability coefficient
$\cot \Theta$ = cotangent of structure slope.

Note that the wave height (H) is taken to the third power. This implies that potential SLC-induced chance to the design wave height may be significant where waves are depth limited. The other terms in the equation, such as unit weight, specific gravity, and the stability coefficient of the armor unit, are not sensitive to potential SLC.

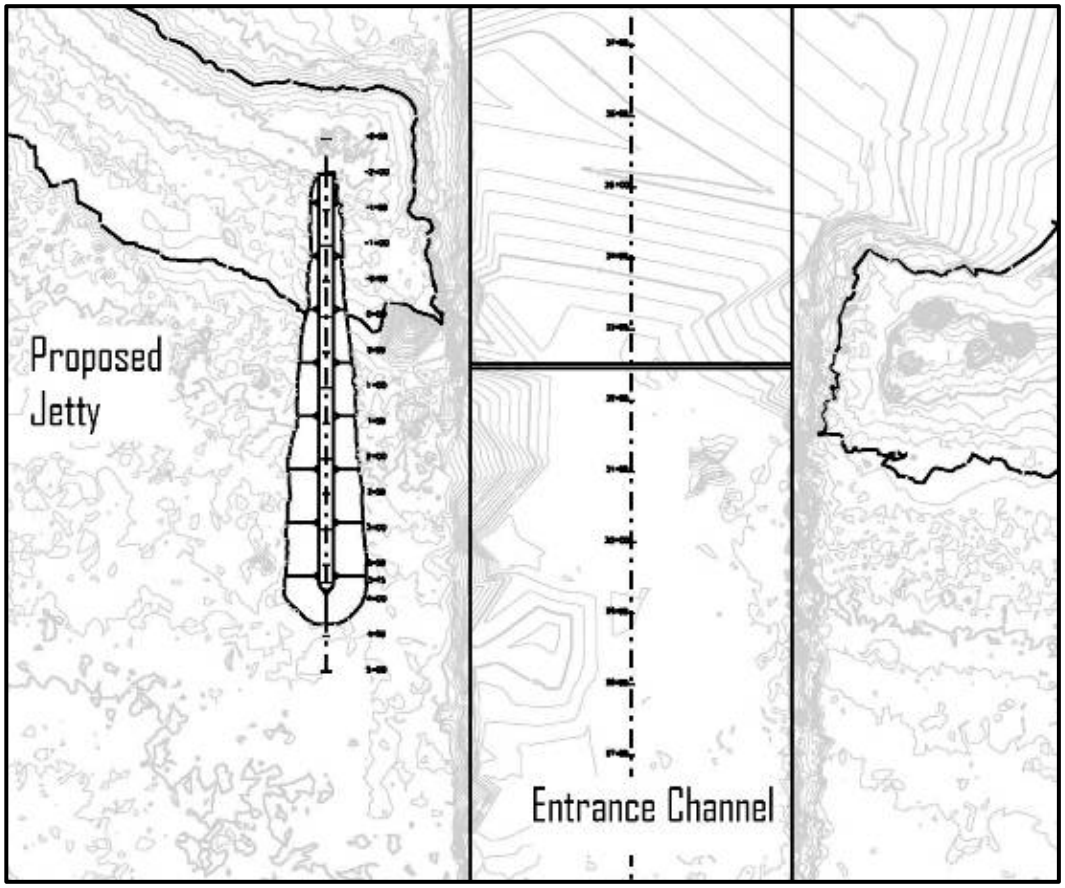


Figure C-13. Proposed jetty alignment relative to the Barber Point Harbor entrance channel. (From USACE 2012.)

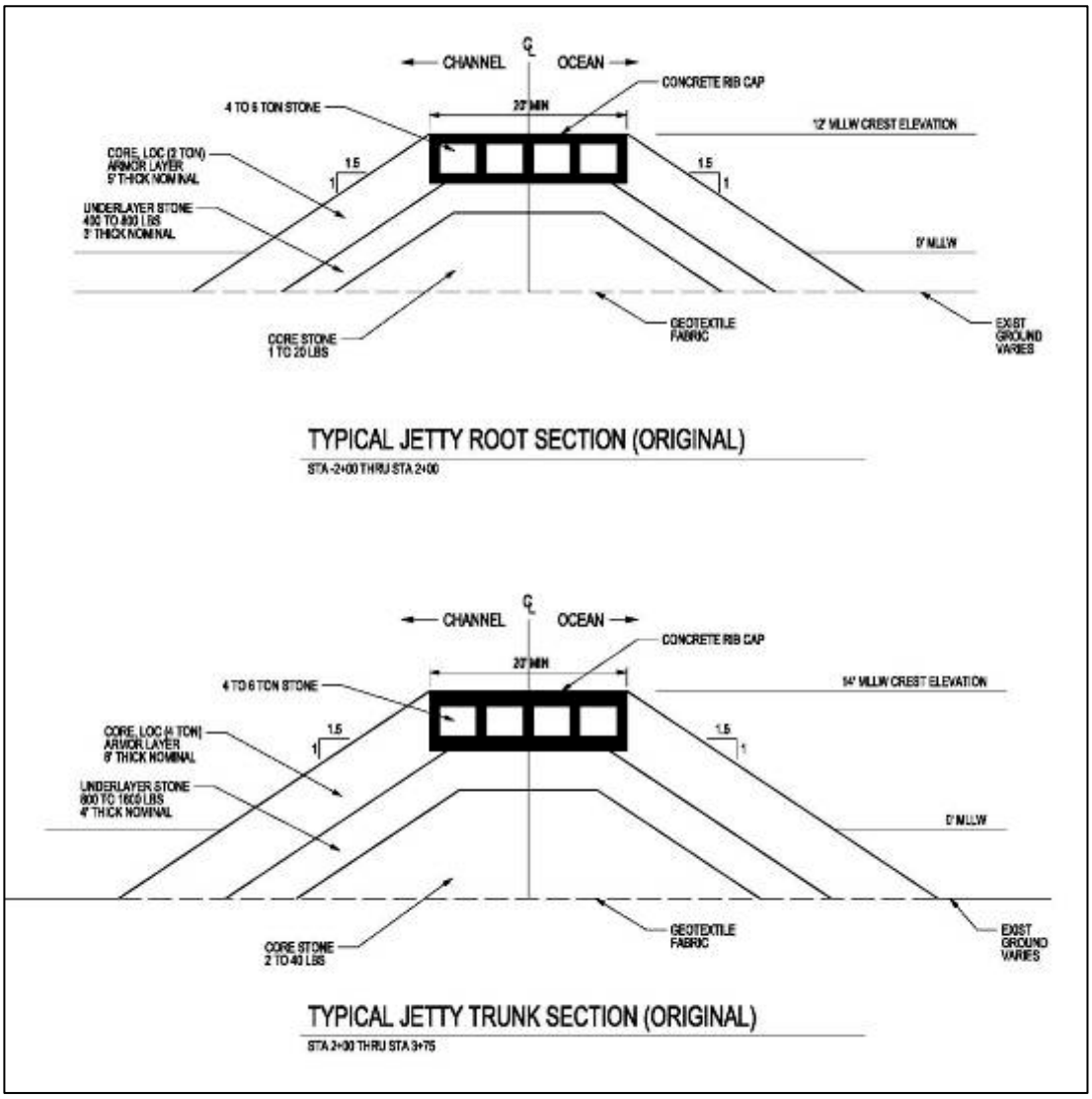


Figure C-14. Typical sections for the original jetty design (without consideration of SLC). (From USACE 2012.)

c. For depth-limited breaking wave conditions, the design wave height H_b will be a function of the design water depth as determined by the following equation:

$$H_b = d_b \times 0.6 \text{ (for reef environments)}$$

where d_b is the design water depth, which consists of depth of water (to the referenced elevation) plus the contributions of depth above the still water level (swl) from tide stage, storm surge, barometric effects, and wave setup (d_{swl}). Table C-5 lists the key variables needed to determine stable armor weight and the associated data required to identify the design wave height and ultimately compute armor stone weight with the Hudson equation. For example, storm surge and wave setup must be quantified to determine the depth of water above the still water level, a storm

frequency analysis is needed to determine water levels for various return periods, and the corresponding total water depths are needed to determine the design water height. The structure side slope and armor stability coefficient are to be identified as part of the design analysis and will most likely not be subject to modification under various SLC scenarios. Table C-5 ranks these variables as low, medium, or high based on their sensitivity to SLC. Variables ranked as highly sensitive to SLC include water depth at structure, design water depth, depth-limited wave height, and design wave height. SLC will have a low to medium effect on the other key variables necessary to identify an armor weight that will be stable throughout the project life cycle.

Table C-5. Key variables needed to determine armor weight, data required to determine the appropriate value for each variable, and sensitivity of variables to SLC.

Variable Category	Variable	Symbol	Data Requirements	Sensitivity to SLC
Water level	Depth above vertical datum	d_{swl}	Storm surge and wave setup	Medium
	Storm surge	S	Storm frequency analysis	Low
	Wave setup	W_s	Shallow water transformation	Medium
Water depth	Water depth at structure	h	Bathymetric survey	High
	Design water depth	d_b	Determined with above variables	High
Wave height	Significant deep-water wave height	H_o	Offshore wave data	Low
	Depth limited wave height	H_b	Total water depth and breaking index	High
	Design wave height	H_d	Determined with above variables	High
Structure	Structure side slope	θ	Design analysis	Low
	Stability coefficient	K_d	Given (based on material used)	Low

d. Base year (2016) design wave heights for the proposed Barbers Point Harbor jetty are 10.8 and 13.8ft (3.3 and 4.2m) along the root and trunk of the structure, respectively (Table C-6). Under sea level rise as predicted through extrapolation of the historic rate, design wave heights would increase to 11.0 and 14.0ft (3.4 and 4.3m) at the end of the 50-year life cycle along the root and trunk, respectively (Table C-7 and Figure C-15). Under this SLC scenario, jetty design changes would not be recommended because the increases in wave height are within the error of the analysis. For the USACE high curve, there is a significant increase in predicted design wave heights over the same period. For the root of the jetty, the design wave height is predicted to increase from 10.8 to 12.1ft (3.3 and 3.7m). Given that jetty armor stone stability equations typically are a function of wave height to the third power, a 38% increase in armor stone weight would be expected. Along the trunk of the jetty, an increase in design wave height from 13.8 to 15.1ft (4.2 and 4.6m) would result in the armor stone weight increasing by 29%.

Table C-6. Depth-limited breaking wave heights (without SLC). (After USACE 2012.)

	Symbol	Sta -2+00 to 2+00 (root) (ft/m)	Sta 2+00 to 3+75 (trunk) (ft/m)
Design still water level	d_{swl}	7/2.1	7/2.1
Depth of water	h	11/3.4	16/4.9
Design water depth	d_b	18/5.5	23/7
Depth-limited breaking wave height	H_b	10.8/3.3	13.8/4.2

Table C-7. Depth-limited breaking wave heights (with SLC). (After USACE 2012.)

		Root			Trunk		
	Year	h (ft/m)	d_b (ft/m)	H_b (ft/m)	h (ft/m)	d_b (ft/m)	H_b (ft/m)
Historic	2016	11.0/3.4	18.0/5.5	10.8/3.3	16.0/4.9	23.0/7.0	13.8/4.2
	2036	11.1/3.4	18.1/5.5	10.9/3.3	16.1/4.9	23.1/7.0	13.9/4.2
	2066	11.3/3.4	18.3/5.6	11.0/3.4	16.3/5.0	23.3/7.1	14.0/4.3
	2116	11.5/3.5	18.5/5.6	11.1/3.4	16.5/5.0	23.5/7.2	14.1/4.3
USACE high curve	2016	11.0/3.4	18.1/5.5	10.9/3.3	16.0/4.9	23.1/7.0	13.9/4.2
	2036	11.1/3.4	18.7/5.7	11.2/3.4	16.1/4.9	23.7/7.2	14.2/4.3
	2066	11.3/3.4	20.2/6.2	12.1/3.7	16.3/5.0	25.2/7.7	15.1/4.6
	2116	11.5/3.5	23.9/7.3	14.3/4.4	16.5/5.0	28.9/8.8	17.3/5.3

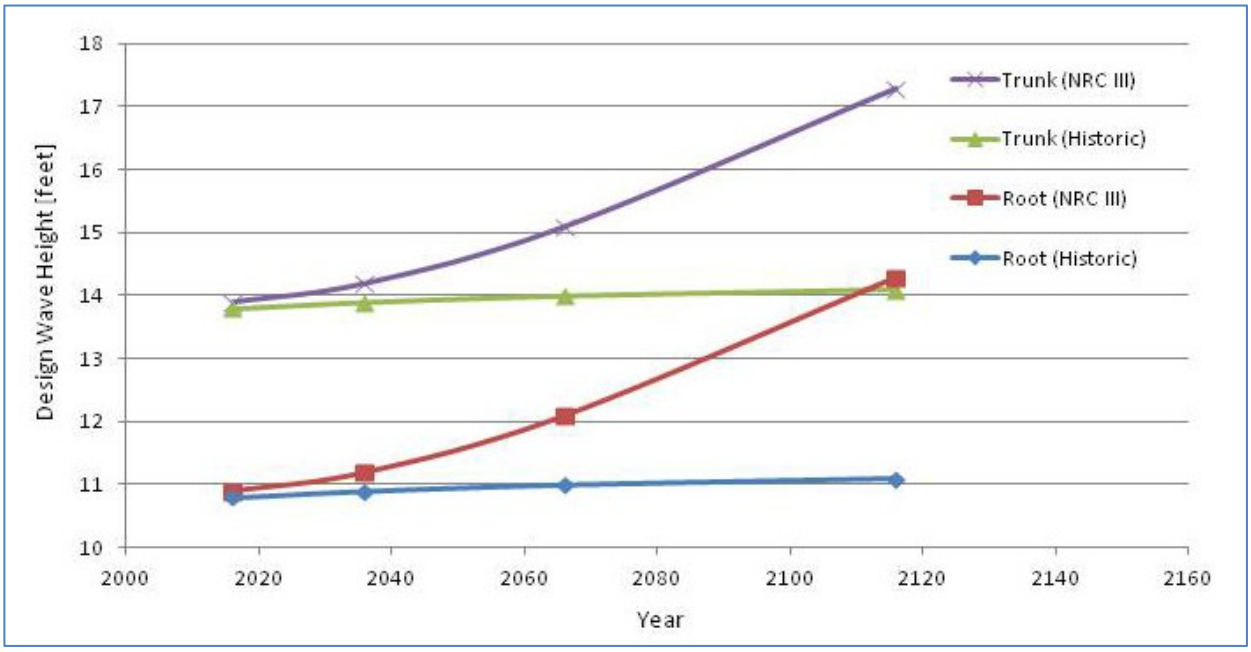


Figure C-15. Depth-limited breaking wave heights (with SLC).

e. Table C-8 is a summary of armor unit design parameters without consideration of SLC. The table presents values for the use of both stone and Core-Loc concrete armor units. Results include stone weights of 10.5 and 24.0 tons along the trunk and head of the jetty, respectively. Core-Loc armor unit weights are significantly lower because they provide superior unit-to-unit interlocking and their corresponding stability coefficient is an order of magnitude higher than for stone. This is evidenced by the fact the 2-ton and 4-ton Core-Loc units are recommended along the root and trunk of the structure, respectively (without consideration for SLC).

Table C-8. Armor unit design (without SLC). (After USACE 2012.)

Parameter	Symbol	Trunk (Sta. -2+00 to 2+00)		Head (Sta. 2+00 to 3+75)	
		Stone	Core-Loc	Stone	Core-Loc
Unit weight	w_r	156 pcf	150 pcf	156 pcf	150 pcf
Wave height	H	11ft/3.4m	11ft/3.4m	13ft/4m	13ft/4m
Stability coefficient	K_d	1.6 (assume two layers)	16	1.2 (assume two layers)	13
Specific gravity	S_r	2.44	2.34	2.44	2.34
Slope	cot Θ	2	1.5	2	1.5
Weight of armor unit	W	10.5 tons	2 tons	24.0 tons	4 tons
W (range)	0.75–1.25 W	8.5–14 tons	n/a	18–30 tons	n/a

f. The 2- and 4-ton requirements for Core-Loc weight shown in Table C-8 would still be applicable under the project's historic rate of sea level rise (Table C-9). Even at 100 years out, armor stone weights of 11.2 and 30.6 tons are predicted to be stable along the trunk and root of the jetty, respectively. For the USACE high curve, significant differences need to be addressed. The extreme example of the change is shown in Figure C-9 as an increase of armor stone weight from 24.0 tons in the original design to 37.5 tons along the jetty trunk in year 50 (2066). This is an increase of approximately 56% and requires a stone size that is at the upper limit of availability. The corresponding Core-Loc weight increase would be up from 4.0 to 5.5 tons (Figure C-16). For the jetty root, 14.5-ton armor stones and 2.3-ton Core-Loc armor units would be required at the end of the 50-year life cycle.

Table C-9. Armor unit design (with SLC). (After USACE 2012.)

	Year	Root		Trunk	
		Stone (tons)	Core-Loc (tons)	Stone (tons)	Core-Loc (tons)
Historic	2016	10.3	1.6	28.7	4.2
	2036	10.5	1.7	29.1	4.3
	2066	10.8	1.7	29.6	4.4
	2116	11.2	1.8	30.6	4.5
USACE high curve	2016	10.5	1.7	29.0	4.3
	2036	11.6	1.8	31.5	4.6
	2066	14.5	2.3	37.5	5.5
	2116	24.0	3.8	56.6	8.3

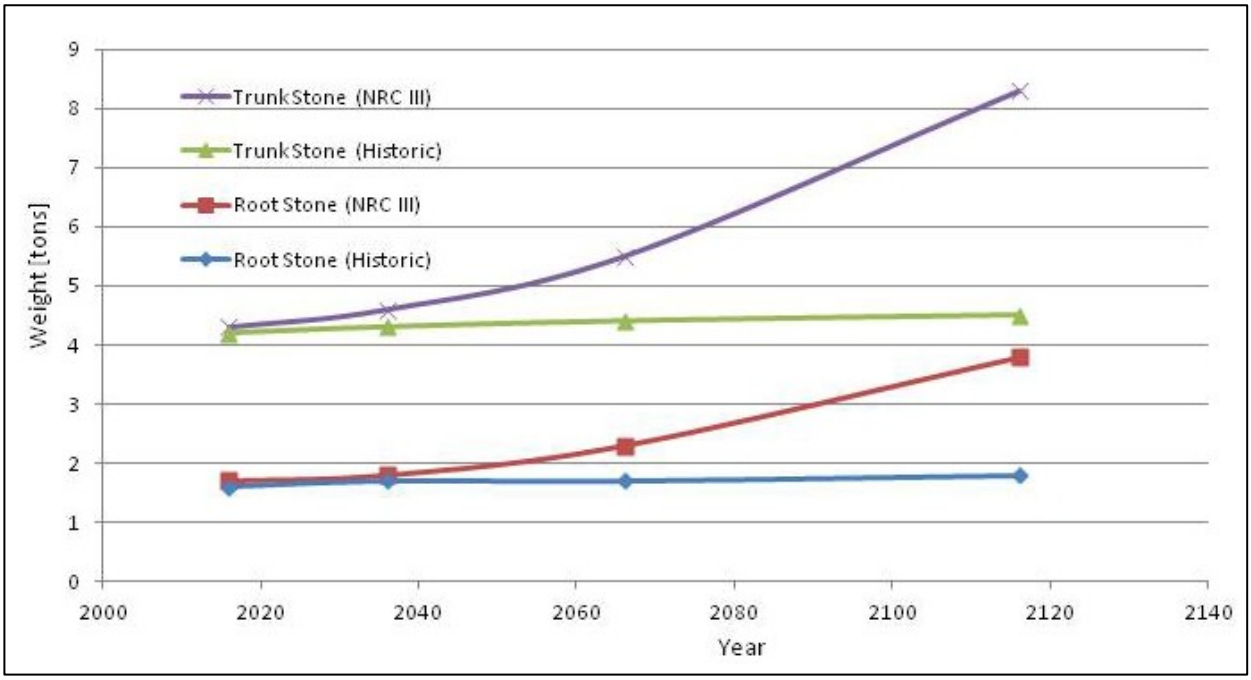


Figure C-16 . Increase in Core Loc weight for the historic and USACE high curves.

g. Due to unavailability of stone within the appropriate weight range, it was determined that Core-Loc concrete armor units will be utilized in the jetty armor layer in lieu of stone. For a jetty using concrete armor units with a stability coefficient $K_d > 12$, underlayer stone are to range from W/10 to W/5. Core stone will be used to level the bottom surface and serve as filler material for the structure. The USACE *Coastal Engineering Manual* (EM 1110-2-1100) recommends a gradation of W/4,000 to W/200 for the core stone. Table C-10 shows the range in sizes for the underlayer and core stone. For the initial design, underlayer stone for the root of the jetty was identified to range from 400 to 800lb (181.4 to 362.9kg), while the core was to consist of 1 to 20 lb (.45 to 9.1kg) stone. Along the jetty trunk, underlayer stone was to range from 800 to 1,600 lb (725.7kg), and core stone was to range from 2 to 40 lb (.91 to 18.1kg). Under the extrapolated historic sea level rise curve, these values remain the same (Table C-11). On the other hand, if the USACE high curve is considered for design, underlayer stone along the root of the jetty would range from 500 to 900 lb (226.8 to 408.2kg) at year 50 in the life cycle. The corresponding core stone range would be 1 to 20 lb (.45 to 9.1kg). For the jetty trunk, underlayer stone range would be 1,100–2,200 lb (499 to 998kg), with an associated core stone range of 3–60 lb (1.4 to 27.2kg).

Table C-10. Summary of underlayer and core stone sizes (without SLC). (After USACE 2012.)

Parameter	Symbol	Sta. -2+00 to 2+00 (root)		Sta. 2+00 to 3+75 (trunk)	
		Underlayer	Core	Underlayer	Core
Avg. weight of overlying unit	W	2 tons	600lb/272kg	4 tons	1,200lb/544 kg

Range of underlayer weights	Wu (range)	400–800 lb/ 181–363kg)	1–20 lb (.45–9.07kg)	800–1,600 lb (363 to 726kg)	2–40 lb (0.9–18.1kg)

Table C-11. Summary of underlayer and core stone sizes (with SLC). (After USACE 2012.)

			Root		Trunk	
	Year		Underlayer (lb/kg)	Core (lb/kg)	Underlayer (lb/kg)	Core (lb/kg)
Historic	2016	Upper	700/318	20/9.1	1,700/771	40/18
		Lower	300/136	1/0.5	800/363	2/0.9
	2036	Upper	700/318	20/9.1	1,700/771	40/18
		Lower	300/136	1/0.5	900/408	2/0.9
	2066	Upper	700/318	20/9.1	1,700/771	40/18
		Lower	300/136	1/0.5	900/408	2/0.9
	2116	Upper	700/318	20/9.1	1,800/816	40/18
		Lower	400/181	1/0.5	900/408	2/0.9
USACE high curve	2016	Upper	700/318	20/9.1	1,700/771	40/18
		Lower	300/136	1/0.5	900/408	2/0.9
	2036	Upper	700/318	20/9.1	1,800/816	50/23
		Lower	400/181	1/0.5	900/408	2/0.9
	2066	Upper	900/408	20/9.1	2,200/998	60/27
		Lower	500/227	1/0.5	1,100/499	3/1.4
	2116	Upper	1,500/680	40/18	3,300/1497	80/36
		Lower	800/363	2/0.9	1,700/771	4/1.8

h. The thicknesses of the armor stone layer and the quarrystone underlayer were determined by the following layer thickness equation [Eq. 7-121, USACE (1984)]:

$$r = k \times n \times (W / W_r)^{1/3}$$

where r = layer thickness
k = layer coefficient
n = number of units in layer
W = layer design weight = W(average)
W_r = unit weight.

Table C-12 shows the input parameters that were used to determine the layer thickness for the original jetty design. Note that the layer coefficient for stone is 1.02, while it is 1.6 for Core-Loc concrete armor units. This is because Core-Loc units are elongated relative to the stone used in rubblemound construction. Also, Core-Locs pack differently than do stones of similar weight. Other differences between Core-Loc units and stone are their unit weight (150 pcf for Core-Locs and 156 pcf for stone) and the number of each to be incorporated in the layer thickness (one for Core-Loc and two for stone). The original jetty design called for a 5ft (1.5m) thick Core-Loc layer along the root and a 6ft (1.8m) thick layer along the trunk. The underlayer thickness was to be 3ft (0.9m) along the root and 4ft (1.2m) along the trunk. Given the extrapolated historic rate of sea level rise, layer thicknesses would remain the same as in the above analysis (Table C-13).

At year 50 in the life cycle under the USACE high curve, the layer thicknesses remain the same except along the trunk, where a 7ft (2.1m) thick Core-Loc layer would be required.

Table C-12. Layer thickness parameters (without SLC). (After USACE 2012.)

Parameter	Symbol	Core-Loc	Underlayer
Layer coefficient	k	1.6	1.02
Number of units in layer	n	1	2
Layer design weight	W	2 tons (trunk) 4 tons (head)	600 lb/272 kg(trunk) 1,200 lb/544 kg (head)
Unit weight	W_r	150 pcf	156 pcf
Layer thickness	r	5.0ft/1.5m (trunk) 6.0ft/1.8m(head)	3.0ft/.91m (trunk) 4.0ft/1.2m (head)

Table C-13. Layer thickness parameters (with SLC). (After USACE 2012.)

		Root		Trunk	
	Year	Core-Loc (ft/m)	Underlayer (ft/m)	Core-Loc (ft/m)	Underlayer (ft/m)
Historic	2016	4.0/1.2	3.0/.91	6.0/1.8	3.0/.91
	2036	5.0/1.5	3.0/.91	6.0/1.8	3.0/.91
	2066	5.0/1.5	3.0/.91	6.0/1.8	3.0/.91
	2116	5.0/1.5	3.0/.91	6.0/1.8	3.0/.91
USACE high curve	2016	4.0/1.2	3.0/.91	6.0/1.8	4.0/1.2
	2036	5.0/1.5	3.0/.91	6.0/1.8	4.0/1.2
	2066	5.0/1.5	3.0/.91	7.0/2.1	4.0/1.2
	2116	6.0/1.8	4.0/1.2	8.0/2.4	5.0/1.5

i. Wave runup (R) was calculated using the Coastal Engineering Research Center's computer programs ACES and "MACE-14-WAVRUNUP, Estimating Irregular Wave Runup Heights on Rough Slopes" (CERC 1985). The non-overtopping revetment crest elevation is equal to the wave runup R plus the design still water level:

$$CE \text{ (non-overtopping)} = R + d_{swl}$$

According to this method, the crest elevation would be over 15ft/4.6m (MLLW). If overtopping is acceptable, than the crest elevation can be determined by adding one-half the design wave height to d_{swl}.

j. Table C-14 compares the crest elevation for overtopping and non-overtopping conditions. The difference in elevation between overtopping and non-overtopping conditions is between 6 and 8ft/2.4m. The primary purpose of the jetty is to reduce currents at the entrance channel. If large waves were present at the entrance channel, it would be hazardous to enter or exit the harbor, regardless of the current. Therefore, the original design of the jetty assumed that

overtopping conditions were acceptable. Table C-15 provides the results of the crest elevation analysis considering the historic and USACE high curves. It was determined that the crest elevation identified in the original design is adequate since the jetty's primary function is to reduce currents during times when wave conditions do not preclude harbor operations. Wave overtopping rates that would occur during such operational conditions do not pose a threat to navigation.

Table C-14. Parameters for crest elevation (without SLC). (After USACE 2012.)

Parameter	Trunk (ft/m)	Head (ft/m)
Design wave height	11/3.4	13.0/4.0
Runup	10/3.0	12/3.7
Design still water level	7/2.1	7/2.1
Crest elevation (non-overtopping)	16/4.9	18/5.5
Crest elevation (overtopping)	12/3.7	14/4.3

Table C-15. Parameters for crest elevation (with SLC). (After USACE 2012.)

	Year	Root (ft/m)	Trunk (ft/m)
Historic	2016	12/3.7	14/4.3
	2036	12/3.7	14/4.3
	2066	12/3.7	14/4.3
	2116	13/4.0	14/4.3
USACE high curve	2016	12/3.7	14/4.3
	2036	13/4.0	14/4.3
	2066	13/4.0	15/4.6
	2116	14/4.3	16/4.9

k. The jetty crest width is calculated using the following equation [Eq. 7-120, USACE (1984)]:

$$B = n \times k \times (W/W_r)^{1/3}$$

where B = crest width
n = number of armor units (three, the minimum for non-overtopping)
k = layer coefficient [from Table 7-13, USACE (1984)]
W = weight of armor unit
W_r = unit weight of armor material.

Table C-16 summarizes the design parameters for determining the crest width for the jetty. Construction access requires a 20ft (6.1m) crest width, so the original design calls for a crest width of 20ft (6.1m). Table C-17 provides the results of the crest width analysis considering the historic and USACE high curves. It was determined that the crest width identified in the original

design is adequate since the jetty's primary function is to reduce currents during times when wave conditions do not preclude harbor operations. Crest width will not impact the functionality of the jetty. As long as construction equipment access is not limited, operations and maintenance of the structure will be possible throughout the life cycle.

Table C-16. Crest width design parameters (without SLC). (After USACE 2012.)

Parameter	Symbol	Sta. 0+00 to 2+00 (trunk)	Sta. 2+00 to 3+75 (head)
No. of armor units	n	3	3
Layer coefficient	k	1.6	1.6
Unit weight armor unit	Wr	150 pcf	150 pcf
Weight of armor unit	W	2 tons	4 tons
Crest width (Eq. 7-120, SPM)	B	15ft/4.6m (min. = 20ft/6.1m)	18ft/5.5m (min. = 20ft/6.1m)

Table C-17. Crest width design parameters (with SLC). (After USACE 2012.)

	Year	Root (ft/m)	Trunk (ft/m)
Historic	2016	16.0/4.9	22.0/6.7
	2036	16.0/4.9	22.0/6.7
	2066	16.0/4.9	22.0/6.7
	2116	16.0/4.9	22.0/6.7
USACE high curve	2016	16.0/4.9	22.0/6.7
	2036	16.0/4.9	23.0/7.0
	2066	17.0/5.2	24.0/7.3
	2116	21.0/6.4	28.0/8.5

l. The major modifications that result from jetty design with the USACE high curve are the increase of the root and trunk Core-Loc weights to 2.5 and 6.0 tons, respectively. These modifications necessitate increases in the underlayer and core stone sizes to ensure that they do not migrate through the armor layer (Figure C-17). The corresponding underlayer stone weight range would be 500 to 2,200 lb (227 to 998kg), with the core stone gradation increasing to 3 to 60 lb (1.4 to 27kg). Since the change in layer thickness can be accommodated by decreasing the core stone cross section, the outer slope of the Core-Loc armor layer will not have to translate outward. The changes to the various line items in the cost estimate result in an overall cost increase of 10%. This is considered an acceptable increase, so the design changes associated with the USACE high curve have been recommended for inclusion into jetty construction.

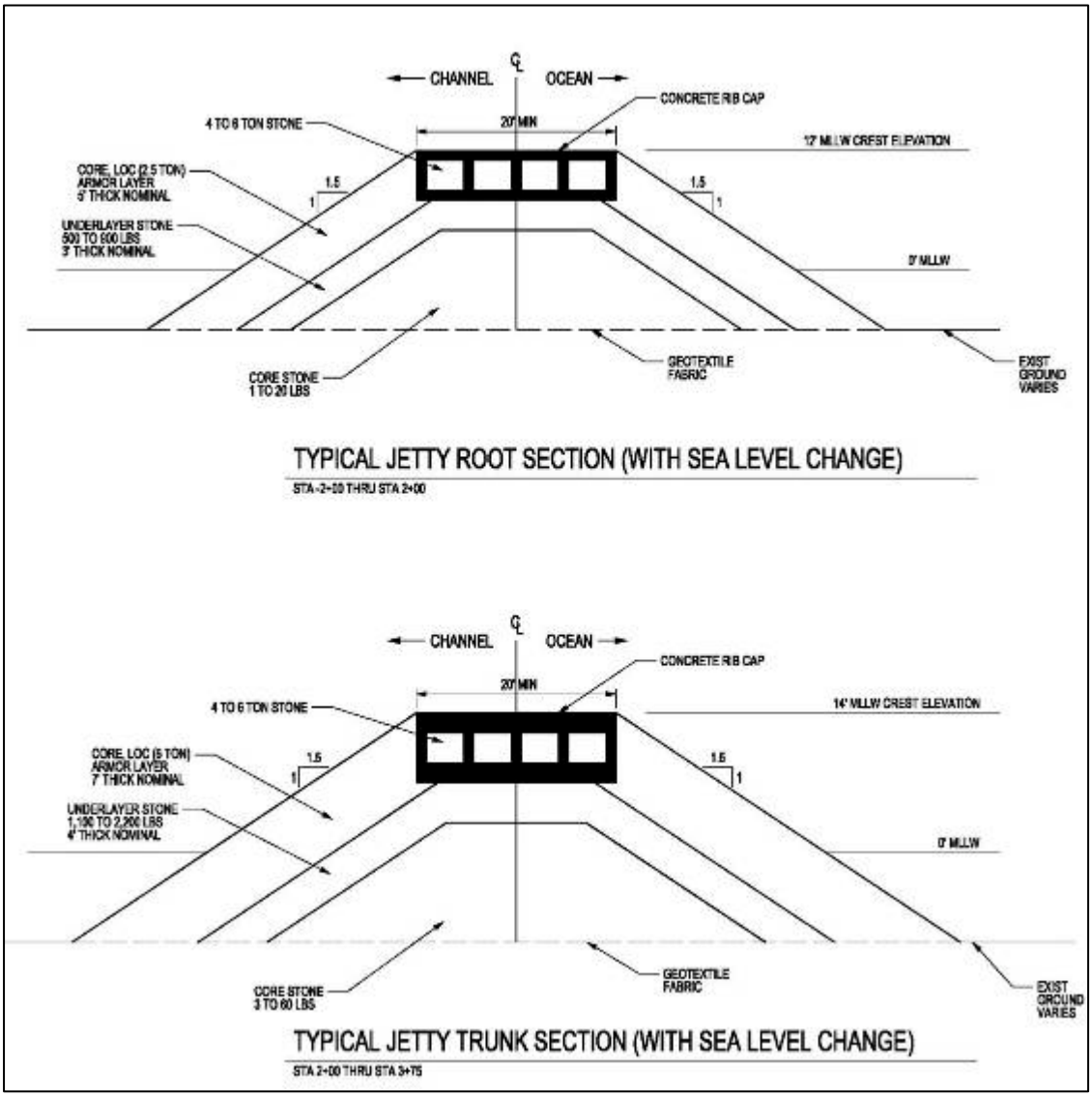


Figure C-17. Typical jetty root and trunk section design based on the USACE high curve for sea level rise at Barbers Point Harbor. (From USACE 2012.)

APPENDIX D

Coastal Storm Damage Reduction Projects

D-1. General Approach and Background. Congress has authorized Federal participation in the cost of restoring and protecting the shores of the U.S. and its territories and possessions. Under current policy, Coastal Storm Damage Reduction (CSDR) projects are designed to reduce damages caused by wind-generated and tide-generated waves, water levels, and currents along the Nation's ocean coasts, Gulf of Mexico, Great Lakes, and estuary shores. This ETL dictates that the direct and indirect physical effects of projected future sea level change (SLC) must be accounted for across USACE mission areas and over the entire project life cycle. For existing projects or projects under construction, SLC has the possibility to change both the loading on existing features and the behavior of natural and engineered coastal systems. For projects under study or in design, SLC effects need to be considered for both the without-project case and the alternatives being proposed. The guidance provided here is intended to help USACE project delivery teams (PDTs) incorporate consideration of SLC effects in CSDR studies and projects. This document is organized around general categories of analysis that may need to be performed for CSDR project evaluation. The categories are shown in Table D-1.

D-2. Scaled Analysis and Decision Making. This ETL suggests a tiered analysis (Figure 9) to determine the consequences of potential SLC, with the results incorporated into the six-step planning process. Each tier represents a decision point that will dictate the level of detail and appropriate methods that are needed for subsequent tiers.

a. Tier 1 – Establish a Strategic Design Context. The initial screening level assesses whether there is potential for significant or catastrophic consequences to life safety, property, critical infrastructure, and/or ecosystems. This initial phase determines the appropriate scale of analyses for incorporating SLC into Tier 2. In addition to what is shown in Figure 9, some questions that can be asked at this stage for a CSDR project include:

- How vulnerable is existing infrastructure to SLC?
- What are the critical thresholds of coastal evolution past which infrastructure is unacceptably impacted?
- What are thresholds and tipping points for human response to SLC?
- How will SLC affect the loading or behavior of the engineered shore protection measures?
- If the infrastructure fails, what might be the impacts on the protected area?

b. Tier 2 – Project Area Exposure and Vulnerability to SLC. The description of the future without-project (FWOP) condition is the foundation for subsequent plan formulation. Tier 2 is a part of the normal USACE planning steps 1 and 2 as shown in Figure 9. The incorporation of SLC scenarios adds another dimension to the without-project description, since there are three potential futures as defined by the three SLC curves. In addition, loading and exposure variables may change through the project's life cycle. Specific CSDR project-related questions at this tier might be:

- How will SLC affect other coastal forces, such as storm surges or storm waves?
- Will changes to the local mean sea level change the frequency or severity of flooding?
- What are the dominant forces and are they impacted by SLC?
- What are the expected human responses?
- How might riverine, estuarine, or barrier island back bay processes change?

c. Tier 3 – Alternative Development, Evaluation, and Adaptability. Tier 3 incorporates planning steps 3 through 6, formulation and evaluation of measures directed at the identified problems. SLC may be only one of the considerations for alternative development. The Tier 3 analysis will inform the study team regarding the relative importance of SLC on without-project and with-project alternatives. Key questions for CSDR projects in Tier 3 might include:

- What are the critical thresholds of coastal evolution past which infrastructure is unacceptably impacted?
- What are tipping points past which project stability and/or performance will be adversely affected?
- How can the project be adapted for changing water levels and through what range of water levels?
- Does the selected plan include thresholds where the existing project alternative ceases to be optimal and another becomes more beneficial?

D-3. Discussion of Principles.

a. In the context of this ETL, principles are those concepts that are commonly accepted to be true and that underpin assessments of the effects of SLC on USACE projects. Issues are matters specific to each principle that should be considered to properly address the effects of SLC. Issues cannot necessarily be solved with a single answer or method. Methods encompass tools ranging from first-level screening to higher-level modeling (i.e., rules of thumbs to complex computational models) available to address each of the issues. Table D-1 summarizes principles, issues, and methods for the CSDR project mission area.

b. Nonstationarity of SLC. Stationarity refers to an analysis and design context in which past environmental forces are extrapolated to represent future environmental forcing. CSDR projects are traditionally evaluated based on the assumption that past measurements of coastal forces such as waves, currents, and sediment transport accurately represent expected future site conditions. Though the extrapolation of the current tide gauge record (low scenario) may be stationary in many cases, the intermediate and high scenarios may exhibit nonstationarity. Since SLC scenarios as outlined in this ETL are inherently nonstationary, and since changes in mean sea level may have impacts on many other coastal forces, the incorporation of SLC into analyses means that stationarity can no longer be assumed outright for other coastal forces. In some cases, the changes to other forces may be difficult to discern or predict, and they may be insignificant changes in the overall context of the project, but nonetheless the assumption of stationarity of coastal forces is no longer valid.

Table D-1. Incorporating SLC in CSDR projects: principles, issues and methods.

Category	Principles	Issues	Methods
Coastal Forces and Processes	SLC has the potential to act directly on the landscape and affect other coastal forces that act on the landscape. The configurations of coastal landscapes are dictated by the interaction between a site's physical characteristics and the coastal forces that act on it. Increased water levels combined with shoreline recession will increase both the magnitude and the frequency of impacts along the coastline.	How will SLC affect other coastal forces such as storm surges or storm waves? Will changes to the local mean sea level change the frequency or severity of flooding? How might riverine, estuarine, or barrier island back bay processes change?	Review of existing literature and professional elicitation regarding SLC impacts on other coastal forces. Superposition of storm surge return interval analysis with future SLC projections to determine future storm surge frequency. Numerical modeling of waves and/or storm surge including the effects of SLC. First-level calculation of how a change in SWL impacts other forces or variables.
Morphological Response	Coastal landscapes vary in their degree of vulnerability to SLC. Cross-shore and along-shore morphological evolution will together define how a system responds.	What is the future response of the coastal landscape to ALL coastal processes (including SLC)? What are the dominant forces and are they impacted by SLC? How vulnerable is the landscape to SLC?	USGS Coastal Vulnerability Index (CVI). Analysis of long-term beach evolution via the Bruun Rule or other similar methods. Application of numerical models of sediment transport and without-project life cycle.
Infrastructure Vulnerability	Man-made infrastructure may have vulnerabilities to SLC that may or may not depend on the natural characteristics of a coastal landscape. The frequency and severity of various impacts that are acceptable to human stakeholders are relevant to vulnerability.	How vulnerable is existing infrastructure to SLC? What are the critical thresholds of coastal evolution past which infrastructure is unacceptably impacted? Is the infrastructure adaptable to become more resilient to SLC? If the infrastructure fails, what might be the impacts on the protected area?	Expert elicitation: derive a qualitative matrix to evaluate the vulnerability of resources and infrastructure. Corps Coastal Systems Portfolio Initiative (CSPI), which provides information on CSDR resources at risk. Numerical modeling of future without-project behavior in the presence of SLC to evaluate infrastructure vulnerability and consequences.

Category	Principles	Issues	Methods
Human Response	SLC will, at some water level threshold, cause a human response. Some human responses to SLC may have a strong influence on the future behavior of the beach system. Anthropogenic response must therefore be accounted for when determining future existing project or future without-project conditions.	What are thresholds and tipping points for human response to SLC? What are the expected human responses? What are the economic thresholds past which responses are not sustainable? Will any human responses influence future morphological evolution?	Analysis of site-specific historical human response to threatened coastal infrastructure. Economic sustainability analysis of future response costs in the presence of SLC (economic thresholds). Review of relevant existing regulations/ laws that might limit future responses (e.g., prohibition of hard armoring).
Project Feature Response	On existing projects, SLC may impact both the stability and the performance of engineered features. An engineered project may result in a site being more or less sensitive to SLC compared to that site with no project. The nonstationary nature of SLC may result in the need to transition to different alternatives at different threshold water levels. An optimum project is adaptable, resilient, and cost effective and has a plan for adaptation.	How will SLC affect the loading or behavior of the engineered shore protection measures? What are tipping points past which project stability and/or performance will be adversely affected? How can the project be adapted for changing water levels and through what range of water levels? Does the selected plan include thresholds where the existing project alternative ceases to be optimal and another becomes more beneficial?	Analysis of project feature response to SLC, which should be incorporated into all relevant project alternative design and plan formulation steps. Numerical model simulations of alternatives using engineering/ economic model (e.g., Beach-*fx*). Use of design tools and engineering/ economic models to establish critical SLC thresholds at which engineering measures need to be modified or where they cease to be viable economically, socially, etc. Use of engineering/economic analysis techniques to develop an adaptation strategy that includes thresholds, tipping points, and project adaptation responses.

(1) Future Viability. The term “threshold” describes a critical water level when SLC begins to have some effect on the system in question. A threshold may be a future point in time, during a rising sea, when a particular feature becomes viable or becomes the optimal measure to reduce storm damage. An example would be construction of a sea wall at some future threshold water level when a currently preferable method, such as beach nourishment, ceases to be a cost-effective storm damage reduction measure.

(2) Societal Thresholds. Evaluation of CSDR in the context of SLC may also involve societal thresholds. An example would be a coastal town located on a marsh coastline with a relatively low upland elevation. At current mean local sea level, the frequency of flooding from coastal inundation is once every 100 years. Under a scenario of rising sea levels, the site would cross a threshold where flooding frequency begins to increase. This increase may be tolerable initially, but eventually flooding frequency may reach a tipping point and action must be taken to reduce the frequency of infrastructure impact via protective structures, relocation, or other measures.

(3) Morphological Thresholds. An example of a morphological threshold and a tipping point is the process of barrier island over-wash and rollover. During storm surge events, some barrier island systems experience periodic over-wash during which water breaches the dune system and sand is transported to the landward side of the dune. Rising mean sea levels increase the frequency of this process until the beach and dune system as a whole has been transported and re-formed landward of its original position. In some situations, rising sea levels may overwhelm the ability of the dune to recover in a new position, in which case the dune’s volume and elevation will decline. The presence of permanent infrastructure on developed coasts is normally incompatible and inhibits this behavior.

(a) Example of Morphological Threshold: Barrier Island. Figure D-1 depicts the behavior of a barrier island system as predicted by the USACE planning model Beach-*fx*. Beach-*fx* is a life-cycle model in which multiple iterations of the project life cycle (normally 50 years for Federal CSDR projects) are simulated; each simulation contains a random sample of storms occurring at various stages of the tidal cycle. The results indicate that the low and medium SLC scenarios produce a linear increase in probability of dune rollover, so there is no indication that the behavior of the dune has reached any morphological tipping point. The high SLC case shows a point at the 12-year mark (arrow) where the dune begins to behave differently and dune rollover becomes rapidly more probable.

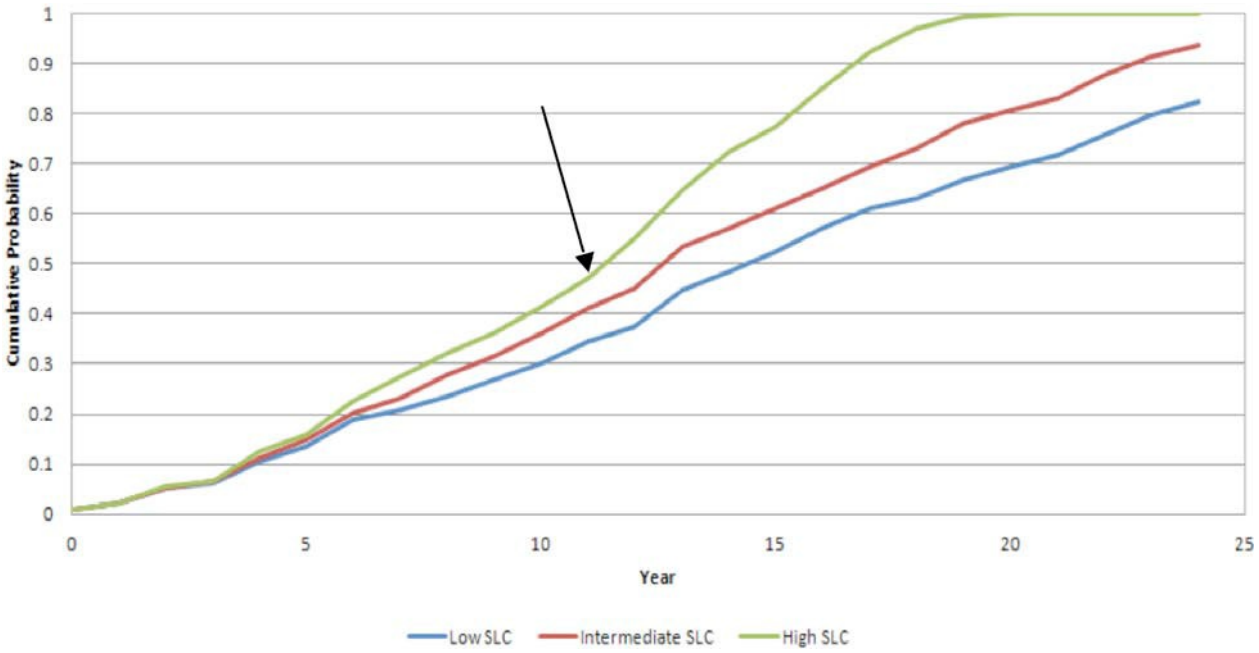


Figure D-1. Cumulative probability of dune rollover at a particular location along a barrier island for low, intermediate, and high SLR rates.

(b) Example of Morphological Threshold: Dune. Figure D-2 illustrates the probability of the dune being lowered in elevation for the same set of simulations. None of the three SLR scenarios creates any increase in probability of dune lowering until year 8. Beginning at that point, the low and intermediate SLR rates have a smooth, consistent rate of increase over the 24-year simulation period, again indicating a consistent behavior of the dune. The high SLR rate creates a critical point at approximately year 13, after which the probability of dune lowering rapidly increases through time. This likely indicates that the dune system has a tipping point at that particular sea level (or that SLR rate) after which the dune becomes less and less able to resist storm energy. Based on the above information, under the low and intermediate SLC scenarios, the dune system functions in a consistent manner throughout the period shown. The high SLR scenario appears to have a tipping point at year 12-13 after which the dune behaves in an ever-declining manner. The same model simulations might be further analyzed to determine the average return interval of flooding damage to structures behind the dune. This could determine that there is a societal tipping point of a particular return interval past which action must be taken.

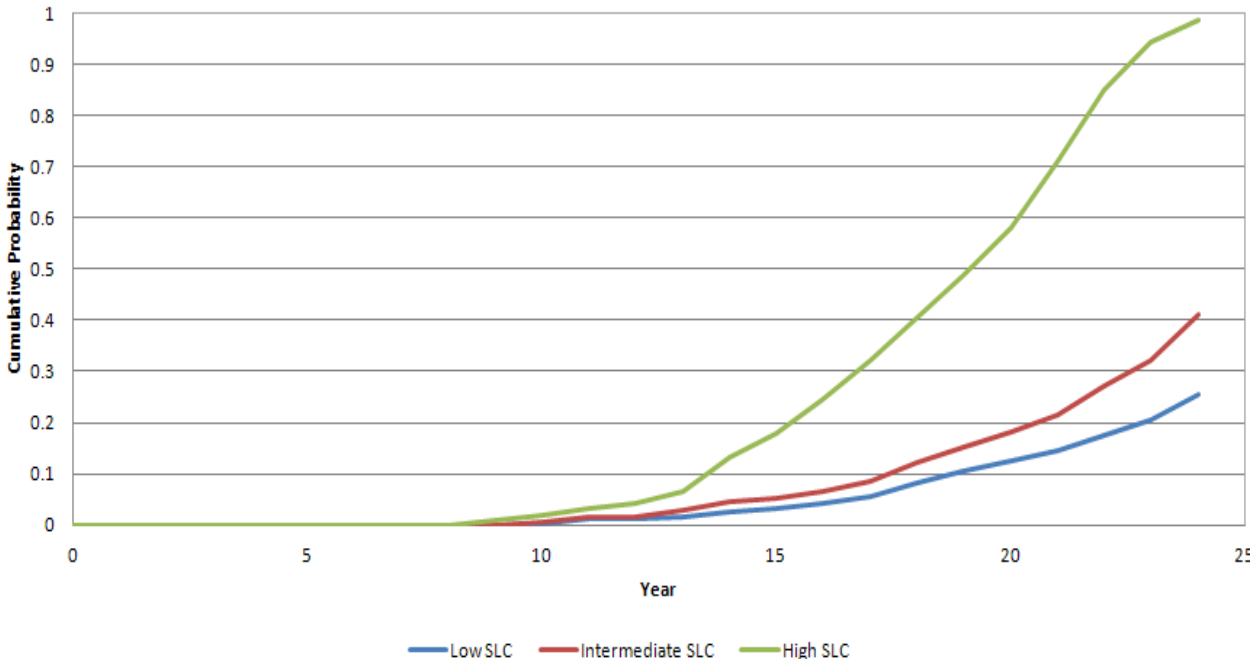


Figure D-2. Cumulative probability of dune crest elevation being lowered.

D-3. Project Area Description. To simplify the initial steps of this phase of the study and yet capture the real areas of potential risk for use in the initial screening, the following bracketing and risk assessment steps are recommended.

a. Extent. Using the high SLC curve elevation at 100 years, the potential future affected area is defined. This area defines both the vertical and the horizontal extent of potential SLC impacts.

b. Inventory. Using the future affected area as defined by the 100-year high rate elevation, an inventory can be conducted to identify the density of impacted resources, including critical infrastructure (schools, roads, water supply, community buildings, etc.), impacted property, and ecosystems. Table D-2 is an example of such an inventory table for CSDR that provides a snapshot of the potential magnitude and severity of consequences in an example project area. The consideration of the potential larger area of impact facilitates the discussion of what actions may need to be considered at certain trigger points. Community as well as other stakeholder expectations will be better defined. Potential system and cumulative effects should be explored. Also included in this table is a qualitative assessment of the expected risk from SLC.

Table D-2. Example of a qualitative matrix for a CSDR project, showing critical resources, expected density of the resource, relevant notes, and the relative risk to the project posed by SLC. [Based on the USACE Coastal Systems Portfolio Initiative (CSPI); see http://cspi.usace.army.mil/.]

Critical resources in study area	Density of resource*	Relevant notes	Risk from SLC*
Structures (residential, commercial)	2	Mostly residential. Highly developed between main evacuation route and ocean. Approximately 6% of the project area is currently protected by revetments or seawalls.	1
Environment and habitat	3	Existing dune is 10–15ft (3–4.6m). Estuary and other wetland partially surrounds the study area.	2
Infrastructure (roads, water and sewer lines, boardwalks, navigation structures)	2	State highway (hurricane evacuation route) and secondary roads, power and service lines servicing residents.	1
Critical facilities (police, fire, schools, hospitals, nursing homes)	1	One fire station, critical services rely on one road (State Road A1A) to reach residents.	1
Evacuation routes	3	State highway (hurricane evacuation route) is located landward of the dune line, within the project area.	2
Recreation	3	Significant recreational use of beaches	1

*3 = high, 2 = medium, 1 = low, X = none present.

D-4. Coastal Forces, Coastal Processes, and SLC. In the context of the USACE CSDR mission, the performance of a coastal system or project is generally assessed based on the level of protection afforded to upland infrastructure by natural and man-made features. The damaging forces that might be mitigated by the natural or man-made features are erosion, flooding, and wave attack. In the context of a project life-cycle approach, damage from these forces may occur gradually over long periods of time, rapidly during storm events, or in both time scales.

a. Principles. The configurations of coastal landscapes are dictated by the interaction between a site's physical characteristics and the coastal forces that act on it. SLC has the potential to interact directly with the landscape and also to affect the coastal processes that act on the landscape. Increased water levels combined with shoreline recession will increase both the magnitude and the frequency of impacts along the coastline. Some CSDR projects, such as those in coastal Louisiana, function more similarly to inland Flood Damage Reduction projects than they do to CSDR beach projects. Practitioners working on such projects should also review the Flood Damage Reduction Appendix (Appendix E) of this Technical Letter for more insight on analyses associated with levees and other FDR project features.

b. Issues.

(1) How will SLC affect other coastal forces, such as storm water surface elevation, depth-limited wave heights, etc.?

(2) Will changes to the local mean sea level change the frequency or severity of flooding?

c. Water Levels. Water levels play an intrinsic role in the dynamic equilibrium of a coastal system. The coastal forces from currents, waves, tides, and storm surges impact the coastline within a vertical range that is a function of tidal range and storm frequency and severity. It is thus necessary to assess how a change in sea level may or may not change these coastal forces. Should these forces change significantly, then an accompanying response would be expected from the coastal system. For example, wave heights at coastal structures are generally depth limited, so SLC scenarios may affect the total depth and therefore the design wave height of coastal structures. Similarly, along-shore and cross-shore sediment transport are both correlated to the depth of breaking waves, the width of the surf zone, and other factors that SLC may directly influence.

d. Tides and Surges. Tidal water surface fluctuations and storm surge occur "on top of" the local mean sea level; therefore, any change in sea level will alter the total water surface elevation, and potentially the inland limit of inundation, that is reached during each tidal cycle and during storm surge events. In the case of sea level rise, the frequency of storm surge reaching a critical total water surface elevation will increase, which might cause more frequent damage to infrastructure or may cause more severe storm-induced coastal erosion. If a site has a tidally driven water surface elevation range that is small in comparison with future SLC projections, then that site may be more sensitive to SLC than a similar one that has a greater tidal range. This is because the infrastructure may be located closer to mean sea level in areas with small tidal ranges. Similarly a site that experiences relatively frequent storm-induced water level variations may be more resistant to future SLC than a site that has fewer and/or smaller events.

e. Methods. The methods used to evaluate the effect of changing water levels range from a simple review of existing literature to large-scale numerical modeling of ocean processes such as storm surge. One effective method for rapidly assessing the increased frequency of extreme water level events is a threshold analysis similar to those done by Kriebel (2012). These analyses highlight an important effect of sea level rise: increasing water levels mean that future storms will reach higher elevations and will produce greater flood damages than past storms of the same magnitude. In an era of rising sea levels, the number and severity of flood events that cross a threshold will increase, leading to more severe damages per storm but also to more damaging storms in a given time, even if there is no change in storm climatology from the present.

(1) Use of Monthly High Water Levels. Kriebel's analyses make use of monthly high water elevations recorded at NOS tide gauges. Some of these gauges are located inside inlets or are otherwise protected from open ocean waves and surge, so they are not recording the total water elevation that may be reached at a CSDR project area. The effects of surge, wave run-up, or other water elevation additions should be incorporated into the analysis if possible.

(2) Screening Level. Kriebel's analysis is intended to be a screening-level analysis that illustrates the minimum possible effect of SLC on frequency of events. More-detailed numerical modeling should be performed for an actual calculation of impacts and damages. A site that is particularly vulnerable to storm surge, such as the northern Gulf of Mexico coastline, might

warrant an in-depth numerical modeling study to determine SLC impacts on the magnitude of storm surge. Barrier islands and marshes that currently protect such coastlines might be less effective with changing relative local mean sea levels. ADCIRC or other numerical models can be used to evaluate the effect of SLC on storm surge.

D-5. Coastal Morphology and Response to SLC.

a. Principles. Coastal landscapes vary in their degree of physical vulnerability to SLC, depending on factors such as characteristic wave conditions; tidal range; upland elevation; dune configuration; beach profile shape and slope; and sediment type, supply, and distribution. Cross-shore and along-shore morphological evolution will together define how a system responds. Understanding the morphology of the site is critical when planning the scale of SLC analysis and making decisions during the planning or operation and maintenance of projects.

b. Issues.

(1) What is the future response of the coastal landscape to ALL coastal processes (including SLC)?

(2) What are the dominant forces and are they impacted by SLC?

(3) How vulnerable is the landscape to SLC?

c. General Approach. Significant variation exists in the near-shore forcing climate, shoreline characteristics, and coastal profile features along coastlines of the U.S. This variability in coastal processes and geomorphology dictates that the shoreline response to SLC will be unique to each region. The planning and engineering design of USACE CSDR projects takes into account a specific area's dominant regional coastal processes, historical shoreline behavior, sediment composition and supply, and geomorphic features (among other items). As such, the incorporation of SLC into these phases of project development should account for such items as well and should consider that different approaches to planning decisions and engineering calculations may be needed, depending on distinct regional features and processes.

(1) Geomorphology. The geomorphology of a coastline can consist of elements as diverse as cliffs and bluffs, dunes, bars, spits, intertidal platforms, reefs, wetlands, and tidal deltas. The area of study may also be bound by complete or partial littoral barriers, or it may be dominated by unconstrained littoral drift. The sediment type of the area, whether it is cobble, terrestrial or calcareous sand, fine to cohesive sediment, or a number of other classifications, is largely influenced by this geomorphology as well.

(2) Sediment. The sediment supply (or lack thereof) within a region can have a significant effect on long-term shoreline behavior as well as on resilience to the effects of sea level rise. Areas with fluvial sediment supply, sand supplied from dunes (either through erosion or aeolian transport), sediment eroded from cliffs, or sediment supplied by onshore or along-shore transport will be better suited to adapt to changes in sea level than will areas where the sediment supply is limited. Imbalances resulting in a lack of available sediment may be due to natural sinks, such as

offshore canyons or flood-dominated inlets, or anthropogenic causes, such as sand mining or hard structures that create along-shore or cross-shore barriers to sediment transport.

(3) Shoreline Position. Of central importance is the fact that shoreline position is directly linked with SLC. On almost any type of coastal system, relative sea level rise will be accompanied by a proportional recession of the shoreline. A change in the rate of shoreline change can have far-reaching effects on other processes, such as frequency of flooding and sediment transport rates. For this reason it is essential to obtain a reasonable estimate of shoreline response to SLC.

d. General Shoreline Characteristics. All of these shoreline characteristics contribute to the overall shape that the shoreline takes and its sensitivity to changes in sea level. For the purposes of this discussion, varying regions will be represented by a typical cross-shore profile. Typical regional profiles for several areas around the U.S. are represented in Figures D-3 through D-7. This is not a comprehensive collection of U.S. beach profile types, but it illustrates the variation (and similarities) between regional shoreline characteristics and the diverse geomorphologic features that may exist.

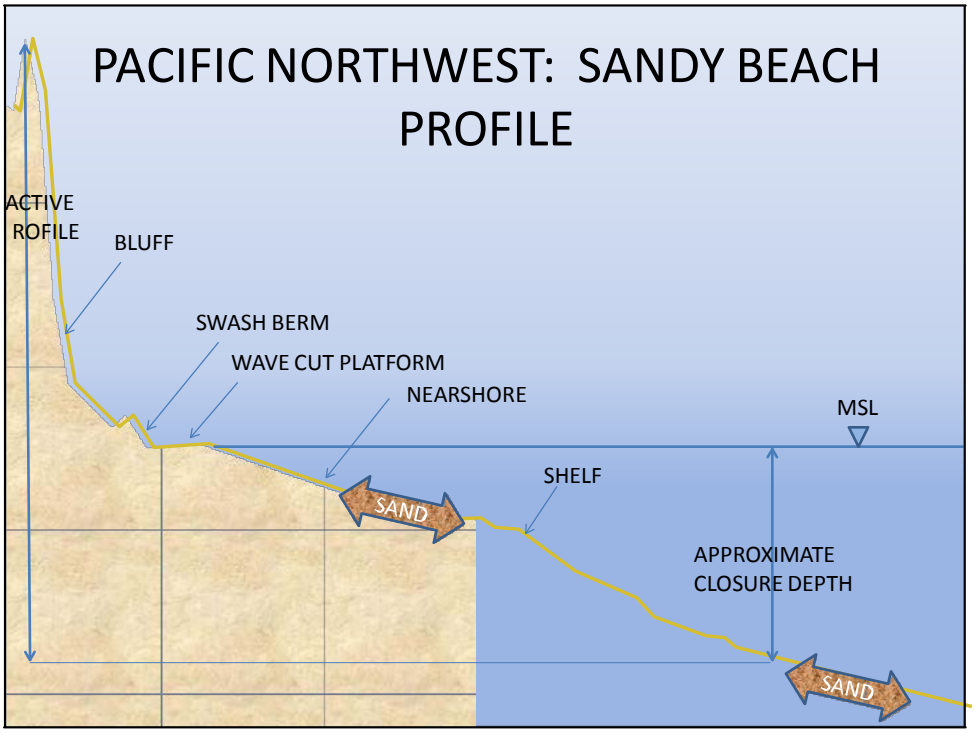


Figure D-3. Typical beach profile for the Pacific Northwest region.

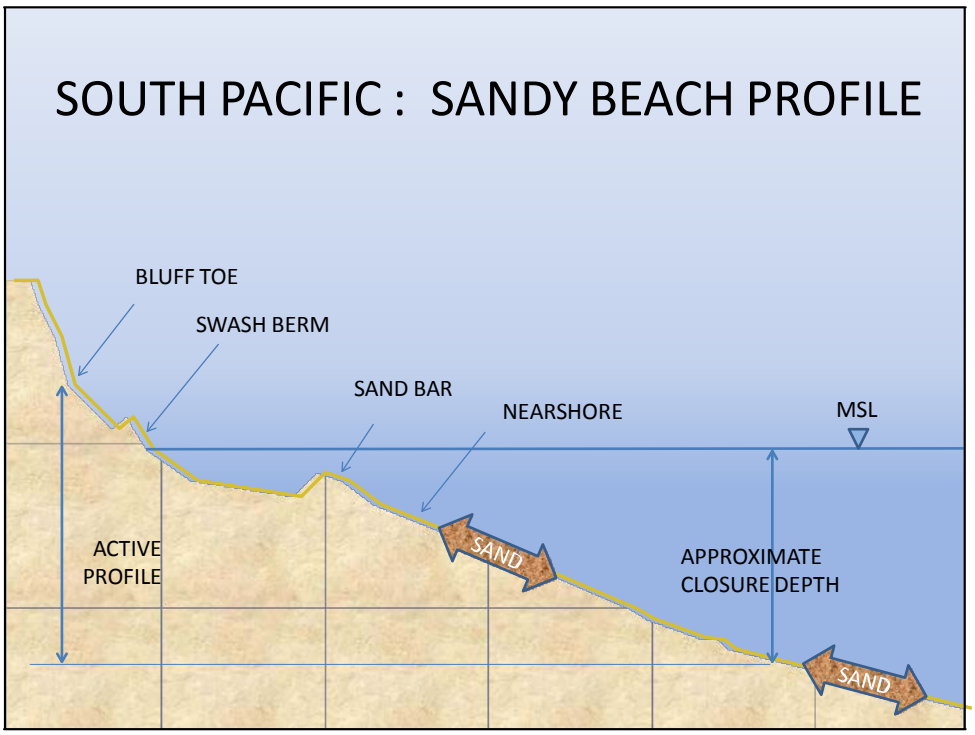


Figure D-4. Typical beach profile for the South Pacific region.

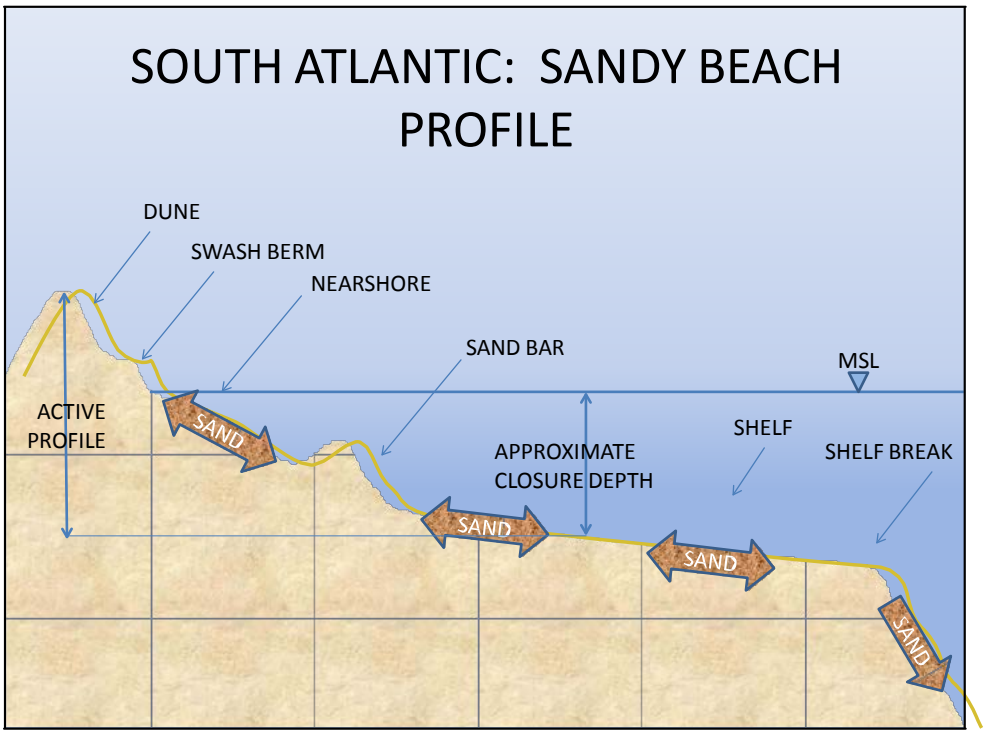


Figure D-5. Typical beach profile for the South Atlantic region (also representative of Gulf of Mexico beaches).

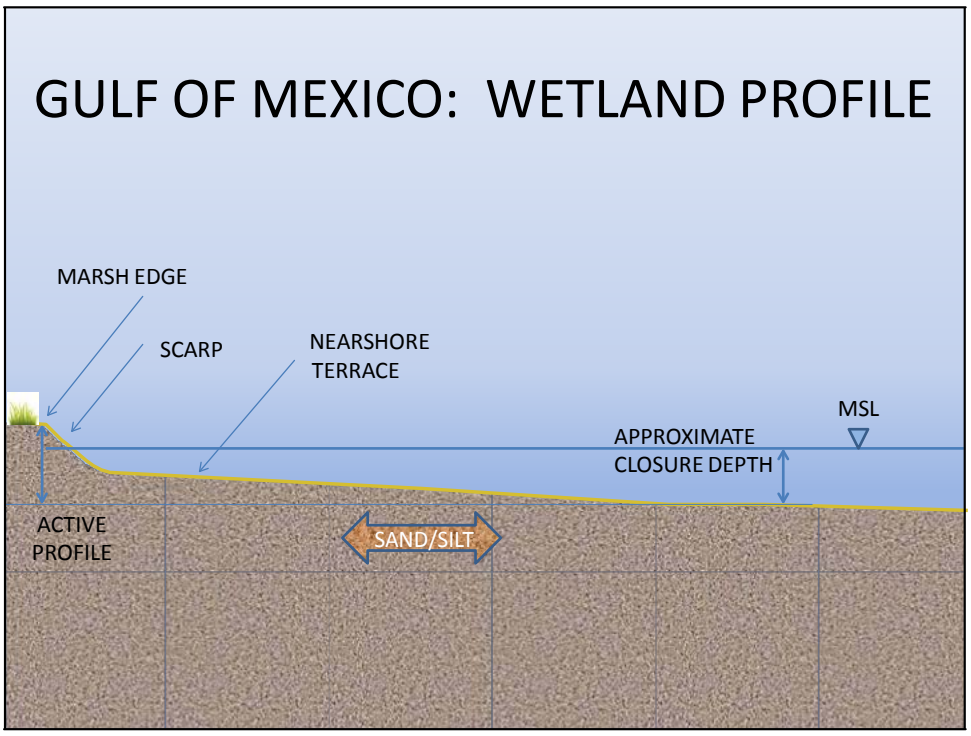


Figure D-6. Typical beach profile for the Gulf of Mexico region.

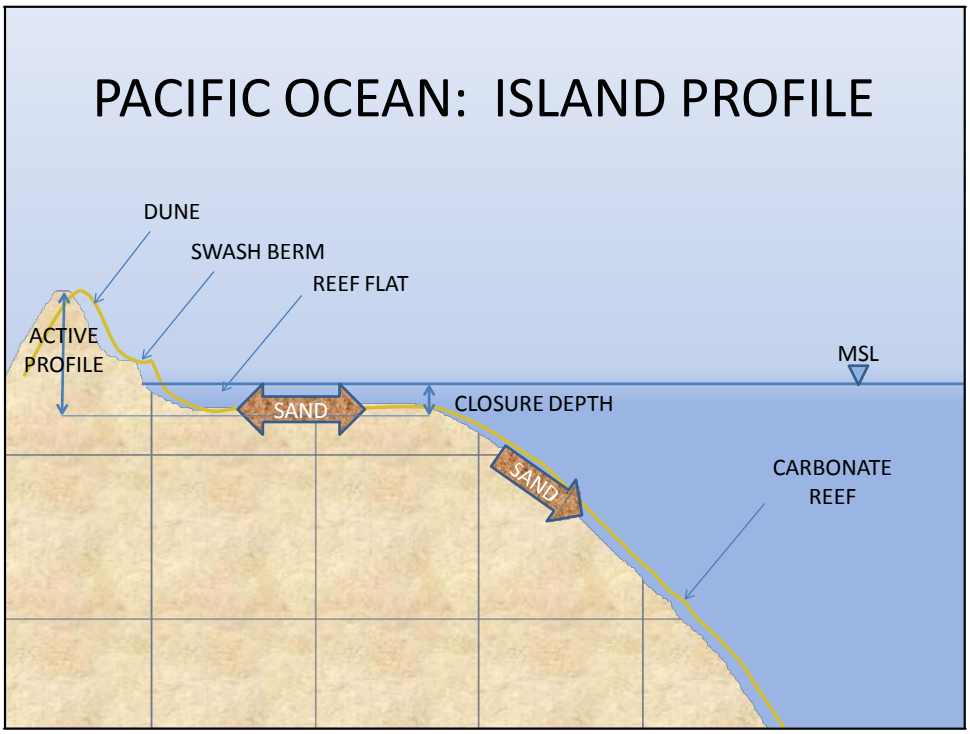


Figure D-7. Typical beach profile for the Pacific Islands region.

e. General Impacts. It is expected that changes in sea level, particularly sea level rise, will have some similar general impacts in almost all low-lying coastal areas. As indicated elsewhere in this report, the extent of high and low tide lines will reach farther landward. Locations that are now submerged only during high tides may be consistently under water. Areas experiencing erosion now will likely see these trends accelerate, while areas that are depositional or stable will shift to erosional. Flooding frequency will also increase, and areas with hardened shorelines may lose any existing fronting beach completely. The extent and evolution of these changes, however, will be influenced strongly by regional characteristics: geomorphology, coastal processes, and sediment supply. Some examples of how the regional variability may affect SLC response are given below.

(1) Erodible Cliffs or Bluffs. In areas where erodible cliffs or bluffs are present (such as those shown in Figures D-3 and D-4), rising sea levels will allow larger waves to attack the cliff or bluff toe. This may result in undercutting and erosion of the base of the cliff or bluff and possibly cause partial or full collapse or slumping of the toe, depending on the geology. Alternatively, it is possible that this cliff or bluff erosion may provide additional sediment to the system and thereby increase the size and protective ability of the beach fronting the subaerial profile. However, it is likely that the impacts of cliff or bluff erosion would outweigh any benefit gained from additional sediment. In addition, wave-cut platforms in such areas (Figure D-3), formed where waves have exposed the surface of a flat, erosion-resistant rock formation (Bird 2008), which serves as some protection to the shoreline by initiating wave breaking, will be more frequently or consistently submerged, reducing their ability to provide this protection. Sediment supply from rivers along these Pacific coastlines, which can be highly variable depending on rainfall, the presence of dams, inland waterway dredging, and other factors, will also play a large part in determining the resilience of the shoreline to these impacts as well.

(2) Backshore Dunes. Where backshore dunes are present, typical along the Atlantic coast of the U.S. and shown in Figure D-5, increases in sea level will potentially cause erosion and landward migration of dunes. Similarly, nearshore bars typical of the Atlantic coast and sandy shorelines of the South Pacific coast (Figure D-4) will also experience landward migration following sea level rise because of greater water depths and resulting larger waves acting in the nearshore. The cross-shore extent and temporal scale of these movements will be highly dependent on the coastal processes at work, as well as the sediment supply available to maintain and replenish these features. For example, if the landward movement of the dune is interrupted by a barrier such as a hard structure, or it is inhibited by sand being lost to a lagoon or wind-blown upland transport, the reduced availability of sand to the dune structure may result in degradation or complete loss of this protective feature. Following this eventuality, the erosive effects of sea level rise on the sandy profile would be further exacerbated.

(3) Coral Reefs. A final example of the regional differences in response to SLC is that of an area where coral reefs or other hard features (as opposed to sand, silt, or mud) are a primary feature of the near-shore profile (Figure D-7). In many Pacific islands, the fringing reef provides significant protection to the sandy shoreline from an often energetic wave environment by causing waves to break on the outer edges of the reef. This causes the near-shore wave environment to be depth limited and the wave magnitudes to depend primarily on water depth as determined by tide, wave setup, and other coastal processes. A rise in sea level will reduce the

protective influence of the fringing reef, as it will be more submerged in the near-shore surf zone, thereby allowing larger waves to penetrate toward the shoreline. It is possible that a rise in sea level may enable reef growth that would counteract this effect; however, this outcome would depend on the existence of a healthy reef, a requirement that may be questionable because of other effects of climate change. In addition, because of the limited vertical extent of the active profile in areas with near-shore reefs (Figure D-7), the cross-shore exchange of sediment is often minor. Sand in many of these regions is primarily calcareous with few terrestrial or other inputs, making the sediment supply finite and limited. This lack of sediment supply makes such areas more vulnerable to sea level rise, because if sediment is lost offshore during a large wave event or is trapped behind a hard structure, there is no source for natural replenishment of the sandy portion of the beach profile.

f. Vulnerability. The effects of SLC on the coastline, as well as the methods employed to prepare for and adapt to these changes, will vary by location, depending on the regional characteristics of the coastal morphology, the sediment supply, and the processes that affect these areas. One or two of these factors may have more influence on the vulnerability or resilience of a particular coastline than the others. In addition, the composition of a shoreline may be such that the response to sea level rise could occur on multiple temporal or spatial scales. The examples shown here illustrate that, similar to the basic planning process or engineering design approach that is tailored to a specific area, the changing requirements for achieving coastal storm damage reduction in the face of SLC mean that a “one size fits all” method will not adequately address the unique problems and needs of each region.

g. Methods of Analysis. The incorporation of SLC into an analysis of project or feature behavior may be approached using a wide variety of methods that vary in level of effort and applicability. The vast majority of the literature on changing sea levels involves documentation of processes by which sea level rise induces recession and erosion of the shoreline and techniques to predict future erosion due to sea level rise. The following is intended to be a framework for considering SLC and the applicability of various methods. It is not intended to be an exhaustive list of methods or a step-by-step approach detailing any one method. The U.S. Geological Survey Coastal Vulnerability Index is a reasonable first-level screening tool that incorporates several of the variables discussed in this section. The following is a brief discussion of some methods for assessing SLC response for different shoreline types. Most CSDR projects are on sandy beaches, so this document contains a more detailed accounting of methods for predicting SLC-induced beach morphology changes.

(1) Sandy Beaches.

(a) Bruun Rule. The best-known method for estimating beach response due to sea level rise is known as the Bruun Rule (Bruun 1962). This is a simple method that uses two-dimensional mass conservation to predict the translation of an equilibrium beach profile in the presence of rising water levels and an adequate sand supply (Figure D-8). This method has been discussed in numerous reports and publications. This method has been the dominant method for predicting beach profile recession due to SLR. Numerous researchers have tested its ability to predict profile recession, some with positive results (Zhang et al. 2004) and others with negative results (Ranasinghe et al. 2012).

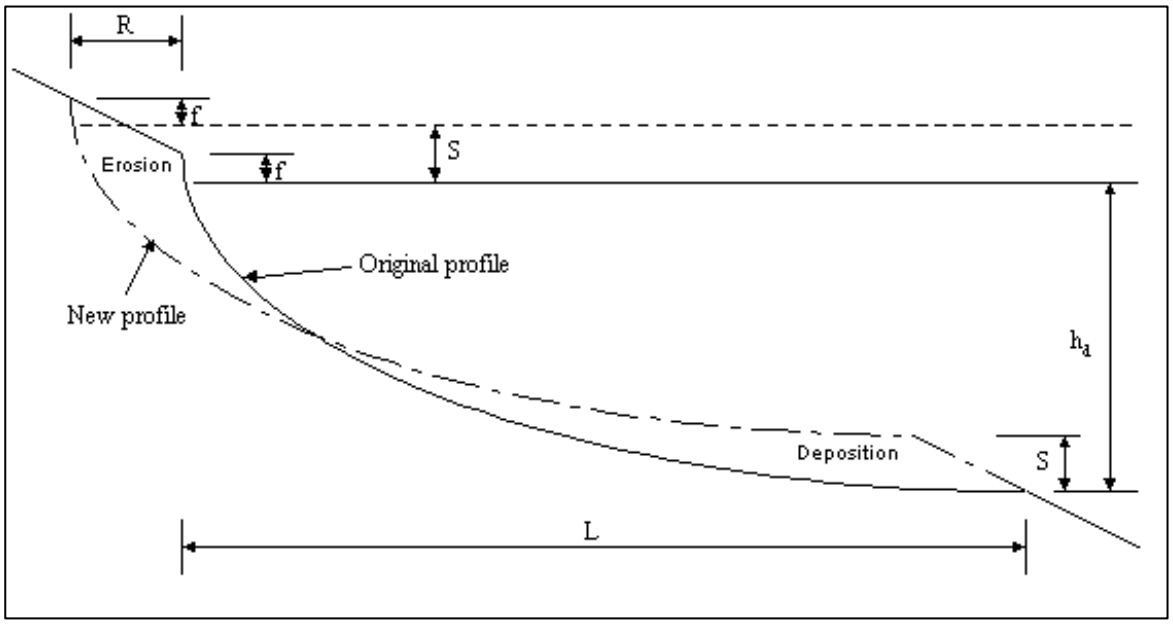


Figure D-8. Diagram of the Bruun Rule method for estimating the beach profile response to SLC.

– Improvements to Bruun Rule. Over the years various researchers have adapted and modified the method to suit different circumstances or improve its performance. Brunn (1988) described a method to incorporate along-shore sediment transport estimates with the two-dimensional Bruun Rule approach in order to create a quasi-three-dimensional approach. Everts (1985) and Dean (1991) developed methods that combine the Bruun approach of profile translation with the equilibrium beach profile concept to predict the response of a beach to SLC.

– Limitations to Bruun Rule. There are significant limitations inherent in the Bruun approach to profile recession due to SLR (Pilkey et al. 1993, Cooper and Pilkey 1994). First, the two-dimensional method is unable to account for regional or local along-shore transport variations that might be caused by changes in shoreline orientation (headlands, outcrops, pocket beaches, etc.) or near-shore sheltering or wave refraction. Therefore, a system that undergoes net sediment loss or gain will not be adequately addressed by the two-dimensional Bruun Rule itself. Also, the accuracy of the Bruun Rule method is highly sensitive to the offshore depth of closure that is established (Ranasinghe et al. 2012). Different methods of establishing the depth of closure may result in very different results, so the accuracy of the Bruun Rule is highly dependent on the particular approach taken to establish depth of closure. Other potential weaknesses of the Bruun Rule include the lack of ability to account for different sediment characteristics across the profile. Finally, the method is deterministic (at least in its original form) as opposed to probabilistic, so it does not account for uncertainty or determine risk.

– Conclusion. Despite the weaknesses of the Bruun Rule approach, it remains widely applied, primarily because it is relatively easy to use. As with any analytical or numerical method, care must be taken to apply it only for the purpose for which it is intended. In the context of CSDR studies or projects, the Bruun Rule should be applied alone only for an order-

of-magnitude estimate. It may also be applied in conjunction with other methods or models to produce a more accurate portrayal of SLC-induced changes to a system.

(b) Other Methods. Several other methods for quantifying SLR-induced profile recession have been published. Stive and de Vriend (1995) proposed an analytical model that considers the cross-shore beach and offshore profile in three zones. This method appears to be promising; however, no other subsequent literature was found indicating that this method was developed or tested further. Recently Ranasinghe et al. (2012) proposed another method that involves a Monte Carlo simulation of (100+ years worth of) storms, from which dune recession and recovery are estimated for each storm. The cumulative dune recession is the final product of this approach. This new method was tested at only one location against the Bruun Rule, but it showed promise. The important distinction with these more modern methods (and others like them not covered here) is that they are more comprehensive and process based and so include additional coastal processes such as waves and sediment transport.

(c) Sandy Beach Morphology. The coastal morphology of sandy beaches can be divided into three categories based on the vertical relationship between the berm, the dune, and the upland. These are the high upland, the low upland, and the low berm, illustrated in Figure D-9. The sensitivity of a coastal system to changing sea levels is distinctly different for these three morphology types. The fundamental principle for these beach types is that there is no inherent lack of sediment supply in either the along-shore or the cross-shore directions. This is important because unencumbered sediment transport simplifies the task of predicting the response to rising sea levels.

– High Upland. The high upland morphology type (Figure D-9) is essentially a bluff-backed beach system. If the upland sediments are unconsolidated and similar in nature to the existing beach sediments, the beach response to sea level rise is expected to be one of continued recession into the upland without a change in beach morphology type, i.e., essentially a Bruun Rule translation of the existing beach profile. The sediment eroded from the bluff is assumed to be a source of sediment that allows for profile translation landward and upward such that the relative depth of the beach profile is consistent even as sea levels rise. (For bluff-backed systems where the bluff and beach have not historically receded at the same rate, see the Soft Cliff section below.)

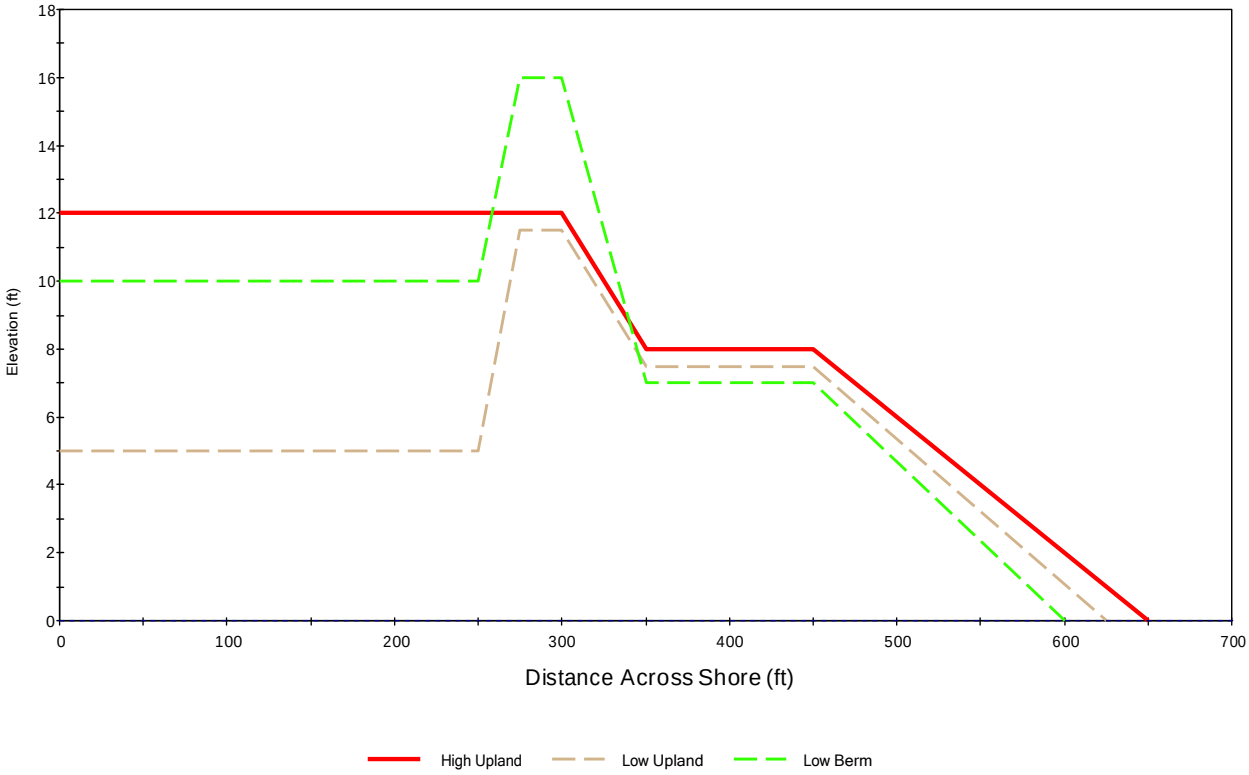


Figure D-9. General beach morphology types: high upland, low upland, and low berm.

– Low Berm. The low berm morphology type (Figure D-9) is similar to the high upland type where the berm is lower than the upland elevation, but the low berm includes a dune between the berm and the upland features. In response to sea level rise, this beach morphology type is expected to transition ultimately into a high upland type, preceded by dune scarping and a reduction of dune elevation above the upland elevation. Of course, this beach profile evolution assumes no human intervention in the form of beach nourishment or construction of coastal armor. Similar to the high upland case, the low berm type would experience dune erosion first and then, once the dune was completely eroded, the upland would begin to erode. Eroded sediment would be deposited on the lower portion of the beach profile as sea levels increase. This would result in a profile that is similar in the future, with the exception of a notable reduction in dune height, width, and volume. The loss of the dune may result in a significant increase in the magnitude and/or frequency of storm damage from erosion, flooding and wave attack, and environmental impacts such as loss of habitat. A reduction in dune volume beyond some minimum may represent a threshold for SLC impacts being felt, or it may signal a tipping point past which the system no longer functions satisfactorily.

– Low Upland. The low upland morphology type (Figure D-9) is characterized by a berm that is higher than the upland elevation. In most cases there will be a dune feature between the beach berm and the upland areas. In response to sea level rise, this morphology type will undergo dune scarping followed by a reduction of dune elevation above the berm elevation. Ultimately, in the absence of beach nourishment, the dune feature will be lost, and the highest elevation on the beach profile will be the berm elevation, which, through continued recession,

will roll over onto the upland. If this morphology type is associated with a barrier island (which it often is), complete barrier island roll-over is expected to occur. If the land-side lagoon is of sufficient depth, the barrier island could transition into a swash bar feature. For this morphology type, loss of the dune feature represents a significant threshold or tipping point. Major landscape changes that might involve barrier island breaching can be expected to occur rapidly, as the loss of littoral sediments to the lagoon represents a new and non-recoverable sediment sink to an already eroding coastal system. Figure D-10 depicts a low-upland barrier island that was over-washed and subsequently breached. SLC impacts on the landward side of a barrier island should also be considered because that infrastructure is often located at lower elevations on the landward side than on the ocean side.

Figure D-10. Example of low-upland barrier island overwash at Summer Haven, Florida. The left panel depicts initial overwash fans; the right panel depicts barrier island roll-over and breaching resulting from storm waves and surge.

(2) Other Morphology Types.

(a) Island/Reef-Fronted Beaches. This type of sandy beach system is described in more detail in Section D-5e(3). This type of system is typically sediment limited, unlike the above three types. Munoz-Perez et al. (1999) described a method to apply equilibrium beach profile concepts on a reef-fronted beach system.

(b) Protected Coasts. This category includes areas that have existing hard or soft structures that eliminate or mitigate erosion of the shoreline. The types of damage that might occur due to sea level rise include beach loss and scour in front of existing hard structures, overtopping and erosion damage to the structure, and increased rate of renourishment, to name a few. Predicting future conditions on protected coasts requires that the existing structures be adequately analyzed for failure thresholds and performance. It also requires that a prediction of future maintenance be made. In particular, locally constructed nourishment projects and their thresholds for future stability and performance must be assessed. In some locations, these projects may reach a point where maintenance overwhelms the ability of their owners to keep pace with SLC. This important threshold from maintenance to no-action may have a strong effect on future projections of storm damage. In the case of a beach backed by a seawall, Dean and Dalrymple (1991) outlined a method for predicting the profile shape given a change in waves and described the behavior of such a system with rising sea levels. Stive et al. (1991) discussed the specific issue of compensating for sea level rise with beach nourishment. Stive et al. noted that such an analysis is complicated by the long time scales (years) over which deeper portions of a beach profile adjust to nourishment and sea level rise. They noted, though, that the periodic nature of nourishment creates a flexibility that is needed in the absence of detailed, highly accurate predictions of beach fill behavior in the presence of sea level rise.

(c) Soft-Rock Cliffs. The behavior of erodible cliffs is fairly well described in the literature. A few examples are Stive and de Vriend (1995), who proposed an analytical model of cliff and bluff profile evolution, and Bray and Hooke (1997), who examined the behavior of soft cliff retreat with SLR.

E-6. Infrastructure Vulnerability to SLC.

a. Principles. Man-made infrastructure may have vulnerabilities to SLC that are dependent on or independent of the natural characteristics of a coastal landscape.

b. Issues.

(1) How vulnerable is existing infrastructure to SLC?

(2) What are the critical thresholds of coastal evolution past which infrastructure is unacceptably impacted?

(3) Is the infrastructure adaptable to become more resilient to SLC?

(4) If infrastructure is damaged or fails, what might be the impacts to the site or project?

c. General Discussion. The third component of how a coastal site will respond to SLC depends on the characteristics of the existing man-made infrastructure. In some locations, the above assessments may determine that there could be significant SLC-induced changes to coastal forcing and that an increase in shoreline recession is expected. However, if the existing coastal infrastructure is robust or sited beyond the reach of these forces, then there may be no, or limited, impacts from SLC. Despite SLC, storm damage reduction over a certain period of time may be feasible; however, elevated sea levels may impact other systems or resources that the project area

relies on and that might not be protected by a CSDR project. For instance, the infrastructure in the study area may rely on gravity storm drainage. As sea level rises, the potential for reduced drainage and subsequent flooding increases. Any CSDR project formulated by this study would not decrease this potential. Other systems and resources that the study area may depend on, and that would not necessarily benefit from a CSDR project, include electrical power and sanitary sewer systems. There may be a threshold past which the infrastructure in question is being greatly impacted by forces that are not mitigated by the CSDR project, thus reducing or eliminating project benefits.

d. Frequency Considerations. Frequency of damage is an important metric on most coastal defense systems. USACE projects are not generally formulated to prevent *all* future damage, but they are designed to maximize net benefits (those benefits provided in excess of construction and maintenance costs) while protecting the environment. Future project behavior has generally been determined through extrapolation of historical trends of erosion, etc. The SLC scenarios outlined in this ETL are nonlinearly increasing in most locations. The nonstationarity of SLC has the potential to change the frequency of storm damage and thus the design loading on the project. In fact, within some coastal settings, changing sea levels have the potential to affect multiple damage-driving forces simultaneously, which can create a cumulative effect in which a relatively large change in damage frequency results from a small change in sea level.

e. Vulnerability. The vulnerability of existing shore protection features needs to be assessed. For infrastructure or existing engineered features that lie in or very near the water, any increase in the coastal forcing may have an immediate effect on the stability or performance of that feature. Hard coastal structures such as a groins or revetments are designed for a maximum design wave height, from which the size of stone, crest height, etc. are established. Such a structure has a specific threshold wave height at which the structure stability begins to be affected—where its design criteria are being exceeded. If the recommended design wave is one that recurs on a 25-year interval, sea level rise may create a condition in which the waters surrounding the project are deeper, resulting in the potential for exceedance of the design wave. Similarly, larger waves and elevated water levels may result in an inadequate crest height relative to water depth, so that a hard structure may no longer perform as intended.

(1) Variables of Interest. The variables to be considered for vertical construction are highly dependent on the type and location of existing structures. Variables may include the first floor elevation, foundation type and depth, construction material, building code design thresholds (pile depth, etc.), location and elevation of critical components (HVAC, etc.), to name just a few. Estimation of the societal and economic implications of SLC depends on the accurate prediction of the interaction between the ocean, the coastal morphology, and the coastal infrastructure. The resilience of coastal infrastructure may be enhanced (redesign, flood proofing, relocation, etc.), which in some cases may be the only practical response to address SLC impacts in certain coastal regions.

(2) Detailed Analysis. A detailed analysis of coastal damage in the presence of SLC needs to merge the predicted shoreline response with the location and attributes of vulnerable infrastructure. Such an approach should rigorously account for risk and uncertainty, which generally requires a statistical and probabilistic approach as opposed to a deterministic methodology.

f. Methods

(1) Coastal Systems Portfolio Initiative. One method that may be employed to make a preliminary Tier 1 evaluation of infrastructure is based on critical resources identified by the USACE Coastal Systems Portfolio Initiative (CSPI). CSPI describes the resource risk in a project area relative to the density of the resource, the population density that the resource serves, or, in the case of environment/habitat and recreation, the value placed on the resource. See http://projects.rsm.usace.army.mil/CSPI for more information. The CSDR example problem in Appendix G illustrates this approach in detail.

(2) Engineering and Economic Numerical Models. The numerical modeling approach is more time consuming and costly but reduces the uncertainty and residual risk of the vulnerability analysis. CSDR studies employ engineering and planning models that are capable of modeling future conditions in the presence of SLC.

– Beach-*fx* is an event-driven life-cycle model that estimates damages and associated costs over a period of analysis based on storm characteristics (waves, surge), tidal cycle, tidal phase, beach morphology, and many other factors. Data on historic storms; beach survey profiles; and private, commercial, and public infrastructure within the project area are used as input to Beach-*fx*. The model is then used to estimate future project hurricane and storm damages. The model links the predictive capability of coastal evolution modeling with project area infrastructure information, structure and content damage functions, and economic valuations to estimate the costs and total damages under various without- and with-project scenarios. Beach-*fx* fully incorporates risk and uncertainty and is used to simulate future hurricane and storm damages at existing and future years and to compute accumulated present-worth damages and costs. Storm damage is defined as the damage incurred by infrastructure as a direct result of waves, erosion, and inundation caused by storms that impact the coast.

– The plan formulation process requires that models such as Beach-*fx* be used to evaluate without-project future conditions since these are used as the basis of comparison for evaluating project alternatives. These without-project simulations give a very detailed account of potential future infrastructure damage. Such models can be used to evaluate the relative impacts of different SLC scenarios and to establish thresholds and tipping points for different features and infrastructure.

E-7. Human Response to SLC Impacts.

a. Principles. SLC will, at some water level threshold, cause a human response (retreat, nourishment, armoring, etc.). SLC has the potential to affect the behavior of individuals; businesses; and local, state, and Federal governments. Some human responses to SLC may have a strong influence on the future behavior of the beach system. Anthropogenic response must therefore be accounted for when determining future existing project or future without-project conditions.

b. Issues.

(1) What are thresholds and tipping points for the human responses to SLC?

(2) What are the expected human responses?

(3) What are the economic thresholds past which responses are not sustainable?

(4) Will any human responses influence future morphological evolution?

c. Discussion. Determining whether SLC-induced physical change to the natural and built environment is acceptable to human stakeholders is critical to establishing what the human response will be and when it will occur. Depending on the specific site circumstances, it may be valuable to evaluate the future without-project condition assuming no human intervention. This establishes a limiting case and gives some context to the effectiveness of possible human responses to SLC and coastal impacts. Common types of human intervention or response to storm damage and erosion fall into two categories: nonstructural, such as retreat and land buyout/abandonment/condemnation, and structural, such as armoring, dune/beach nourishment, breakwaters, and groins.

d. Methods. Methods for determining the human response to SLC include analysis of site-specific historical human responses to threatened coastal infrastructure, economic sustainability analysis of future response costs in the presence of SLC (economic thresholds), and review of relevant existing regulations and laws that might limit future responses (e.g., prohibition of hard armoring). Human response must be factored in to future without- and with-project planning forecasts.

D-8. Project Response to SLC.

a. Principles. On existing CSDR projects, SLC may impact both the stability and the performance of engineered features. SLC might reduce the life of the feature or increase its maintenance requirement. An engineered project may result in a site being more or less sensitive to SLC than that site with no project. For these reasons, the benefit–cost ratio (or other important planning parameters) for a given alternative might be higher or lower for different SLC scenarios. The nonstationary nature of SLC may result in the need to transition to different alternatives at different threshold future water levels. An optimum project is adaptable, resilient, and cost effective and has a plan for adaptation.

b. Issues.

(1) How will SLC-induced changes to coastal forces, morphological response, and human response change the loading or behavior of the engineered shore protection measures?

(2) What are future mean relative sea level or SLC rate tipping points past which project stability and/or performance will be adversely affected?

(3) How can engineering measures be adapted for changing water levels and through what range of water levels?

(4) What is the optimal adaptation strategy for the project alternative?

(5) Does the selected plan include thresholds where the existing project alternative ceases to be optimal and another becomes more beneficial?

c. Methods. For the purpose of this discussion, measures, used singularly or in combination with others, create alternatives, and varying scales of each create additional alternatives. An alternative may be implementable for an entire reach or for only a portion of a reach. The combination of management measures results in alternatives that merit further analysis during plan formulation. Individual measures may be impacted by SLC through different mechanisms, and some measures are more or less vulnerable or resilient to SLC. Due to the nonstationarity of SLC, a project alternative may have an adaptation strategy that calls for a transition from one measure to another at one or more critical threshold water levels—this is called an alternative pathway.

(1) Optimal Alternative. The objective of this final step in the planning process is to determine the optimal project alternative as defined by the Corps' Plan Formulation process. Project alternatives have traditionally employed a single set of measures that are intended to provide the design level of CSDR benefits throughout the entire project life cycle. This approach assumes that the coastal forcing at the site will be consistent throughout the project life—that coastal processes are stationary through time. As discussed earlier, this assumption can no longer be made, since SLC is a nonstationary coastal force that will act directly on the coastal landscape and can affect other coastal forces, effectively making them nonstationary as well.

(2) Alternatives Analysis. The final alternative analysis should be able to demonstrate the range of water levels across which a single management measure is optimal, and it should describe the threshold points at which a new set of measures should be implemented. As described in the main text, alternative strategies fall into three categories: anticipatory, adaptive, and reactive. An example of an anticipatory measure for a CSDR project is to design a revetment or seawall using a maximum design still water level that is equal to the sea level associated with the high SLC scenario at year 50; this design would require no further SLC-induced action as long as actual sea level rise rates do not exceed the high scenario. An example of an adaptive strategy for a CSDR project is to design a beach nourishment alternative that will be adaptively renourished in the future to keep pace with increased erosion associated with rising sea levels. On a project that received regular maintenance like a nourishment project, there is no need to place more sand before SLC is observed, as might be the case with a hard structure that is less easily adapted later. A reactive strategy for a CSDR project might be to increase the crest elevation of a structure such as the one in the anticipatory example but not until the SLC impacts begin to cause an increase in flooding behind the structure. This strategy will likely save costs compared to the anticipatory measure, but the reactive approach will create a higher risk for the protected infrastructure. In practice, the final plan for addressing SLC in project design and O&M may contain elements of all three of the above approaches.

(3) Thresholds. The beginning threshold may not be immediate but at some time in the future when sea level reaches a point that makes the measure acceptable for environmental, economic, social, or other reasons. The ending threshold indicates a sea level height where the alternative no longer functions or can no longer be adapted to provide storm damage reduction. Between these thresholds, the alternative can be adapted as sea level increases. For instance, beach nourishment can likely be implemented immediately in the project area, at a relative sea level equal to zero. As sea level rises, the alternative can be adapted by adding more sand to maintain the desired beach height and width (an adaptive strategy). Eventually, sand sources may be depleted or become too costly, or the necessary beach dimensions may not be constructible for various reasons. The relative sea level at this point indicates the alternative's ending threshold. Flood proofing of structures can be considered adaptive if flood proofing is applied initially to only the most vulnerable structures and then incrementally to others as sea level rises. Or it could be anticipatory if all structures in a project area are flood proofed at a relative sea level equal to zero.

(4) Temporal Considerations. Note that adaptability is dependent on relative sea level and is independent of specific SLC scenarios. The different SLC scenarios only affect the future point in time when the relative sea level is reached that corresponds to an alternative's ending threshold. These thresholds could be developed with model output, with qualitative methods, or with a combination of both. Thresholds are based on experience from similar project areas and on environmental, social, and economic factors in the study area.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX E

Flood Damage Reduction Projects

E-1. General Approach and Background.

a. Congress has authorized Federal participation in the cost of reducing the risk of damaging floods in the United States and its territories and possessions. USACE also participates in international reimbursable and non-reimbursable flood damage risk reduction (FDR) projects. Whether domestic or internationa, these projects are designed, operated, and maintained either to reduce the flooding risk in specified areas to particular acceptable levels or to provide risk reduction from specified design events.

b. Current USACE guidance dictates that the direct and indirect physical effects of projected future relative sea level change (SLC) must be accounted for across USACE project life cycles. SLC impacts must be evaluated in all phases of project life. For existing projects, SLC has the possibility to change the loading on existing features and the behavior of FDR systems. For projects under study, SLC effects need to be considered for both the without-project case and the alternatives being proposed. The guidance provided in this appendix is intended to help USACE project delivery teams (PDTs) incorporate consideration of SLC effects on FDR studies and projects.

E-2. Performance Function Sensitivity and Metrics.

a. FDR projects are designed and maintained to provide risk reduction from floods of up to a certain magnitude, while simultaneously providing resilience (i.e., survivability or sustainability) from floods of some larger magnitude. Both of these functions are sensitive to the impacts of sea level rise and must be considered in the design and management of FDR projects. Risk reduction performance is typically expressed in terms of the return period or exceedance probability of the residual flood risk to the project area. For example, an interior drainage project may provide risk reduction from a rain event with an intensity that has a 10% chance of occurrence in a given year (commonly but less preferably referred to as a ten-year storm). If a rain event with an intensity greater than this design level occurs, the project cannot evacuate all rainwater without impacts to the project area; therefore, the residual flood risk to the project area is 10% per year.

b. As an example of the effect of SLC on FDR project performance, consider an interior drainage project that uses pumps to drain rainwater to a river near to the ocean. If the water level in the river rises because of the increased sea level at its mouth, the opposing head at the pump is increased, the project can no longer evacuate the rainfall from the design event, and the level of residual risk to the project area is increased (the opposite effect could occur in the case of sea level fall). In this case the project may require modification, such as enlargement of drainage canals or more powerful pumps, to maintain or regain the design level of residual risk.

c. In contrast to performance, resilience concerns the ability of a project element to survive a flood, again expressed as an event with a given probability of occurrence. Using the same example as above, if sea level rise at the river mouth causes the river's flowline to increase at the project area, the probability of an extremely high river flood may increase. The width of the river at high flow may also be increased, allowing a greater fetch for larger and longer-period wind-driven waves. The project may therefore be at greater risk of catastrophic failure due to an extreme flood overtopping and destroying the pump station. To mitigate this decreased project resilience, the pump station may require greater fronting protection and/or structural superiority relative to surrounding project elements such as levees.

d. One important consideration affecting the future performance and resilience of any FDR project that may be impacted by sea level rise, which by definition is located near the coastline, is the possibility of the project's primary purpose shifting from FDR to coastal storm damage reduction (CSDR) at some point during its operating life. As sea levels rise, coastal flooding impacts may extend farther inland, causing the governing risk criterion for a given project to shift from river flooding to coastal storm surge. Coastal surges are generally very large, infrequent, and brief, so the primary design considerations for coastal levee systems are often (a) sufficient height to provide risk reduction up to a particular surge and (b) hardened elements such as specialized turf to provide resilience up to a design overtopping rate if the design surge is exceeded. Riverine levees, in contrast, are designed to resist the extended high water levels associated with river floods and are not typically designed to withstand overtopping. Re-purposing of project elements, as when a reservoir's primary purpose changes from flood control to recreation, is not a new concept for USACE, but for planners and maintainers of FDR projects in areas impacted by SLC, anticipating re-purposing of the project to CSDR at some point in the future is an important part of design and management.

e. Table E-1 outlines the principles and issues covered in this guidance. This is not an exhaustive list of potential SLC impacts on flood risk, but it is a starting point for consideration of possible impacts to a coastal FDR project or system. Some key questions and concepts:

(1) Will SLC affect hydrologic boundary conditions governing the performance and operation of FDR projects?

(2) How could measures taken at an FDR project to adapt to SLC impact coastal storm damage reduction (CSDR), ecosystem restoration, navigation, or other projects nearby?

(3) At what temporal scale or magnitude of change in these processes will rainfall runoff or fluvial geomorphological processes begin to impact basic FDR design considerations?

(4) What regional differences exist in the effects that SLC will have on FDR projects, and can they be addressed using the same methods?

Table E-1. Incorporating sea level change on FDR projects: principles, issues, and methods.

Category	Principles	Issues	Methods
Coastal Forces and Processes	As sea levels change, river discharges and flowlines will be impacted due to backwater effects. Altered sea levels will affect design still water levels in coastal water bodies used as receiving areas by interior drainage projects. Altered sea levels will affect water table depths and groundwater gradients. Altered sea levels will affect the salinity of coastal aquifers.	How will altered stage–discharge relationships change the frequency of floods and therefore the residual risk delivered by the FDR system? How will drainage efficiency of interior drainage projects be impacted by water level change in their receiving areas? How will altered groundwater tables affect interior drainage and therefore the risk of rainfall flooding? How will salinity intrusion to groundwater impact ecosystem services associated with the FDR system, such as batture forests that protect river levees from wave run-up?	Evaluate effects of each of three future SLC scenarios on river flowline. Design systems that are robust and/or adaptable to flowline changes. Evaluate effects of each of three future SLC scenarios on interior drainage (gravity or pump) efficiency. Design systems that are robust and/or adaptable to water level changes in receiving areas. Evaluate effects of each of three future SLC scenarios on interior drainage to groundwater. Design systems that are robust and/or adaptable to groundwater level changes. Manage the water table to mitigate rapid subsidence due to water table fluctuations. Consider altered ecosystem services when evaluating future flood risk under SLC scenarios.
Morphological Response	As sea levels change, hydraulic gradients will be impacted, affecting sediment transport in rivers. As local water tables respond to SLC, subsidence rates will vary in space and time.	How will altered sediment transport affect flowlines and therefore the risk reduction delivered by the FDR system? How will locally variable subsidence impact catchment rainfall runoff processes and therefore flooding depth?	Evaluate effects of each of three future SLC scenarios on sediment transport capacity. Design systems that are robust and/or adaptable to flowline changes. Consider phased nonstructural alternatives (such as constructed wetlands) for areas at risk of rapid subsidence. Design systems with room for additional subsurface drainage infrastructure for areas at risk of rapid subsidence.

Infrastructure Vulnerability	Raising flood defenses transfers risk to other areas. It may also impact drainage, ecosystem services, or other elements of flood risk. As sea levels change, the extent of coastal storm impacts will move upriver or downriver.	How will proposed changes to infrastructure affect nearby projects under varying sea level scenarios? Coastal storm surges will impact areas farther upriver as sea levels rise. Coastal surges may cause riverbank failures and/or levee slides if those elements were designed only for slowly rising and falling river floods. FDR projects may transition from riverine/estuarine/rainfall-governed to coastal storm-governed as SLC impacts move upland.	Assess the 100-year, high-curve footprint for unintended consequences, plus assess outside the footprint based on expert judgment. Surges travel farthest upriver when river stages are lowest. Assume a low river condition when evaluating the upstream extent of storm surge impact on riverine flood risk reduction infrastructure under future sea level conditions. Elements with the potential to be impacted by a moving crossover point must be designed to adapt to this eventuality. The 100-year, high-rate SLC curve should be used to outline areas that could become governed by coastal storm conditions during that time.
Performance Vulnerability	In estuaries, bays, and coastal rivers, floods at the same location may be caused by coastal or riverine forcings, or a combination of the two.	How will SLC affect the performance of co-located project elements, which must provide risk reduction from both coastal and riverine threats?	Collaborate with coastal storm damage reduction teams to ensure an integrated response to sea level impacts to co-located project elements.
Human and Biological Response	Increased flood risk due to SLC will force impacted populations to respond. The future without-project condition, given SLC, cannot be assumed to be the same as today. Reducing flood risk to a particular area may induce development, putting a larger population at risk than previously existed.	What thresholds and tipping points exist for future human responses to increasing flood risk? What options exist for adaptation under the without-project condition? How will these impact flood risk and future project viability? How will populations change in response to the construction of flood risk infrastructure? What effects will this have on overall future flood risk under SLC?	Analyze historical responses and legal/ regulatory options open to residents. If mass depopulation is possible, assess risk to future property tax base and resulting viability of local cost sharing of future projects, and impacts to future flood risk. Research prior experiences with demographic shifts to assess possible population changes. Proactively acquire real estate needed for future SLC adaptation if it is at risk of development. Propose nonstructural alternatives that discourage maladaptations while also providing options for future adaptation needs.

Project Feature Response	FDR projects should be adaptable to future sea level conditions, but different project elements are adaptable to varying degrees.	How does the existing or proposed FDR project lend itself to adaptation?	Utilize a more proactive strategy for less adaptable elements such as gated structures and floodwalls and a more adaptive strategy for levees and other more modifiable elements. Consider how different structural elements and alternatives will subside at varying rates. Construct a portfolio of structural and nonstructural solutions that is adaptable to the high-rate scenario at a 100-year time horizon. Ensure that all project elements use a consistent project datum so that adaptation options and risk balancing across elements is appropriate.
System Response	Increased precipitation, storminess, groundwater and surface water flow, and interaction with ecosystems and other projects are all areas of potential cumulative effects.	Nonstationary hydroclimatology is highly uncertain. How might feedback effects with sedimentation, ecohydrology, infrastructure changes, or other climate changes affect flood risk?	Design systems that are adaptable and/or robust to uncertain hydraulic, hydroclimatological, ecohydrological, and societal futures.

E-3. Coastal Forces. In this guidance, FDR projects are those that provide risk reduction from flooding induced by riverine, estuarine, or rainfall flooding, or combinations of these. In contrast, coastal storm damage reduction projects are designed to provide risk reduction from direct coastal forcings such as storm surges from oceans or lakes; direct hazards from coastal water bodies are discussed in Appendix D. Figure E-1 shows some of the direct and indirect coastal forcings on FDR systems through which SLC manifests itself as altered flood risk; these forcings should be considered when assessing the effects of SLC on an FDR project.

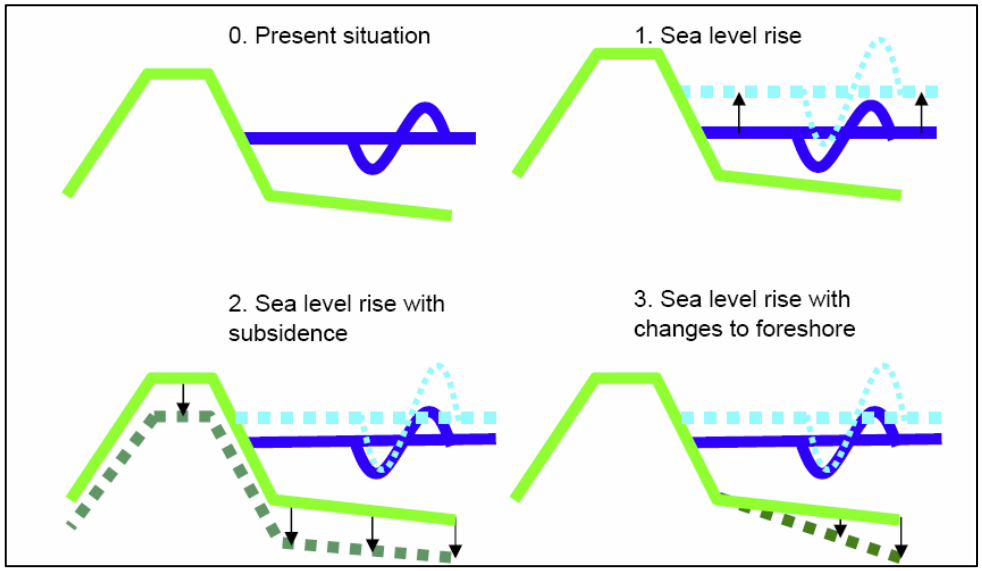


Figure E-1. Potential load cases on FDR elements under sea level rise. Relative sea level change can alter forcings on FDR infrastructure in various ways, depending on the interactions of subsidence and eustatic changes.

a. Backwater Impact on River Flowline. As sea levels change, stages in rivers emptying into the sea will also change, assuming river discharge remains unchanged (Figure E-2). This change in the stage–discharge relationship alters the risk reduction performance of the FDR system, as the same stage will occur with increasing or decreasing frequency (Nicholls et al. 2011, Huang et al. 2004). Precise estimates of future flowlines and return periods of floods require hydraulic modeling under multiple future sea level scenarios. However, the sensitivity of an FDR project to future river flowline changes can be assessed quickly by perturbing the stage associated with given discharges. The magnitude of backwater effects decreases with distance upstream, so a conservative (over)estimate for screening purposes could assume that a given magnitude of SLC will alter the river flowline by the same amount up to the limit of tidal influence. When conducting hydraulic modeling to determine the backwater effect more precisely, note that SLC at the mouth of the river is the driver of the backwater effect, but each river reach will have its own rate of SLC that depends on its particular rate of subsidence or uplift. Ultimately, FDR projects should be adaptable and/or resilient to a range of future scenarios, including SLC scenarios.

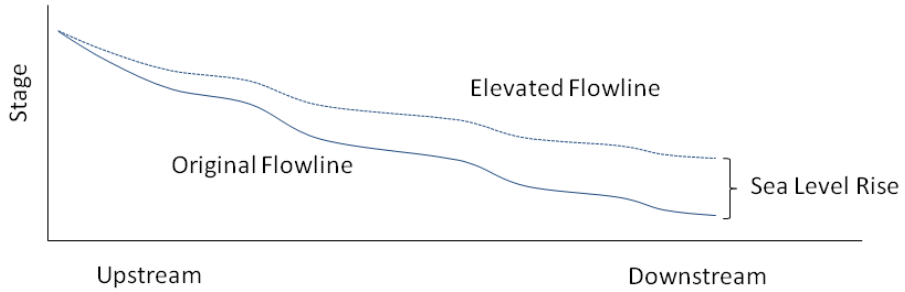


Figure E-2. Backwater effect. As sea levels rise, the downstream boundary stage of a coastal river also rises. This change propagates upstream, causing higher river stages for the same discharge and increasing the frequency of flood stages.

b. Altered Interior Drainage Performance due to SLC in Receiving Basins.

(1) Many FDR projects reduce the risk from rainfall flooding by discharging either via gravity drainage or via pumping to a receiving area, which may be a river, lake, estuary, bay, or similar water body. If these bodies are connected to the sea or influenced by mean sea level changes, they may be susceptible to changing water levels associated with SLC, with consequences for the performance of the drainage system (Titus et al. 1987). Gravity drainage systems will function less efficiently, or not at all, if sea level rise causes the water level in their receiving basins or downstream hydrologic boundaries to increase. Pumped drainage systems will lose efficiency and possibly not perform to design capacity if their pump outfalls are impacted by rising water levels and become submerged. Assessment of the impact of SLC on gravity drainage systems requires hydraulic modeling of the drainage canals, whereas lost pump efficiency can be determined from pump performance curves in combination with hydraulic modeling.

(2) Pumped drainage systems that discharge into the air at heights above the future receiving basin level provide one option for a system that is robust to future sea level scenarios, but at considerable cost. Pumped drainage systems may also be designed to be adaptable to future SLC by making room for additional pump capacity, should it be needed. Many existing designs may tolerate increases in water levels induced by sea level rise, with a loss in mechanical efficiency that may be managed by increased operation and maintenance costs. Gravity drainage systems, in contrast, may require expensive expansion to improve drainage capacity, though they may be cheaper to operate. In some cases, gravity systems may have to be augmented with pumping to overcome the loss of ability to manage water using gravity drainage alone.

c. Altered Efficiency of Drainage to Groundwater. In many areas, drainage of surface waters to the vadose and saturated zones comprises a significant portion of rainfall runoff and therefore reduction of risk from stormwater flooding. In coastal areas, SLC has the potential to change the depth to groundwater and affect the amount of runoff needed to cause saturation-excess overland flow (Rotzoll and Fletcher 2012, Titus et al. 1987). Infiltration capacity, and therefore infiltration-excess overland flow, may be affected in unexpected ways due to ecohydrological feedbacks with plant communities (Ludwig et al. 2005). For example, a shallower groundwater table as a result of sea level rise could encourage plant growth, decreasing soil bulk density and increasing macropores, with the result that infiltration capacity is increased

and rainfall runoff is decreased. Conversely, shallower groundwater may drown the root zone and cause the opposite result. Groundwater levels are also impacted by other climatic and ecological factors, including human activity, so predicting their future levels under SLC may be difficult. Groundwater models may be employed to quantify the impacts of altered water tables on drainage, but the best course of action may be to ensure that interior drainage systems are robust and adaptable to future groundwater levels. Loss of infiltration capacity and groundwater storage has an impact on rainfall runoff processes that is similar to that of an increase in urbanization, which creates more impervious surfaces resulting in higher runoff volumes and peak discharges.

d. Altered Salinity of Coastal Aquifers. Coastal aquifers may become more or less saline due to SLC (Taniguchi et al. 2002), with ecohydrological implications for flood risk. Saltwater intrusion to groundwater may impact the health of plants (and soil-dwelling animals) that maintain infiltration capacity as mentioned above (Ross et al. 1994). Plants may also shield levees from wave run-up, reduce the force of vessel impact, or improve resilience to overtopping. These changes may be problematic to predict, but alteration of flood-reducing ecosystem services due to saltwater intrusion should at least be considered as a part of potential SLC impacts to FDR systems.

E-4. Morphological Response. Changing sea level may induce land surface or river channel changes, with impacts on flood risk. These should be anticipated to the maximum extent practicable.

a. River Channel Geometry Change. As sea levels change, the slope of a river's hydraulic grade line changes in response to downstream areas impacted by sea level rise or fall (Figure E-3). This may affect sediment transport and alter sedimentation patterns (Parker et al. 2004, Muto and Swenson 2005). These changes may then affect channel capacity, with impacts on the stage–discharge relationship and ultimately on the frequency of flooding stages (Kondolf et al. 2002, Plate 2002). The impacts of these potential changes may be assessed through analyses ranging from gross, simplified techniques (such as stream power) and simple geomorphic relationships (such as Lane's balance), to more complex and difficult analyses, to three-dimensional hydraulic modeling. The results of these analyses, regardless of level of detail, may be highly uncertain. Sedimentation changes may be manageable with dredging, the potential quantities and costs of which may be difficult to estimate accurately. A quick and rough proxy may be simply moving the upriver line of present maintenance dredging (if any) farther upriver based on the anticipated vertical relative sea level change and the average water surface slope.

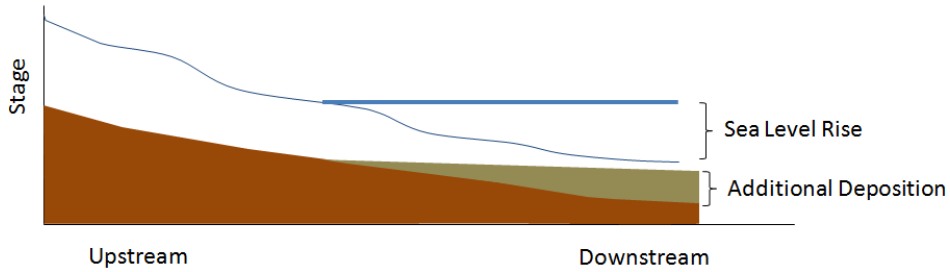


Figure E-3. River channel geometry change. SLC can alter the hydraulic slope and bottom shear stress, altering sediment transport and causing river channels to gain or lose cross section. The resulting change in the stage–discharge relationship alters the frequency of flood stages.

b. Land Surface Changes. Spatial and temporal patterns of land subsidence are affected by groundwater depth (Chai et al. 2004, Nieuwenhuis and Schokking 1997), and changing sea levels affect the depth to groundwater (Rotzoll and Fletcher 2012). Subsidence is thus both affected by and a component of relative sea level rise. Feedback effects like these can be difficult to predict, so adaptive strategies may be more effective than anticipatory ones. Phased nonstructural solutions such as structure and road elevation, conversion of developed area to wetland, and financial instruments may be appropriate for low-lying, poorly drained areas experiencing rapid subsidence. When a structural alternative is chosen, it should be designed to allow for expansion of the drainage capacity when water tables become shallower. Regional deep subsidence is impacted more through underlying geologic conditions and is expressed in a more uniform rate over a large area. This rate may be in addition to locally higher rates of shallow subsidence caused by water table changes that induce a chain of physical and chemical processes resulting in rapid compaction of the soil layer.

E-5. Infrastructure Vulnerability. SLC poses several specific issues for the vulnerability of FDR systems. Those listed below are a few of the most critical, and they should be considered in any assessment of coastal FDR systems.

a. Risk Transfer. When levees and floodwalls are raised, dams strengthened, diversion structures enlarged, or other similar improvements made, whether in response to SLC or for other reasons, flood risk is transferred from the area protected by the improved section to nearby areas with lower or weaker defenses (Yen 1995, Plate 2002). This is not to mean that flooding is worsened in all nearby areas for all events; each event is unique, and the effect of an improvement in one area on flood impact in another is a complex question, depending on the magnitude, duration, and nature of the particular flood event. Furthermore, the increased risk may be negligible or undetectable, particularly if distributed over a wide area. Nevertheless, proposed changes to FDR systems should be analyzed to assess the potential for unintended negative consequences in other areas. The 100-year, high-rate sea level rise curve should be used to establish the minimum area for an analysis to assess the potential for unintended negative consequences, though this area may be extended based on expert judgment. Risk transfer analysis requires an estimate of the volume of overtopping into the protected area that would have occurred (but will now be prevented by the improvement in question), which must now be retained in the flood channel and conveyed safely away. Computing this volume requires an assumption of the hydrograph shape corresponding to the stage or discharge associated with the return period under analysis. This shape may be generated through routing a unit hydrograph associated with a rainfall event or by scaling a historical, typical, or average flood hydrograph, or other technically acceptable methods (see, e.g., EM 1110-2-1417). Hydrograph shape parameters may also be assumed to have their own return periods and joint probabilities associated with stage or discharge. Each of these methods involves significant uncertainty, and this uncertainty must be carried through to the ultimate result when discussing the effects of the proposed FDR improvement in response to SLC.

b. Altered Extent of Coastal Forcings. In many areas, coastal storm surges can travel great distances up rivers and estuaries (Westerink et al. 2008), and the same reach of levee or floodwall provides risk reduction from both coastal surges and river floods. Although coastal storm surges are not the main focus of this appendix, assessment of the vulnerability of FDR

projects under SLC must consider the fact that coastal surges will extend farther upriver under sea level rise. (In areas experiencing sea level fall, this may not be a concern, at least until sea levels begin to rise again due to acceleration in the eustatic rate.) Coastal surges represent a distinct type of risk to a levee system compared to riverine floods. For example, the rapid rise and fall of a storm surge can cause bank failures and levee slides if the geotechnical design was based only on a slowly rising and falling river flood. Surges propagate farthest upriver when river discharge is lowest, so estimates of the extent of future coastal surges under sea level rise should employ the three SLC curves and a low river stage that is appropriate for the season of expected storm surge, if any. Simulation of surge propagation will most likely require numerical models such as ADCIRC.

c. Governing Condition Change from Riverine Flood to Coastal Surge. Where co-located levees and floodwalls provide risk reduction from both riverine floods and coastal storm surges, a "crossover point" defines the boundary between the riverine and the coastal governing conditions. Under SLC, this crossover point will move over time (Figures E-4 and E-5), so FDR systems that may switch from riverine governed to coastal governed in the future must be designed to be robust and/or adaptable to this eventuality. The three SLC curves should be used in combination with storm surge modeling to estimate the possible future locations of this crossover point. Collaboration between river and coastal engineers and scientists is essential for successful adaptation planning on this and related issues.

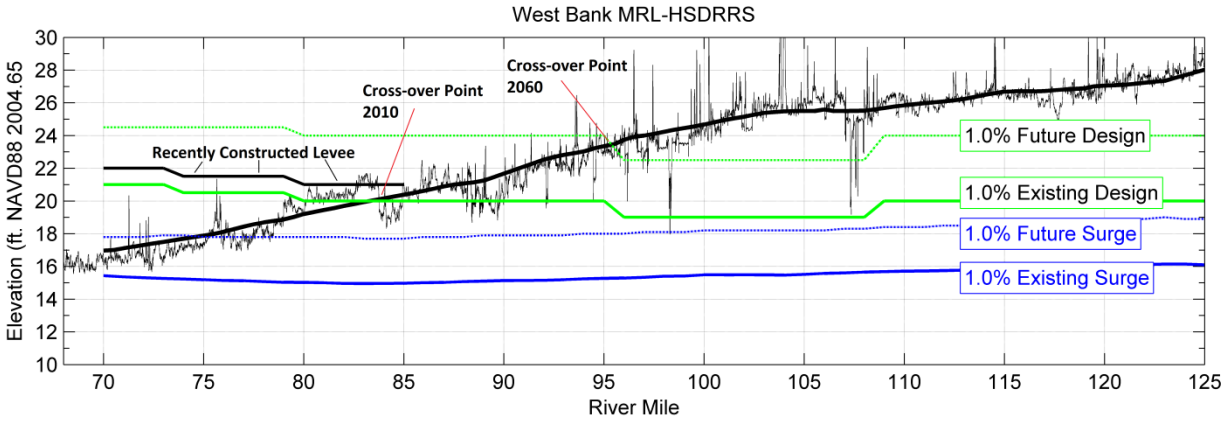


Figure E-4. Example of a moving crossover point for the west (right descending) bank of the Mississippi River near New Orleans. This example assumes a relative sea level rise of 1ft (0.3m) over 50 years, which, when added into storm surge models, would cause storm surges to increase in height and the coastal storm governing condition to move upstream. A full explanation of the methods of this example can be found in USACE (2011b).

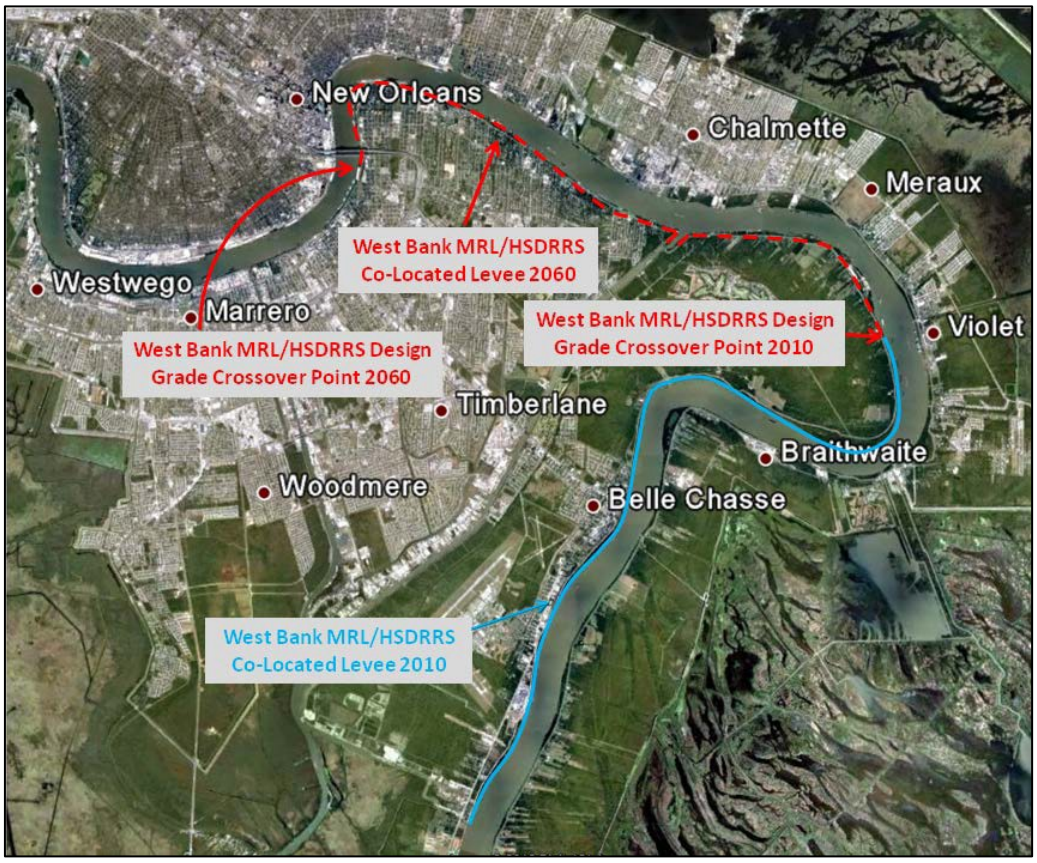


Figure E-5. Location of present and future crossover points between the riverine-governed and coastal-surge-governed flood risk reduction infrastructure near New Orleans (assuming 1ft (0.3m) of relative sea level rise). This figure is based on the results shown in Figure E-4.

d. Tipping Points and Thresholds. The vulnerability of an FDR project to SLC should not be expected to change linearly over time or even with respect to sea level; instead, tipping points and thresholds define key points in space and time where flood risk changes in response to SLC. Thresholds are points in time or key water stages or discharges when SLC begins to impact the performance of the FDR system in question. Tipping points are critical points when stability and/or performance begin to decline rapidly. Figure E-6 illustrates the distinction between the two. In this figure the surface represents possible states of a system in three-dimensional space; for example, it could represent an FDR system, where the x axis represents sea level, the y axis represents rainfall intensity, and the z axis represents the level of risk reduction delivered by the FDR project. In this example, as rainfall intensity increases and the system moves from point A to B, initially there is little change in risk to the project area. As the sea level rises and the system moves from A to C, a threshold is crossed and the level of risk reduction declines gradually. However, given the higher rainfall intensities of point B, as sea level rises and the system moves from point B toward point D, a tipping point is crossed where risk reduction drops dramatically in a short time. As Figure E-6 shows, thresholds and tipping points are not simply points in time or trigger water levels; they depend on other variables and on the system's internal state. Any

examination of the impacts of sea level change on the vulnerabilities of an FDR system must carefully consider thresholds and tipping points where the residual flood risk delivered by the system changes due to sea level change.

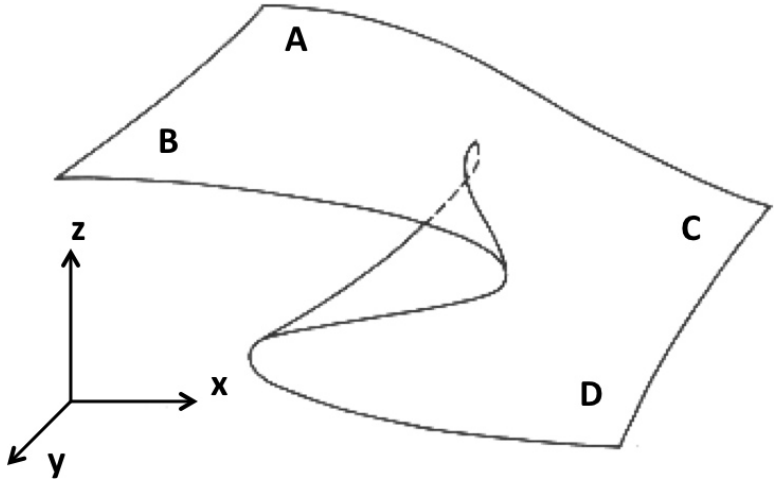


Figure E-6. Three-dimensional representation of an FDR system, illustrating tipping points and threshold responses, with the x axis representing sea level, the y axis representing rainfall intensity, and the z axis representing risk reduction. (After Zeeman 1974.)

E-6. Risk-Based Analyses for Flood Damage Reduction Studies.

a. EM 1110-2-1619, dated August 1996, describes procedures for accounting for risk and uncertainty in USACE FDR studies. By definition, an FDR plan includes measures that reduce damage by reducing discharge, stage, or damage susceptibility. EM 1110-2-1619 details procedures for incorporating risk-based analyses into planning studies and assessing risk in post-planning and engineering activities. EM 1110-2-1619 summarizes procedures for FDR studies in three categories:

(1) Estimation of expected benefits and costs of proposed FDR plans (economic analyses),

(2) Description of the uncertainty in those estimates, and

(3) Quantitative and qualitative representation of the likelihood and consequences of exceedance of the capacity of selected measures.

b. Outside of planning studies, it is common practice to re-evaluate levels of protection and risk periodically. Most commonly, a major flood event may initiate a re-evaluation of flood risk or a change in base conditions. In some cases where conditions are dynamic and changing, flood risk is evaluated on a regular basis to ensure that the project continues to function as designed. An example of this is the Mt. St. Helens Project (USACE-Portland), where flood risk for the Cowlitz River levee projects is periodically revised as channel capacity changes due to residual

sedimentation impacts upstream. If a reactive or adaptive management strategy is adopted, flood risk response to sea level rise could be re-evaluated on a periodic basis.

c. In response to SLC, future flood risk can be evaluated using the procedures in EM 1619-2-1619 for a range of future conditions. When evaluating future conditions, it is important to consider that hydrologic conditions impacted by sea level rise may require changes in the flood risk analysis. In many cases, areas where flood risk likelihood is described using discharge–frequency may require a change to stage–frequency curves as the governing conditions become more tidally and backwater influenced. This shift may also be accompanied by a design change as the hydrologic loading transitions from riverine to a coastal-storm-surge design case.

d. Specific and detailed discussion incorporating sea level rise and climate change into risk-based analysis is beyond the scope of this appendix and will be addressed in updates to the existing guidance.

E-7. Human and Biological Response. As sea levels change, populations both within and outside of any given FDR system will respond to the change over time. The future with- and without-project conditions should not assume that affected populations will do nothing in the face of SLC.

a. Human Response to Increased Flood Risk.

(1) Where an FDR system is proposed but does not exist, rising sea levels may put populations at gradually increasing flood risk. In response, they may take individual or locally coordinated steps to reduce their risk, with important impacts for the future without-project condition. Local levees and berms, elevations of homes, and buyouts and relocations may all change the overall flood risk as sea levels rise. If mass relocation is possible, the resulting decrease in property tax base may make future FDR system construction or adaptation unaffordable, with consequences for flood risk beyond the immediate, depopulated area. Consideration of future flood risk without an FDR system might include analyses of historical responses to similar situations, legal and regulatory options open to residents, and expert opinions.

(2) Within an existing FDR system, populations may also respond to rising sea levels, with important implications for flood risk. For example, consider a pump outlet for an interior drainage system; as the sea level rises, the pump must work against a higher opposing head, reducing its efficiency and therefore increasing the risk of rainfall flooding in the project area. As a response, the pump operator may run the pump more frequently, lowering water levels in the internal canal network and providing more storage space for rainfall runoff. In so doing, however, the operator may inadvertently lower the groundwater table to the point that the soil underlying the project area becomes dehydrated and oxidizes, causing rapid land subsidence and resulting in a canal network that is perched above the surrounding land surface. At this point a tipping point has been crossed, and the project area faces increased risk from the water in the internal canals, now elevated above the populated area.

b. Human Response to Decreased Flood Risk. When an FDR system is completed, improved, or adapted as a result of SLC, resulting in decreased flood risk to the protected area, the affected population should be expected to respond. The population in this area may increase, both increasing the population at risk (Burby 2006) and making future adaptation more difficult as available real estate becomes scarcer. Inhabitants may no longer elevate their homes, purchase flood insurance, or maintain emergency plans. Careful consideration of previous demographic shifts should be made to avoid maladaptations leading to an overall increase in flood risk. Changes in human behavior and preferences in the face of SLC should be anticipated to the greatest extent possible, and proactive strategies may be necessary if future populations may oppose adaptations they perceive as negatively affecting their quality of life. Adaptive strategies imply trust in future stakeholders.

E-8. Project Feature Response. FDR projects should be designed to be robust, resilient, and/or adaptable to future SLC, but several principles should be considered when anticipating future changes to an FDR project.

a. Varying Adaptability of Elements within an FDR Project.

(1) Just as various FDR project designs may lend themselves to adaptability to varying degrees, elements within a given FDR project design may be adaptable to varying degrees. Hard structures such as floodwalls and gated structures may be difficult and expensive to adapt to future SLC, whereas it is comparatively easy to add height to levees as needed. In general, more-adaptive strategies may be used with more-adaptable elements such as levees, while hard structures should be designed and built with a more proactive approach. Adaptive management of levees also avoids unnecessary rapid compaction and subsidence associated with the construction of a single large levee. Where future adaptation, such as levee lifts, will require additional real estate, however, it should be acquired proactively while it is available.

(2) Where differential subsidence is a significant component of relative sea level rise, various elements of an FDR project may vary in their adaptability because of their locations and subsidence rates. It is essential that a consistent orthometric project datum that is tied sea level be used so that these differences may be compared to each other and to SLC as measured at nearby water level gauges. Differing subsidence rates associated with relict ridges and other geological features should also be considered when comparing project alternatives and future potential for adaptation to SLC, rather than assuming that all project elements will subside equally over time.

(3) The combination of more and less adaptable elements of an FDR project, requiring proactive and adaptive strategies, should result in a coherent portfolio of structural and nonstructural solutions that minimizes expected flood impact while maximizing overall value regardless of future SLC.

b. Surprises and Unforeseen Events. SLC may interact with other climate changes, groundwater and ecohydrological processes, and nonstationary hydroclimatology in unpredictable ways and with cumulative effects for flood risk. The possibility of unpredictable events will always exist. Designing FDR systems that are robust, resilient, and adaptable to uncertain futures ensures that risk can be reduced as new information becomes available.

E-9. Level of Analysis and Methods. In the example qualitative project matrix in Table E-2, the information in the "relevant notes" column should guide analysis. When used for a real FDR project, this column should include notes referring to the actual project.

Table E-2. Example qualitative project matrix.

Critical resources in study area	Density of resource*	Relevant notes	Risk from SLR*
Federal and local levees and floodwalls	3	Size and state of flood risk infrastructure will determine stability and maintenance impacts.	2
Federal and local pump stations, flood gates, drainage network, etc.	3	Number, type, and location of these features will determine stability and performance impacts.	2
River, channel, lake exposure	3	Length of river and/or channel potentially affected	2
Potential area of impact	2	Land area that falls within the potential impact area	2
Commercial and industrial infrastructure	3	Type, value, spatial distribution (distribution of oil/gas pipelines vs. single refinery)	2
Transportation infrastructure	2	Roads, rails, ports, switching yards, etc. (length, type)	2
Utilities, sewage, communication networks	3	Connectivity, support systems, decreased resilience and performance	2
Private infrastructure	3	Performance of existing Federal structures under modified flood risk conditions will result in increased magnitude and frequency of impacts (type, value).	2
Evacuation routes	2	Impaired evacuation efficiency	2
Environmental and habitat areas	1	Ecosystem services reducing flood risk by reducing wave energy, etc.	1
Potential for impacts at adjacent navigation, coastal storm damage, or ecosystem projects	2	Impact to adjacent projects due to adaptation to SLC at FDR project	2

*3 = high, 2 = medium, 1 = low.

E-10. Potential Regional Differences.

a. Regional differences in geology, hydrogeology, ecosystem function, and infrastructure can cause varying rates and impacts of SLC, while each of these, along with cultural attitudes, can also impact potential adaptation strategies. Many coastal areas are relatively geologically stable, but in some areas, subsidence is the dominant component of relative SLC (RSLR). Where subsidence rates are highly variable in space, drainage may be impacted as some areas sink below others and hydraulic gradients are decreased or reversed. Flood risk is locally increased when levees subside, transferring risk from nearby areas with less severe subsidence and lowering the flood probability there. Differential rates of subsidence also affect planned drainage projects, especially when drainage canals cross areas with different rates or connect to

structures such as pile-founded culverts, which will not subside as quickly as an earthen canal. In such cases the project may need to be adapted or replaced during the design life if the discontinuity in the drainage network becomes severe. In formerly glaciated areas, the relative sea level may fall over time due to isostatic rebound, possibly lowering flood risk but also possibly compromising levee stability. Each of these effects of differential subsidence should be considered when evaluating the potential impacts of SLC.

b. Hydrogeology is also an important factor in assessing SLC impacts. As a rising sea level causes a corresponding rise in groundwater tables, drainage may be impaired. Saltwater intrusion to aquifers may impact ecosystem health, reducing the flood risk reduction performance of batture vegetation, which reduces wave energy and the force of ship or barge impacts on levees.

c. Interactions between groundwater and surface water are likewise important when considering alternative FDR projects. Sea level rise may require an interior drainage project to increase drainage capacity by adding or increasing pumping, but if the hydraulic conductivity of the underlying sediment is extremely high, this may not be a feasible option. For example, in areas with a karst aquifer system, pumping may draw in large amounts of groundwater without improving interior drainage.

d. Finally, cultural attitudes may differ regionally, with impacts on the acceptability of project alternatives. Elevating structures or buying out flood-prone areas may be realistic alternatives in some areas and not in others, so acceptability should be considered if these alternatives are proposed either at the beginning of the project life or as part of later adaptive management.

E-11. Example: Algiers, Southeastern Louisiana (SELA) Project.

a. Introduction. This example is an FDR project in which the controlling or governing flood risk is from rainfall-induced flooding in a small, urban catchment enclosed by levees that provide flood risk reduction from larger Mississippi River floods. These floods or hurricane-induced storm surges could overtop the levee system bordering the navigation canal, flooding low-lying wetland areas south of the project area. It is important that the specific flood risks and authorized project purposes be understood in order to correctly address the problem at hand. The levees also serve as hydrologic boundaries.

b. Background. As a result of extensive rainfall flooding in May 1995, Congress authorized the Southeast Louisiana (SELA) Project with the enactment of Section 108 of the Energy and Water Development Appropriations Act for Fiscal Year 1996 and Section 533 of the Water Resources Development Act of 1996, as amended, to provide for flood control and improvements to rainfall drainage systems in Jefferson, Orleans, and St. Tammany Parishes, Louisiana. The Algiers Sub-basin is an unincorporated area in the Parish of Orleans and lies east of the City of New Orleans on the west (right descending) bank of the Mississippi River, comprising approximately 6500 acres (Figure E-7). It is bounded by the river on the west and north sides, by the Algiers Navigation Canal on the east side, and by the Donner Outfall Canal (Donner Canal) on the south side.

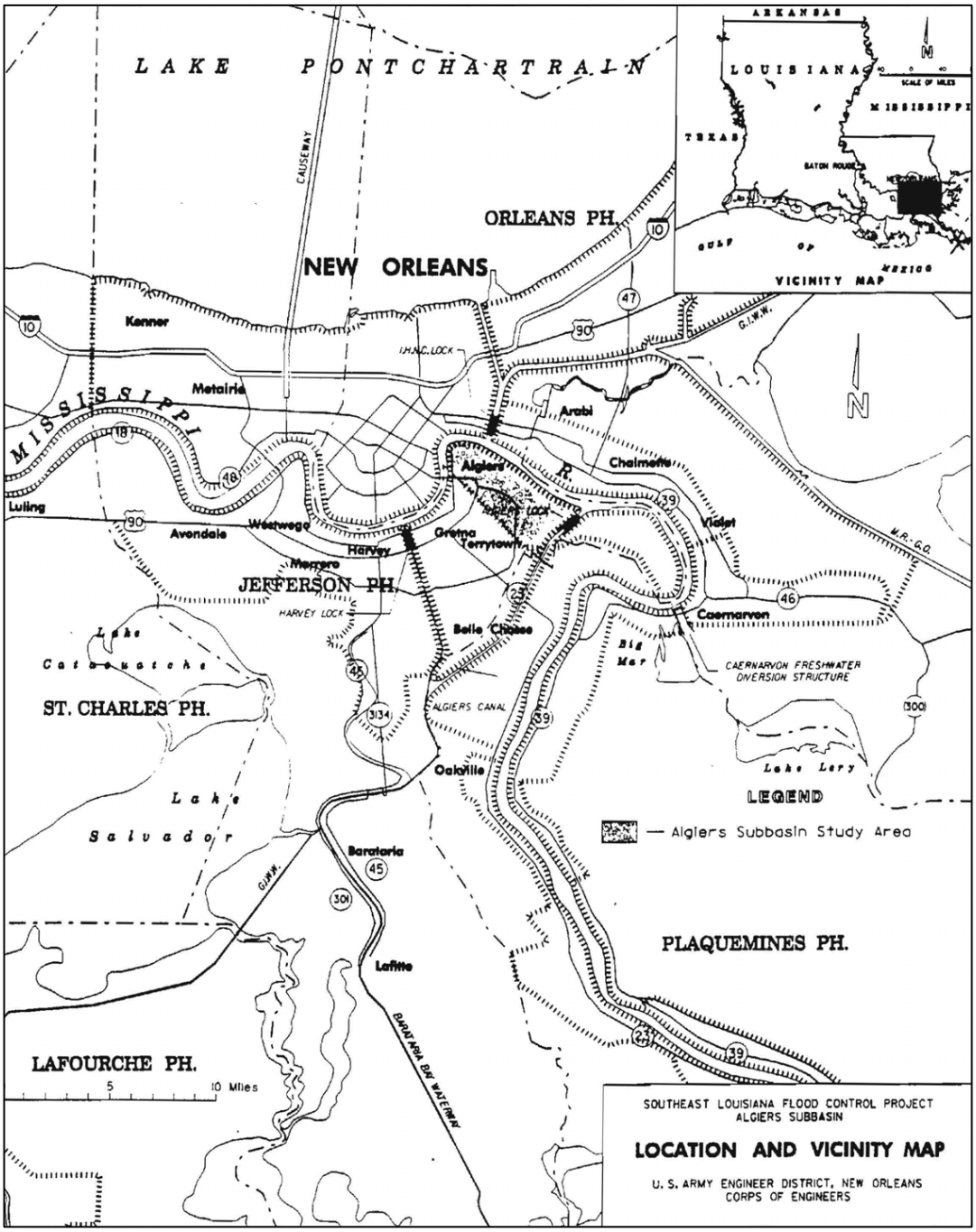


Figure E-7. Location of the SELA project.

c. RSLR Rates. Figure E-8 shows the RSLR rates for the project area. As the area is hydrologically separated by levees from water bodies impacted by sea level rise, mapping of the project area is not necessary (Figure E-9). The drainage outlet, though, is impacted by sea level rise through the drainage canal systems outside the levees and navigation channels, which transfer water levels to the Pump Station No. 13 discharge basin. The pump station is the primary project element impacted by RSLR.

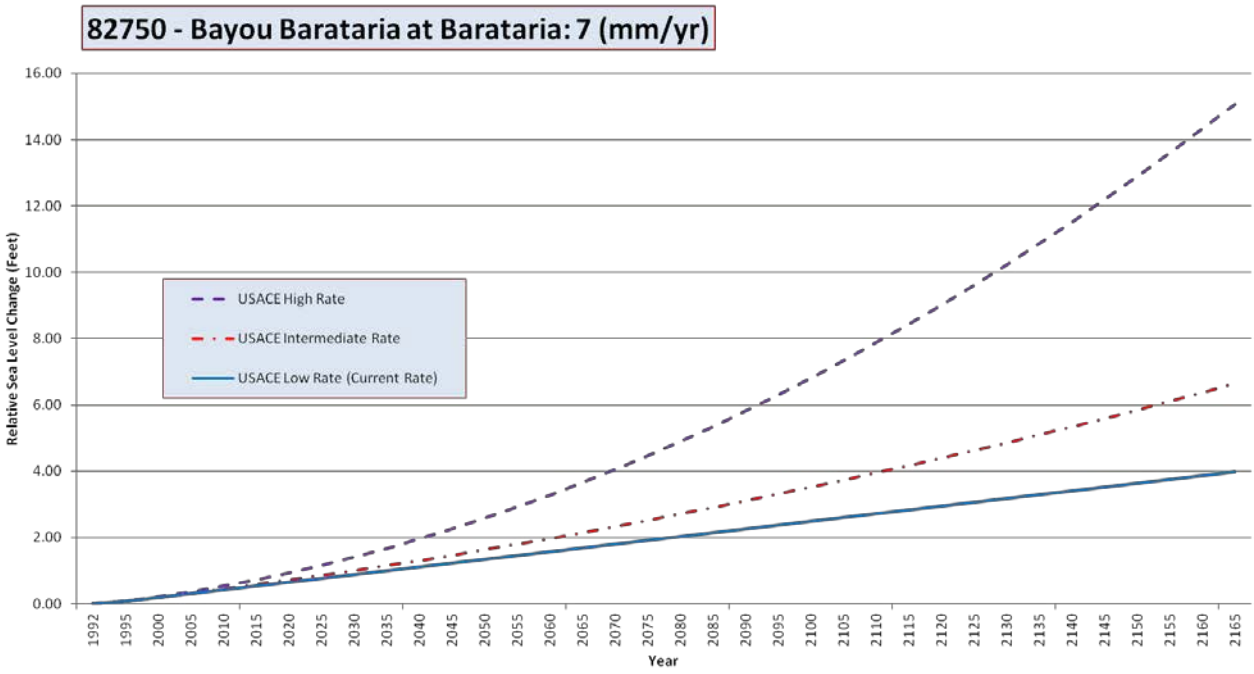


Figure E-8. Relative sea level rise curves for the nearest long-term tide gauge.

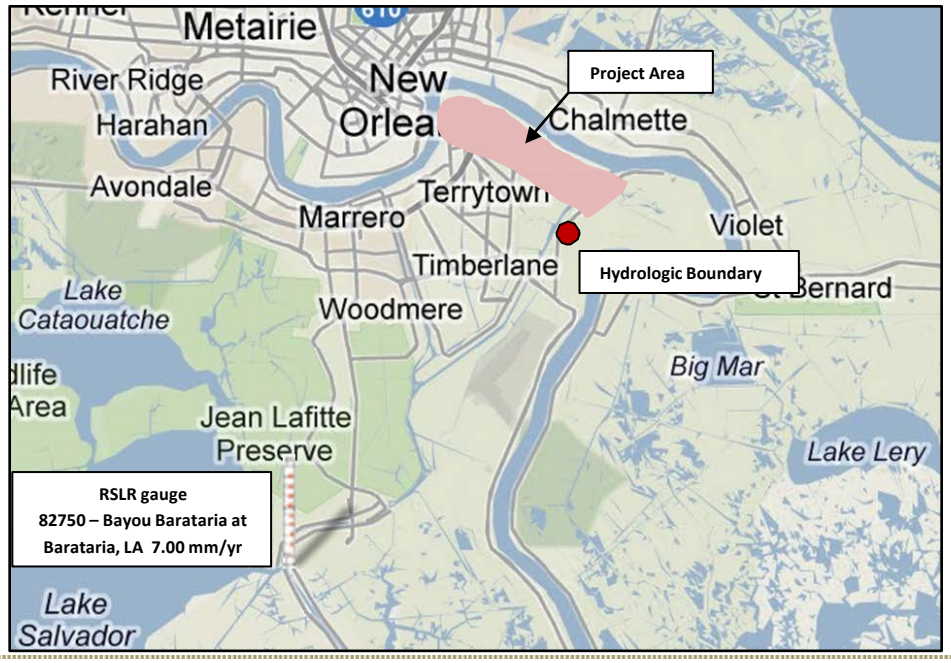


Figure E-9. Gauge location relative to the project area for the Algiers SELA feasibility study.

d. Plan Formulation.

(1) Strategic Decision Context. Alternative analysis addressed modification of the existing drainage system to provide risk reduction up to and including the 10-year or 0.10% rainfall event. Flood risk reduction from Mississippi River flooding and hurricane-induced storm surge flooding is provided by the Mississippi River and Tributaries Project and the Hurricane and Storm Damage Risk Reduction System. The primary design elements of the existing drainage system are the major drainage canals and structures and Pump Station 13 (Figure E-10). The drainage system is surrounded by canals and levees that define the 6500-acre catchment. The Mississippi River Levee to the north provides flood risk reduction from river flooding and coastal storm surge. The Navigation Canal system to the south forms a definite hydrologic boundary and is protected from hurricane storm surge by a large sector gate downstream (the West Closure Complex). This complex, which is a post-Hurricane Katrina feature of the larger hurricane protection system, provides additional protection to the area outside the smaller levee that forms the catchment boundary at the navigation canal. The principal hydrologic boundary and the drainage outlet for the project are the tailwater area at Pump Station 13. Table E-3 lists relevant project processes and measures and their sensitivities to RSLR.

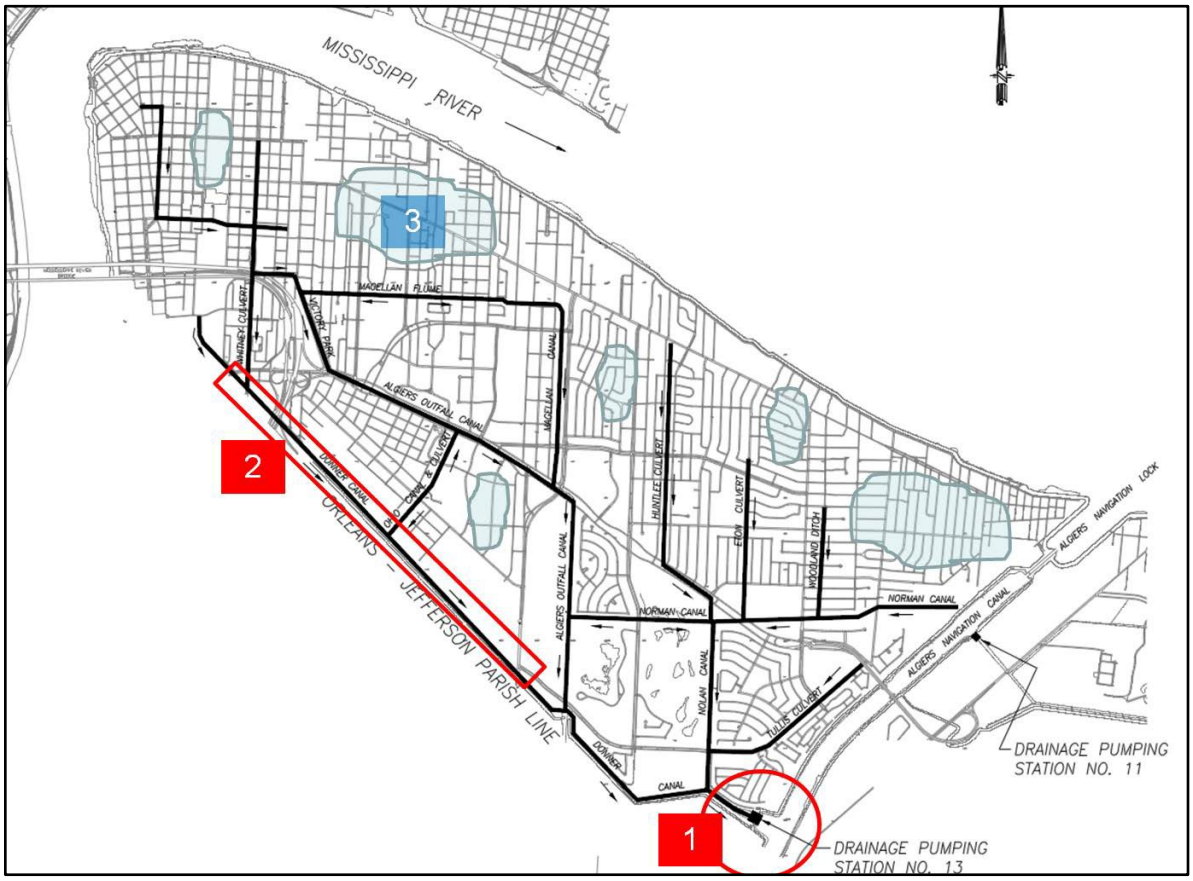


Figure E-10. Algiers catchment showing primary design elements and topographic aspects of the catchment sensitive to RSLR: (1) pump station capacity/efficiency, (2) drainage channel conveyance, and (3) higher water tables due to subsidence.

Table E-3. Impacts to processes and sensitivity of measures to RSLR.

Feature or process		Sensitivity to RSLR	Adaptability	Comment
Processes	Groundwater level	Moderate	Moderate	Water table may be actively managed through stable water levels in drainage canals.
	Rainfall-runoff relationship	Moderate	Moderate	Flooding depths may increase in areas that subside. May be mitigated through measures to control subsidence.
	Subsidence	Low	Moderate	Subsidence induced by drainage improvements may be mitigated by water table management.
Measures	Nonstructural measures	Low	Moderate	Areas where differential subsidence causes higher flood depths may adapt through non-structural measures.
	Channel improvement/ drainage structures	Low	Low	Channels may become "perched" if water table is not actively managed to mitigate subsidence in the catchment.
	Pump station capacity	Low	Low	Capacity may be maintained through a wide range of head differentials.
	Pump station efficiency (O&M cost)	High	High	Pumps run at higher horsepower to achieve design discharge. Additional horsepower requirement increases with RSLR.

(2) Level of Detail Discussion.

(a) The project scale and type require detailed hydraulic modeling to develop the with-project condition reflective of the existing drainage system, which consists of earthen and concrete-lined drainage canals, drainage structures, and a pumping station. An alternative screening process may be initiated using a tiered approach starting with a qualitative assessment as presented in Table E-3. Since most of the features are not sensitive to RSLR, design may proceed using one of the three rates. An appropriate planning strategy may be developed from the qualitative assessment.

(b) Figure E-10 shows the 6500-acre Algiers catchment and three pump areas impacted by RSLR. These three areas have been identified as sensitive to RSLR, so potential impacts should be addressed in the feasibility-level design. The pump station modification was assessed for robustness in the feasibility phase. It was determined that the design capacity was able to perform against the range of potential future sea level rise scenarios. The impact was found to be one of efficiency. More detailed analysis will optimize the correct design in the pre-construction engineering and design phase of the project.

(3) Future Without-Project Conditions.

(a) All drainage improvements previously approved for construction under the Southeast Louisiana Project, as well as additional non-Federal improvements constructed by local entities, are considered to be in place and, therefore, are included in the existing conditions model. Because of the population trends in the Algiers area and the movements of preservation associations and historical societies, who are channeling new construction toward replacement in kind rather than modernization, it is unlikely that significant changes in total impervious area or other pertinent hydrologic factors will occur in the Algiers Sub-basin over the next 25 years. Because of the flat relief in the study area, the potential increase of impervious area would do little to worsen future flooding without project improvements.

(b) Future without-project conditions are discussed in relation to sea level rise and subsidence in accordance with USACE guidance for three scenarios of SLC. Three rates of relative sea level rise (RSLR) increase were determined based on historic RSLR rates at a nearby USACE tide gauge. RSLR stage increases for future conditions (50-year period of analysis) were estimated at 1.61ft/0.49m (low RSLR), 2.04ft/0.62m (intermediate RSLR), and 3.42ft/1.04m (high RSLR). These levels represent additions to the current water level elevations at the pump station outfall canal. It is anticipated that all sea level rise estimates would impact the performance of the pump station in the future. The pumps may need to run for a longer period of time, and they may not effectively remove water from the drainage canals, which could potentially cause more flooding in the project area. Modifications to the pump motors may be required in the future to allow for more efficient pumping against the higher head to reduce the potential for increased flooding.

(4) Planning Strategy. A planning strategy may be developed based on sensitivity to RSLR using the range of approaches shown in Figure 5 and Table E-4.

Table E-4. Project measures assigned to potential implementation strategies.

Measures	Sensitivity to RSLR	Strategy	Comment
Nonstructural	Low	Anticipatory/ adaptive/ reactive	Nonstructural measures may be implemented in any of the three strategies.
Channel improvement/ drainage structures	Low	Adaptive/ reactive	As the channel elements, including drainage structures, are not sensitive to RSLR, the most likely approach would be reactive. The tipping point for modification would be performance based and not directly linked to RSLR.
Pump station capacity	Low	Anticipatory	Pump station capacity is not readily adaptable, since pipe sizes and other main components combine to determine capacity. Due to the cost of adaptation, this measure would best be handled with an anticipatory strategy.
Pump station efficiency (O&M cost)	High	Reactive	If capacity can be maintained by exchanging motors to achieve improvement, a cost–benefit analysis should be made to compare replacing motors as they are needed or buying a larger motor.

(5) Alternative Selection.

(a) Alternatives were developed using the recommended improvements listed in the existing Algiers Master Drainage Plan. Alternatives included Plans A, B, C, D, and E and a nonstructural plan. A rudimentary scoping effort utilizing the hydraulic model results from each alternative plan and the economics modeling data showed that Plans B and D did not result in adequate lowering of interior stages. These alternatives were eliminated during the hydraulic modeling process and are therefore not presented here as viable alternatives. Plans A, C, and E and the nonstructural plan proceeded to further analysis. Alternative plans were analyzed for eight storms representing a range of frequency events between the 1- and 500-year storm. These plans were compared to determine which provided the greatest net economic benefit.

(b) Plan A includes canal modifications and a pump station increase in capacity to 1800 cfs.

(c) Plan C includes canal modifications and pump station improvements.

(d) Plan E includes canal modifications and a pump station increase in capacity to 1800 cfs. This plan is the same as Plan A, except that a concrete flume section is added.

(e) A structure-raising option was considered for all residential structures in the subbasin within the 100-year floodplain. Photographs taken in 1995 show there are 2600 residential structures within the floodplain. The nonstructural analysis involved raising all residential structures located within the 100-year floodplain to the elevation of the stages associated with the existing-condition 100-year storm event.

(f) It is anticipated that sea level rise and subsidence will impact the project area over the 50-year period of analysis. A range of future conditions for all alternatives was qualitatively assessed for performance using the project 50-year RSLR rates of 1.61ft/0.49m (low RSLR), 2.04ft/0.62m (intermediate RSLR), and 3.42ft/1.04m (high RSLR). All structural and nonstructural plans would be impacted to some degree by the RSLR projections. For the structural plans, design of the pump station improvements would need to take sea level rise into consideration. The new motors included in the improvements at Pump Station #13 would include an additional horsepower (HP) requirement of 432 HP for the low RSLR rate, 548 HP for the intermediate RSLR rate, and 918 HP for the high RSLR rate to pump efficiently against the projected sea level increases in the Algiers Canal. In addition, to maintain optimum efficiency, future modifications of the HP for the existing system by 822 HP for the low RSLR rate, 1118 HP for the intermediate RSLR rate, and 2098 HP for the high RSLR rate would need to be considered to pump effectively against the higher projected stages in the Algiers Canal. The nonstructural plan would also need to consider future modifications to the existing pump station to allow for efficient pumping against the potential higher projected stages in the Algiers Canal.

(g) Since the main impact to the project was at the pump outfall, the performance of each of the alternative plans was equally sensitive to changes in RSLR across the range of future conditions represented by the three RSLR rates.

(h) The structural and nonstructural plans would not see any major impacts from subsidence during the project life. Any differential subsidence is negligible, as soil settlement and consolidation has already occurred since the area has been under forced drainage for over 30 years. The man-made subsidence should be stabilized because a constant water level is now maintained in the drainage canals. It is anticipated that the majority of the proposed improvements would be susceptible to the same subsidence rate as the surrounding area, since they are primarily earthen canals. Lowering the invert of the canals and adding new canals as a part of the structural plans are not anticipated to increase the subsidence rate because the local water table will be managed by maintaining unchanged water levels in the canals. If canal inverts are lowered, the canals must also be widened for stability, which provides additional canal capacity. In addition, the secondary system drainage canals are pressurized so that future subsidence rates are not impacted by man-made factors. Catch basins included in the structural plans are built to be adjusted to allow for future subsidence. Considering the conditions mentioned above and since the drainage system is controlled by pumps, future subsidence should not have a significant impact on the project area without proposed improvements.

(i) Plan A provides the greatest hydraulic efficiency and delivers the greatest reduction in flood-caused damages. Plan E has the greatest benefit–cost ratio. Based on the results of the economic analysis, Plan E provides the greatest net benefit, providing a reduction in flood-caused damages that is only 1% less than Plan A at a 16% cost saving. Although Plan C is 10% less costly than Plan E, Plan C provides 18% less flood damage reduction than Plan E. The nonstructural plan assumed 100% participation and did not account for all residual damages, such as automobile damages, structures located in the 100-year floodplain that did not produce a positive benefit when analyzed individually, commercial structures, and structures that may have damage outside the 100-year floodplain. These residual damages not addressed through the nonstructural plan are included in the flood damage reduction received with the structural plans. Therefore, the nonstructural plan cannot be used in comparison to the structural alternatives. On the basis of these findings, Plan E was selected as the recommended plan.

(6) Project Performance Sensitivity. The recommended design included an 1800-cfs pump station element. This element was the most sensitive to RSLR since it was at the hydrologic boundary, and RSLR changes directly impact performance. The 1800-cfs pump is able to maintain design capacity over the range of potential RSLR through the economic analysis period of 50 years and is adaptable to the high rate of RSLR up to 100 years. Performance sensitivity is expressed as additional horsepower necessary to maintain the design pumping capacity of 1800 cfs. Figure E-13 shows the additional horsepower required for the three RSLR rates and the 100-year adaption period.

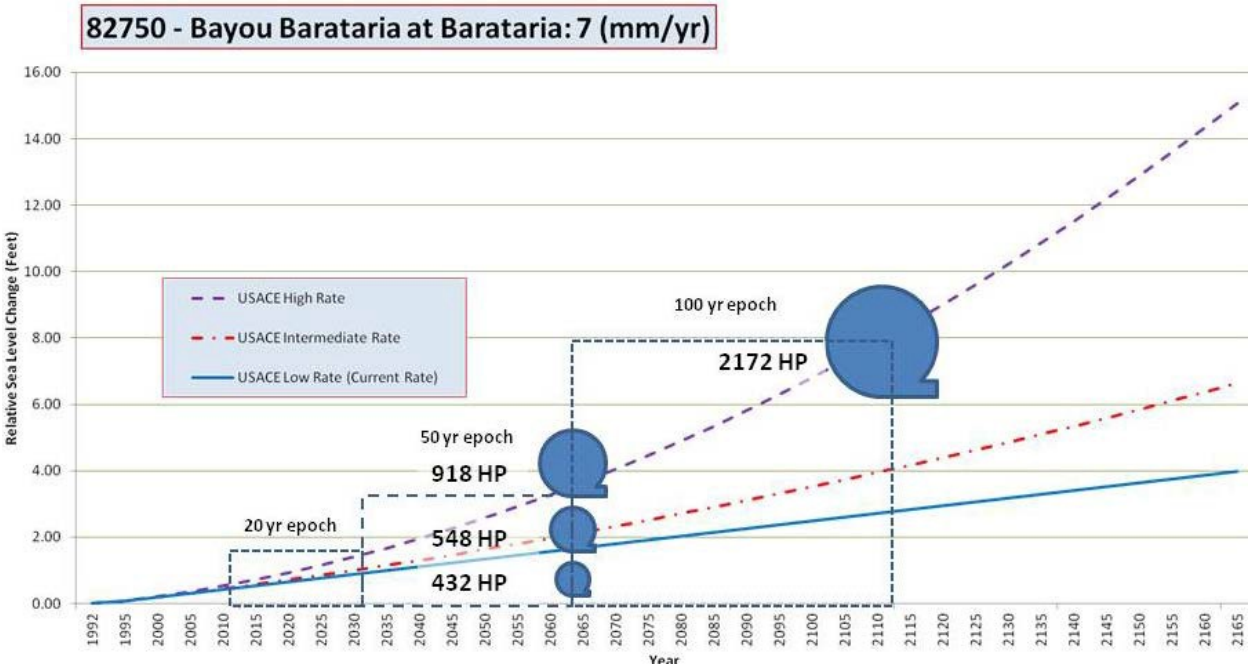


Figure E-13. Algiers SELA pump station capacity required for the three RSLR rates.

(7) Summary. The Algiers SELA FDR example project application was chosen because it has a fairly simple plan formulation and project objective. Planning and engineering under multiple futures and consideration of sea level rise were accomplished through careful consideration of sea level rise impacts on physical processes. Consideration of measures included a qualitative assessment of the individual measures' sensitivity to sea level rise. These steps provided the strategic decision context and also informed the correct level of technical analysis necessary to develop the means to identify the correct alternative in consideration of sea level rise. For a feasibility-level design, it is important to identify any potential cost-risk items or adaptation costs to the stakeholders and decision makers; this was illustrated through performance sensitivity analysis on a key design feature, the pump station capacity increase. Further detailed design and analysis may be undertaken during the pre-construction engineering and design phase to optimize project features sensitive to sea level rise. In this phase, the question of further adaptability beyond the 50-year economic analysis period may be addressed as part of the design optimization as the additional HP necessary to operate the pump increases substantially at 100 years. The cost formulation for the project accounted for this uncertainty in this critical design item.

E-12. Conclusion.

a. In addition to the more obvious impacts on coastal storm risk, SLC can affect riverine, estuarine, and rainfall flood risk in multiple ways. This appendix outlines several of those mechanisms, along with their underlying physical causes, the vulnerabilities that make them significant, and the human responses that bring these physical effects into the world of integrated water resource planning. Though it is by no means an exhaustive document, engineers and

planners should be able to use this appendix as a reference for common issues to consider when analyzing FDR projects in the coastal zone.

b. As water resource engineering moves from a paradigm of stationarity and conservatism to scenario analysis and risk awareness, increasingly greater emphasis will be placed on constructing robust, resilient, and adaptable portfolios of elements that will perform regardless of future conditions or that can be adjusted to do so with minimal additional investment. While floods in the coastal zone can never be eliminated, this appendix represents a tool to help better match flood risk to societal preferences of flood risk and to ensure that both are as accurately understood as possible.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX F

Ecosystem Projects

F-1. Background.

As the Nation's environmental engineer, the U.S. Army Corps of Engineers manages one of the largest Federal environmental missions. In that role, USACE:

- Works to restore degraded aquatic ecosystem structure, function, and dynamic processes to a less degraded, more natural condition under its ecosystem restoration mission.
- Constructs ecosystem features and maintains targeted environmental conditions to meet environmental stewardship responsibilities at projects constructed under other mission areas.
- Seeks to restore ecosystems that mimic, as closely as possible, conditions that would occur in the area in the absence of human changes to the landscape and hydrology with a minimum of continuing human intervention.
- Focuses on restoration of wetland, riparian, and other floodplain and aquatic habitats with an emphasis on native species.
- Undertakes ecosystem restoration as single-purpose projects or as components of multiple-purpose projects that may include navigation, flood damage reduction, coastal storm damage reduction, and other purposes.

b. Ecosystem features include restored and protected habitats[*] and associated built structures. Ecosystem quality factors include targeted water quantity, quality, timing, and distribution conditions that result from USACE projects. Ecosystem features and conditions may be produced as the principal project benefit, as a secondary benefit, or as a permit requirement.

c. SLC may adversely affect ecological benefits, ecosystem function, or environmental features or conditions of USACE projects. The guidance provided here is intended to help USACE project delivery teams (PDTs) incorporate consideration of SLC effects on ecosystem features and conditions for projects conducted under all USACE mission areas.

d. USACE restores and manages a wide range of subtidal, intertidal, and supratidal ecosystems that could be affected by SLC. These ecosystems occur in nontidal waters, such as rivers and lakes, and in tidal waters of rivers, bays, and the coastal ocean. These projects also occur on shorelines and low-lying coastal areas of the mainland and islands. USACE's ecosystem restoration and management activities include the following:

- Constructing substrate of these habitats by placement of dredged material, shells, earth, and other materials.

[*] Habitats are the places where plants and animals live, feed, find shelter, and reproduce. Habitats are characterized by distinct assemblages or communities of plants and or animals, including their supporting environment. USACE often uses the terms ecosystem and habitat synonymously.

- Excavating channels in tidal and nontidal waters to establish open water and direct water flow.
- Establishing native flora and fauna on these substrates by active means such as plantings of grasses, shrubs, and trees and placement of live mollusks.
- Constructing a variety of structures to protect project substrates, flora, and fauna from waves and currents, including groins, breakwaters, and bank stabilization works.
- Utilizing weirs, dams, and pipes to control water levels and maintain target water quality and salinity conditions.

e. All USACE coastal projects incorporating ecosystem features and conditions as project outputs or permit requirements that could be affected by SLC are covered by this appendix. If a project is not subject to SLC impacts within the next 100 years, then SLC impact analysis per this ETL is not necessary.

F-2. Principles and Issues.

a. SLC, over geologic and historic time, drove the creation, maintenance, and destruction of intertidal and subtidal coastal ecosystems. Supratidal ecosystems have evolved with and without SLC acting as a driving force, depending on the ecosystem type. The rate of future SLC, particularly if the rate accelerates, will be an important factor determining inventory[*], distribution, and position for many coastal ecosystems. Eustatic sea level rose continuously over the last 10,000 years and induced a general landward migration of coastal ecosystems. However, ecosystem evolution varied regionally or locally in response to physical factors acting at those geographic scales. Depending on local conditions, ecosystems showed a range of vertical and lateral responses to SLC [migration (retreat, prograding), upward growth, conversion to other habitat types, drowning-in-place, erosion].

b. The factors that should be considered to assess the effects of SLC vary as a function of the ecosystem type(s) of interest for a particular USACE project. SLC drives direct and indirect physical (hydrologic, chemical, and geologic) environmental changes to which coastal ecosystems respond. Other biological interactions and anthropogenic stressors that may or may not be related to SLC may also warrant consideration in the SLC assessment. For ecosystems with physical structures made up in large part of living and dead tissues of plants or animals (biogeomorphic ecosystems), the ecological tolerances and vulnerability[†] of these component organisms can govern the response to SLC. If organisms forming a biogeomorphic ecosystem's physical structure are stressed or fail, the ecosystem may degrade or fail. Table F-1 presents principles and issues for assessing the effects of SLC on ecosystem projects. Ecosystem restoration mission projects involving geologic materials that lack biogeomorphic organisms[‡], such as beaches and tidal flats, should also review the principles and issues presented in the CSDR, FDR, and navigation mission appendices for potential applicability.

[*] Habitat inventory is a function of the balance between the processes that create, maintain, and destroy the habitat.
[†] Inability to self-maintain and lack of resiliency such that conversion to a substantially different habitat type would be likely.
[‡] A biogeomorphic organism is a microbe, plant, or animal whose living or dead tissues form prominent physical structures in ecosystems. Example structures include reefs formed by worm tubes, corals, or shellfish, and peat substrates formed by non-woody and woody wetland plants.

Table F-1. Principles and issues for ecosystem projects impacted by SLC.

Principle	Issues to consider (under existing and SLC scenarios)
SLC drives direct and indirect hydrologic changes to which coastal ecosystems respond.	Water surface elevation and depth Hydrologic regime (tidal vs. nontidal, frequency and duration of inundation/submergence) Wave energy Surface water quality and salinity (mixing of oceanic, estuarine, and riverine waters) Groundwater salinity
SLC drives indirect geologic, substrate, and soil changes to which coastal ecosystems respond.	Shoreline change rate and position (lateral retreat [erosion] or progradation) Bathymetric form and landform character (e.g., shoals and dunes) Sedimentation or erosion rate Substrate/soil character (grain size and biogeochemical condition)
Other biological interactions can affect the vulnerability of biogeomorphic ecosystems to SLC. These can be independent of SLC.	Excess herbivory or predation Competition from invasive exotic species Availability of biogeomorphic organism propagules to colonize newly converted habitats
Migration space availability and condition would affect future ecosystem inventory.	Area (acreage) Slope Substrate Depth or elevation Vertical stability (e.g., subsidence or uplift rate)
Anthropogenic activities can affect the ecosystem response to SLC.	Usurpation of habitat migration space and migration barriers (e.g., development) Stabilized shorelines (i.e., hardened) Beach nourishment Boat wakes Dredging (navigation channels) Water quality impairment via inputs of pollutants, restricted flushing/exchange Groundwater or hydrocarbon withdrawal Excess or inadequate sedimentation (via reduced or increased erosion or altered waterway flows) Nutrient loading increasing substrate decomposition rate Vegetation management practices (e.g., burning, grazing) Altered populations of native or exotic species (altering competition, herbivory, etc.) Emerging global change issues (e.g., ocean acidification, climate change [storm intensity, precipitation patterns, temperature], permafrost thawing)
Important biogeomorphic organisms have a finite range of ecological tolerances to forcing factors and conditions (above).	Ecological tolerances of important biogeomorphic organisms vs. conditions resulting from above forces, factors, and stressors

F-3. Project Settings.

a. USACE focuses on habitat as the primary output in its aquatic ecosystem restoration mission, makes beneficial use of dredged material to restore aquatic habitats under its navigation mission, and undertakes the restoration of habitat as compensatory mitigation for project impacts under other mission areas.

b. Habitats at a site are commonly described based on the presence of prominent biogeomorphic plants and/or animals when this is applicable. Habitats lacking prominent biogeomorphic organisms are commonly described based on the geologic material present and the topographic characteristics (Table F-2). Open water of the water column is also a habitat, although it lacks a fixed physical or biological structure.

Table F-2. Coastal habitat types restored under USACE aquatic ecosystem restoration mission.

Ecosystem (habitat) type	Prominent substrate / structural material	Tidal range	Vertical range of occurrence (deepest to shallowest or lowest to highest) (ft)
Kelp forest	Plant	Subtidal	Tens
Coral reefs*	Animal	Subtidal	Tens
Unconsolidated bottom (loose sediment)	Geologic	Subtidal	Tens
Shellfish beds	Animal	Subtidal	Tens
Submerged aquatic vegetation and benthic algae	Plant	Subtidal	Up to several
Vegetated tidal wetlands†	Plant	Intertidal	Up to several
Non-vegetated tidal flats	Geologic	Intertidal	Up to tens
Beaches (non-vegetated)	Geologic	Intertidal and supratidal	Up to tens
Nontidal vegetated wetlands	Plant	Intertidal and supratidal	Up to tens
Rocky shoreline	Geologic	Intertidal and supratidal	Up to tens
Riparian habitats (non-wetland)**	Plant	Supratidal	Up to tens

* Not including deep-water corals because USACE is not involved in their restoration.
† Including various marshes, mangroves, shrub thickets, and swamps
** Tidal habitats included in previous "vegetated tidal wetlands" category of this table.

c. The Nation possesses about 90,000 miles of ocean, estuarine, and riverine coastline along the Atlantic, Pacific, and Arctic Oceans and their embayments (NOAA 2011). This vast length occurs over a wide range of climatic, hydrologic, and geologic conditions. Sea-level-controlled habitats also occur inland from the shoreline, with the distance inland at which these occur being controlled by tidal range and slope of the land*. Coastal habitats contain a great diversity of plant and animal species, with distributions that vary nationally as a function of geologic history, climate, salinity, and other factors. Anthropogenic effects are of pronounced

* Water levels occurring during infrequent severe storm and tsunami events can also control habitat distribution.

importance locally and regionally. Ecological conditions at USACE project sites can be formally classified by a variety of schemes (Table F-3). Which scheme to utilize depends on a variety of considerations, including project goals, important conditions and processes acting at a site, and communication needs.

Table F-3. Ecosystem and habitat classification schemes potentially applicable.

Classification scheme	Source
Classification of Wetlands and Deepwater Habitats of the United States	Cowardin et al. (1979)
Hydrogeomorphic Classification for Wetlands	Brinson (1993)
Ecoregions of North America	USEPA (2011)
Coastal and Marine Ecological Classification Standard	FGDC (2012)
Marine Ecoregions of North America	Wilkinson et al. (2009)
Coastal Classification Map	USGS (2012)

d. Paleoecological studies characterize ecosystem evolution over several hundred to thousands of years through sediment investigations. Human effects during this time period in coastal areas in what is today the U.S. were generally negligible. Historical ecology studies characterize ecosystem conditions over hundreds of years. Historical trends can be characterized over tens to hundreds of years by review of historic maps, aerial photographs, and other documents. Human effects over this time period impacted many ecosystems substantially, and restoration projects often seek to reverse these effects.

e. Where an ecosystem type occurs over a broad geographic region with substantial variation in environmental conditions, the effects of ongoing rapid SLC at one place might be a useful analog from which to forecast future accelerated SLC at other sites not yet subject to those conditions.

F-4. Exposure and Vulnerability. Assessment of SLC impacts is required of authorized projects as well as projects in the planning phase. Assessment of SLC begins with a determination of whether a project is subject to associated impacts. As with other USACE missions, the SLC analysis for ecosystem projects includes establishing the strategic decision context, assessing project area vulnerability, and formulating alternatives. For ecosystem restoration projects, the evaluation of SLC impacts on projects is done by estimating how SLC may reduce the non-monetary project environmental benefits (habitat area or volume, populations of fauna and flora, etc.). For non-ecosystem restoration projects in the planning phase, such as flood control, navigation, or storm damage reduction, the evaluation should also consider whether project features will reduce any nearby ecosystem functions at some point in the future as a result of SLC. For instance, a storm protection levee located inland from the shoreline might present no impact to ecological resources at present, but it might become a barrier to habitat migration as sea level rises. Additionally, how the project would meet the required environmental conditions (such as water quality or other permitted parameters) that could be impacted by SLC must be considered.

a. SLC Applicability – Maximum Vertical Datum of Concern. The preferred method for determining if a restoration project is subject to SLC is to see if any project ecosystem features

or water quantity or quality conditions are impacted by the projected sea level as defined by mean higher high water (MHHW) or spring high water level under the high-rate scenario (Curve III) at 50 years post-construction (the project service life as defined by ER 1105-2-100). [Note that although previous guidance calls for the use of mean sea level (MSL) as the indicator of whether a project is subject to SLC impacts, ecosystems are potentially susceptible to changes in surface water and groundwater salinity conditions that usually track MHHW rather than MSL.[*]] Projects not impacted by the 100-year high SLC rate scenario need no further assessment until SLC projections are revised.

b. Establishing Strategic Decision Context.

(1) The strategic decision context for ecosystem restoration projects and required environmental features/conditions of USACE projects could be determined based on applicable conservation status hierarchies determined by government agencies and recognized international authorities and/or by USACE budgetary priorities. A site would be of high strategic importance from a conservation status perspective if it provides, contains, or maintains (a) critical habitat for a Federally listed threatened or endangered species, or (b) a globally or nationally imperiled ecosystem as recognized by NatureServe[†]. In these cases, loss of habitat at the project site or adjacent areas could threaten the species' or ecosystem type's future survival. The U.S. Fish and Wildlife Service and the National Oceanic and Atmospheric Administration's National Marine Fisheries Service list species recognized to be endangered or threatened at a national level and have designated critical habitat for numerous threatened or endangered species. NatureServe tracks the conservation status of species and ecosystems at global, national, and sub-national scales. The designation of an ecosystem occurring at a project site as critically imperiled or imperiled at either the global or the national scale would qualify the project site as being of high conservation status.

(2) If a project site provides or contains an ecosystem or species recognized to be imperiled at the sub-national level by NatureServe or provides important habitat for a state-listed threatened or endangered species that is not Federally listed, the site could also qualify as being of high conservation status if the species or ecosystem is not otherwise abundant elsewhere in the U.S. Otherwise, such sites would qualify as being of medium conservation status. All other ecosystem restoration projects and environmental components and features of USACE projects would be considered to be of low conservation status.

(3) When assessing SLC impacts, PDTs should address the USACE ecosystem restoration project budgetary prioritization criteria (scarcity, connectivity, special species status, hydrologic character, geomorphic condition, self-sustaining, and plan recognition). However, connectivity, hydrologic character, and geomorphic condition are likely to be problematic to assess in many cases, particularly when non-project-area changes are also considered. Information about the physical scale of the restoration, the cost, the phase, the relationship to other purposes for

[*] Note that MHHW can be substantially affected by wind-tidal effects, seasonal freshwater input/runoff variation, and concomitant seasonal sea levels in estuaries with restricted ocean connections.

[†] NatureServe is a non-profit conservation organization whose mission is to provide the scientific basis for effective conservation action. NatureServe and its network of natural heritage programs are the leading source for information about rare and endangered species and threatened ecosystems. USACE maintains a collaborative relationship with NatureServe.

multipurpose projects, the watershed status for studies, and the status of cost-share agreements will also be used to arrive at a determination of budgetary prioritization that ensures continued positive contributions to the Nation's resources for strategic purposes. In some cases, SLC impacts to adjacent non-project habitat would be so extensive that adaptive measures to maintain project ecosystems would not be a sensible means to manage the regional sustainability of the resource. It could be concluded in such cases that efforts to maintain non-project ecosystems may be of greater importance to the Nation than efforts to maintain USACE project ecosystems. It would be outside of the USACE mission to undertake work outside project lands or waters.

(4) Ecosystem projects and environmental features or required conditions that also provide flood or coastal storm damage reduction or navigation functions should be separately evaluated according to the strategic contexts provided in the appendices for those mission areas.

c. Assessing Project Area Vulnerability.

(1) Substantial variation in vulnerability to the effects of SLC among coastal habitats of interest to USACE is expected. The elevation range of occurrence of the habitat with respect to sea level (Table F-2) and the habitat's maximum SLC tolerance (Table F-1) provide an initial means to coarsely evaluate habitat vulnerability. Subtidal habitats other than submerged aquatic vegetation (SAV) occur over a vertical range of tens of feet. These subtidal habitats could likely self-maintain with substantially greater rates of SLC. Accordingly, because this occurrence range is substantially greater than the potential SLC scenarios that must be considered for USACE projects, subtidal habitats other than SAV would all generally be expected to be invulnerable to the direct effects of SLC, considering only changes in water depth. SAV and vegetated tidal wetlands would show substantial variation in vulnerability to SLC. SAV could be highly vulnerable in estuaries with limited water clarity, where the SAV occurs only over a several foot range or where little shallow water habitat is available. SAV could be invulnerable in settings where the photic zone extends to depths of more than several feet or where substantial shallow water habitat is available. Vegetated tidal wetlands generally occur over a limited range of intertidal elevations [mean waterlevel (MW) to MHHW]. However, freshwater tidal wetlands can have floating leaved vegetation that is permanently inundated. Vegetated tidal wetland ecosystems generally build their surfaces by accretion of plant remains and sediment concomitantly with SLC at rates of millimeters per year. These ecosystems can be highly vulnerable to more rapid rates of SLC, and the vulnerability of these habitats to SLC generally requires scrutiny. Numerous other factors (Table F-1) can exacerbate or mitigate vulnerability. High sediment inputs (such as from great tidal range or riverine or shoreline sources) can partially or completely mitigate the effects of higher rates of SLC on vegetated tidal wetlands.

(2) The issues presented in Table F-1 provide a checklist of physical environment, biological, and anthropogenic factors that should be considered in identifying applicable concerns for the SLC vulnerability assessment. For biogeomorphic habitats in which plants or animals are critical substrate components (Table F-2), the vulnerability of the organisms themselves can be the most critical factor controlling habitat vulnerability. Table F-4 includes examples of stressors and ecological receptors as impacted by changes to physical processes. Table F-5 shows differences in SLC vulnerability of intertidal habitat types (flats, vegetated tidal wetlands, beaches, nontidal wetlands) as affected by several physical environmental factors. Additional environmental factors (other than SLC) important to coastal ecosystem health may

also change concomitant with anthropogenic global climate change (Table F-1). These factors may interact with SLC to produce effects greater than those of SLC alone and should also be considered by PDTs when assessing future with- and without-project conditions.

Table F-4. Example of stressors, receptors, and relevant data for several processes impacted by SLC.

Processes	Stressors (Changes in)	Receptors	Relevant data
Sediment dynamics	Depth of inundation, wave height, water clarity	Coral reefs, benthic organisms, crustaceans, fish, SAV, tidal wetlands vegetation	Sediment accretion rate, sediment characteristics (size, source, organic content, oxidation)
Tidal hydrology	Depth of inundation, salinity, nutrient availability	Fish, mollusks, SAV, tidal wetlands vegetation, upland vegetation	Topography, location of manmade or natural flow obstructions, biological light requirements and salinity tolerance
Groundwater hydrology	Groundwater stage and salinity, withdrawal	Soil microbes, vegetation	Vegetation hydroperiod and salinity tolerances
Storm events	Storm surge	Coastal and upland habitat	Frequency and magnitude of storm surge events, habitat tolerance for inundation and salinity

Table F-5. Physical environment factors controlling the vulnerability of existing coastal intertidal habitats to SLC. (Modified from Thieler and Hammar-Klose 1999, 2000a, 2000b, various USGS publications.)

Factor	Intertidal habitat vulnerability to impact of rising sea level by factor	
	Greatest vulnerability	Least vulnerability
Tidal range	< 1 m	> 1 m
Wave height	High	Low
Landward migration space	Steep coast	Gentle slope
	Developed	Rural
Offshore slope	Steep	Gentle
Shoreline geologic materials	Highly erodible	Low erodibility
Sediment supply	Low	High
Shoreline geomorphic position	Exposed headlands	Protected embayments
Land subsidence rate	High	Low

(3) For ecosystem projects possessing marine or estuarine coastlines, Thieler and Hammar-Klose (1999) identified several factors controlling coastline physical vulnerability to SLC. Factors of importance for the coastline itself include tidal range, wave height, coastal slope, shoreline erosion rates, geomorphology, and historical rate of relative sea level rise. The individual factors vary in importance geographically along the U.S. coastline as a function of variation in physical environmental conditions.

d. Tipping Points and Thresholds.

(1) The coastal habitat types most vulnerable to the effects of SLC are those resilient within only a narrow range of ecological conditions that could be affected by SLC. Outside of their range of resilience, vulnerable ecosystem types would hit tipping points that could lead to rapid change from one habitat type to another; these changes could be difficult and/or expensive to reverse or forestall. Failure would reduce or end ecosystem benefits. For vulnerable projects, both existing and in the planning phase, it is important to identify the current state of critical variables (Tables F-1, F-4, F-5) affecting sustainability versus ecological thresholds that approach or define tipping points. Tipping points for coastal ecosystems that have their location fixed by substrate or suitable space availability would be vulnerable to the magnitude of SLC. For ecosystems that evolve and respond vertically or laterally to SLC, the rate of SLC could be the more important factor. Tipping points based on the rate of SLC have been determined generally for tidal wetlands but not for other ecosystem types.

(2) Tidal wetlands generally convert to unconsolidated bottom and open water on hitting their tipping point via some combination of drowning-in-place and erosion. Natural sustainability of a given tidal wetland parcel depends on the ecosystem substrate being maintained at an intertidal elevation autochthonously via accretion of sediment (mineral and organic), and the parcel not being subject to excessive wave erosion. The availability of suitable migration space is also important in the long-term sustainability of tidal wetlands. At this time, sea level fall, as occurs in Alaska, has not been identified as a concern for ecosystem restoration projects. The rate of fall would actually be reduced with accelerated sea level rise. Accordingly the remainder of this subsection will focus on the consequences of sea level rise.

(3) Vertical accretion rate potential is greatest where tidal range and/or mineral sediment supply are greatest. Climate, vegetation type, and nutrient loading affect organic material accretion rates because they affect plant productivity and decomposition. However, the balance between these processes is not understood well enough to predict accretion rates based on these variables. SLR response of vegetated tidal wetlands will vary as a function of the factors controlling surface accretion and erosion. These differences will give rise to a family of response curves. However, several generalizations can be made, and these are adequate to inform plan formulation.

(4) Microtidal wetlands (0- to 2-m tidal range) can perhaps self-sustain over the long term where and when rising local SLC rates are up to several millimeters per year (e.g., U.S. Climate Change Science Program 2009). Microtidal wetlands in locations with local SLC in excess of this are already at or close to their maximum threshold of self-sustainability, other than for systems with substantial sediment loading such as in freshwater rivers. Tidal wetlands in mesotidal and macrotidal settings (greater than 2-m tidal range) where sediment supplies are generally greater than in microtidal settings by virtue of tidal transport and energy subsidy (e.g., Steever et al. 1976) are generally more stable vertically over the range of possible SLC scenarios than microtidal systems (Morris et al. 2002). Tidal wetlands could perhaps survive a maximum SLC of 1.3 cm/yr in optimal settings (Morris et al. 2002).

(5) Factors controlling landward migration opportunities largely relate to the degree of development and the topography of the land inland from the wetlands. Developed lands with

structures of substantial value would likely be defended (Titus et al. 2009), preventing landward migration. Local master plans and land ownership are important considerations in being able to forecast landward migration opportunities. The topography of potential migration space depends on the natural geomorphic character and human cut-and-fill activities. Lands with steep topography would offer little horizontal space for tidal wetland evolution. Anthropogenic fill landward of tidal wetlands may also limit migration space.

F-5. Alternative Formulation. Formulation would include the need to estimate project service life of various alternatives, evaluate adaptive capacity, evaluate risk and uncertainty, and measure outputs of various alternatives.

a. Project Service Life

(1) In general, there are no hard lines that differentiate what ecosystem project service life is acceptable and what is not. The ideal sustainability target for project ecosystem benefits would be that 100% of the identified benefits would be produced for 50 years after the project is completed. However, shorter-lived projects may be acceptable if they meet the sponsors' interests and USACE mission and priority criteria. Shorter-lived projects could still be of particular value in cases where and when they provide ecosystem benefits of high or medium strategic importance. The cost of the project and the consequences for other mission areas could have a bearing in helping determine whether an investment is worth making to construct a new project with a shorter lifespan or maintain an already constructed project to its intended lifespan.

(2) Ecosystems identified as vulnerable to SLC generally have shorter project lives the longer the period of time considered (i.e., 20, 50, or 100 years) and the higher the rate of SLC. PDTs should consider developing adaptive management strategies for project alternatives or implemented project features that would otherwise be anticipated to lose 25% or more of their project benefits at the 50-year planning horizon based on the high-rate SLC curve. For projects that would be subject to losses of 50% or more of their benefits at 50 years (under the high-rate SLC curve), PDTs should consider reformulating the plans. Where or when SLC impacts are significant and adaptation may be costly, PDTs may consider justifying projects using a shorter planning horizon and limited project service lifespan. Projects determined to be vulnerable even with adaptive measures could be determined to be: (a) inappropriate to construct, (b) acceptably providing shorter project benefit life (i.e., premature project failure and abandonment is acceptable), and/or (c) acceptably converting to other ecosystem types if these would also provide valued ecosystem services.

(3) For new projects, site selection and design can be optimized to promote project sustainability under SLC conditions and thus project longevity. PDTs can also incorporate anticipatory, reactive, or adaptive management strategies to optimize life and benefits in formulating new projects proposed for vulnerable ecosystems. For example, for tidal wetlands in microtidal environments other than riverine settings, it would be appropriate for the plan to incorporate measures to optimize for vertical accretion. In urban areas, lateral habitat migration may not be feasible because of the presence of development. In these settings, project boundaries are often armored on the water side. Measures to raise the elevation of water-side protective structures in the future against SLC effects and/or add additional substrate material could be appropriate in some areas.

b. Potential Adaptation Approaches

(1) Table 4 of the main body of this ETL presents potential adaptation approaches to SLC that range from keeping the sea out of the project (protect), undertaking measures to allow ecosystems to be maintained with SLC (accommodate), and/or allowing the ecosystem to migrate (retreat).

(2) Intertidal and supratidal ecosystem projects could be protected against changing water levels and salinities associated with SLC by restricting tidal exchange via dikes and tidal gates. However, this would rarely be appropriate because it could restrict the movements of aquatic life into and out of the project and reduce the ecosystem support services to adjacent estuaries (such as that produced by the export of detrital materials). Of greater concern is keeping the sea out of existing ecosystems that would otherwise gradually become more tidal, which could set the stage for catastrophic ecosystem failure in the future (such as following a severe storm that introduces salt water into a salt-sensitive freshwater ecosystem). In the event that restricting saline water intrusion is necessary to maintain ecosystem functions of high strategic value, it would probably be preferable to offset the increased salinity effects if practicable by purposeful or controlled introduction of fresh water that would not restrict tidal exchange.

(3) It is quite likely, though, that supratidal and intertidal ecosystem projects could be designed and constructed to protect against the altered wave energy accompanying SLC. Ecosystem projects are typically designed and constructed to protect the ecosystem from damage or loss via waves under current conditions. This would entail overbuilding the structure or feature at the time of construction, or facilitating a future increase in the structure's height. This would be generally applicable where minimal to no opportunity exists for lateral migration of ecosystems as SLC occurs, such as for tidal wetlands in urban areas.

(4) Generally, accommodating and retreating are appropriate adaptation approaches for ecosystem projects. Potential measures could be undertaken before (anticipatory) or after (reactive) the effects of SLC occur, as discussed next.

c. Adaptive Capacity Assessment

(1) The scale of an ecosystem project plays a role in determining the extent to which adaptation planning is worth undertaking. Adapting existing projects is of greatest importance from an ecological perspective for projects producing high and medium strategic value and regionally significant ecosystem benefits. However, in some cases, SLC impacts to adjacent non-project habitat would be so extensive that project-specific adaptive measures would not be cost effective to the Nation from a regional scale because adjacent non-project ecosystems of perhaps equal or greater ecological value would also be responding to SLC. In other words, PDTs must evaluate the regional impact of SLC on ecosystems when determining whether project-specific habitat benefits are worth maintaining in the future through adaption measures. For larger restoration efforts, or for restoration projects that provide high or medium strategic value habitat, the PDTs may determine that adaptive measures are worth undertaking because of the regional loss of similar habitat.

(2) The cost and technical feasibility of possible SLC-related adaptations should be considered in determining which adaptations should be proposed. The decision to formally

include the adaptation features should be based on the time frame in which these features are needed to maintain project benefits and the cost of these features relative to the project cost. To the extent practicable, low-cost design and/or operational adaptation strategies should be incorporated immediately into design plans and operation plans for those projects that currently are under design or are operational. More substantial adaptation strategies that require extensive changes to operational projects may require the initiation of supplemental authorization and/or approval of the non-Federal sponsor. If no acceptable adaptation strategies are available to maintain at least 50% of the project benefits under the 50-year, high-rate scenario, the PDT should consult with the project sponsor and USACE Division Managers to determine a viable course of action. It is also appropriate to recommend no further Federal action when SLC impacts are significant and adaptation plans are infeasible.

(3) The adaptation strategy should be incorporated into the basis of design as well as into the draft project operating manual. For projects that are operational, under construction, or already have a final Project Implementation Report (PIR) approved by USACE, the adaptation analysis should be incorporated into the latest design document and/or project operating manual.

(4) Given that both the effects from SLC and the rate of SLC are expected to increase over time, alternatives considered for a project might include anticipatory and reactive features that are intended to be implemented in the future as certain thresholds are exceeded and the project begins to provide fewer benefits (Table F-6).

Table F-6. Example anticipatory and reactive planning approach strategies for tidal wetlands.

Approach strategy	**Potential plan**	**Action required**
Anticipatory	Accept reduced ecosystem outputs or shortened life for all or portions of project	Future: abandon habitat in place, render project habitat and features harmless (e.g., remove if future navigation risk)
	Accept/expect habitat conversions	Present: design to accommodate/promote this (e.g., nontidal to tidal wetland)
	Allow/provide for landward translocation of habitats	Present: ensure that migration space is available (secure real estate)
	Provide excess protection to stabilize habitat in place as sea level changes	Present: design structures/features to function even as sea level changes (e.g., construct higher shoreline protection structures)
	Design to optimize sediment input/ accretion	Present: conduct appropriate investigations during planning phase (regarding tidal creeks, shoreline, etc.)
Reactive	Future engineering intervention to raise substrate elevation (e.g, future application of dredged material, replantings)	Present: identify potential sources of dredged material
	Raising elevation of shoreline protection structures	Present: design and construct any shoreline stabilization features such that elevation could be economically raised in future

(5) Figure F-1 shows an example of an adaption plan for an ecosystem project subject to SLC impacts. This plan begins as a nontidal freshwater restoration project that is located just inland of the mean higher high water line (MHHW). As sea level increases, the freshwater wetland begins to transition to a tidal wetland habitat. To increase the function of the transitioning wetland, a barrier removal effort is initiated at some point in the future. The barrier restoration effort is followed by tidal wetland restoration. Nonstructural efforts to control upland land use are required to ensure that freshwater and tidal wetland habitat is available in the future as sea level continues to increase. The non-Federal sponsor may be required to purchase land or acquire easements for upland areas to ensure that lands are available for natural habitat migration as sea level inundates existing natural areas. Several of the nonstructural efforts are likely to require actions by parties other than the non-Federal sponsor, but these actions can't be guaranteed because they must go through a political process. These potentially include enacting land use constraints such as construction moratoriums, construction control lines, rolling easements, and development-limiting policies. The timing of the progression of this adaptation plan depends on the rate of SLC. For instance, the first freshwater wetland restoration phase of this project would be viable for the first 1.5ft (0.5m) of sea level rise. These restored wetlands would function for 40 years under the high rate of SLC or for 80 years under the intermediate rate of SLC.

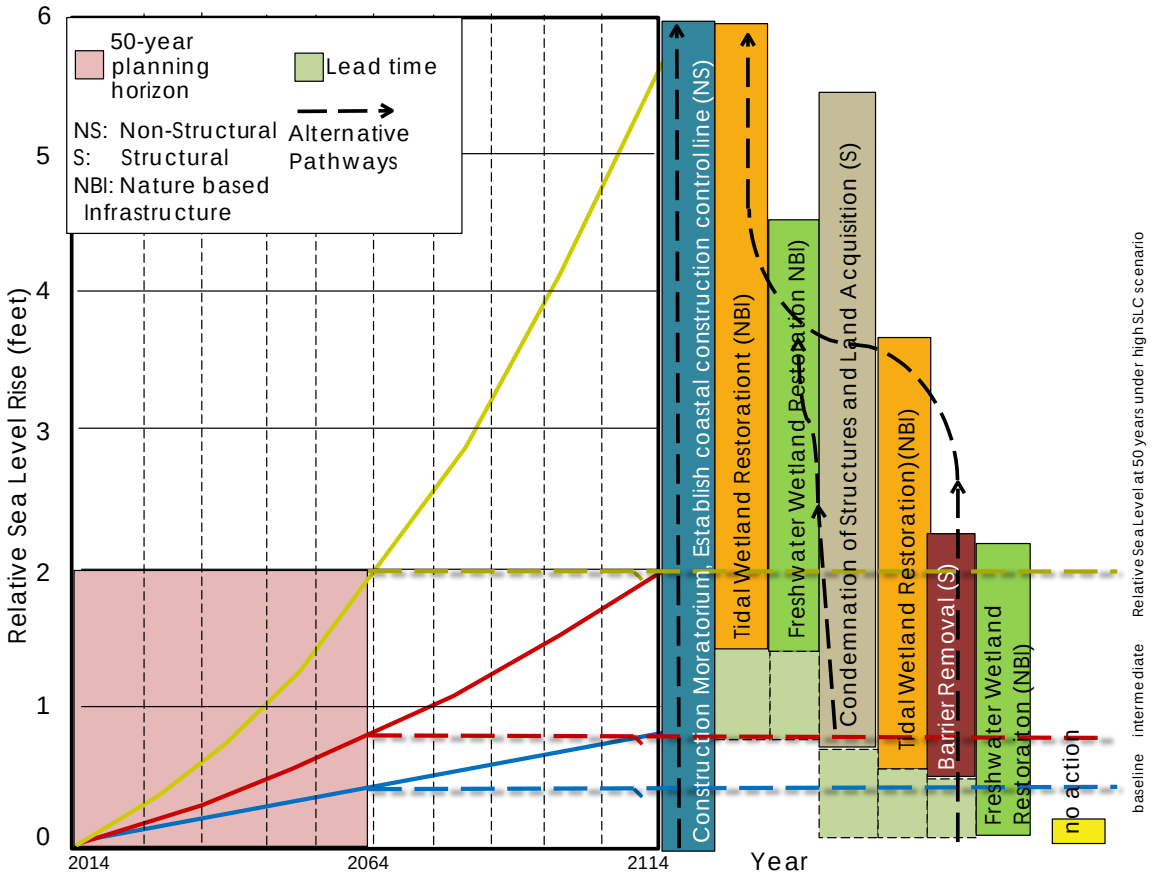


Figure F-1. Example of an adaptive plan for a wetland restoration project subject to SLC.

d. Risk and Uncertainty Assessment. The main body of this TL outlines the procedures for preparing a risk and uncertainty analysis. Because SLC impacts to ecosystem resources generally do not pose immediate and certain threats to human health or valuable infrastructure, the risk and uncertainty analysis for ecosystem restoration projects can be less rigorous than for flood or storm damage reduction projects. The risk analysis rigor should be based on the project's strategic value, cost, size, relationships with other mission areas, and other potential economic or social importance factors. Generally, the risk of the project service life and performance being reduced increases as the vulnerability of the ecosystem of interest to SLC and the magnitude and rate of the future SLC increase.

e. Project Performance Metrics.

(1) For projects still in the planning phase, metrics by which project performance should be forecast are typically utilized in the project's required cost-effectiveness analysis. In many cases, these benefit metrics are derived units selected to ensure accordance with the USACE policies regarding project justification. These metrics ideally align closely with the project objectives, so how they are impacted by SLC is critical to assessing long-term project performance.

(2) Following construction, USACE requires monitoring of ecosystem restoration projects to track project success. USACE implementation guidance requires that criteria for success be established, but it does not stipulate metrics for this purpose. Basic measurements such as area or length of habitat types or water quality and quantity conditions within defined waterways can be utilized for monitoring purposes. Because habitats often have heterogeneous mixes of organisms and open substrate or water, determination of habitat requires the definition of acceptable organisms, the means to determine their dominance and cover, and the area of open substrate and water.

(3) Occasionally, habitats of USACE projects are managed to produce target species of plants or animals of interest to maintain species population levels. In these cases, it would be appropriate to utilize that species population as a performance metric. Otherwise, determining populations of individual plant or animal species at a site is generally beyond the level of accuracy necessary to demonstrate USACE project performance.

f. SLC Analysis.

(1) The protocol for SLC analysis calls for assessing the impacts associated with three SLC scenarios at 20, 50, and 100 years post-construction. SLC analysis of multiple alternatives could impose a significant burden on USACE and local sponsors. To lessen this burden, a three- tier assessment approach is recommended as shown in Figure 9 in the main text. Different levels of analysis will be identified after each tier as necessary to address SLC issues at the project level. For some projects, there will be no additional analysis required following Tier 1. In contrast, some projects may only require use of Level 1 analysis tools, while some may require analysis involving up to and including Level 3 analysis tools (Table F-7). For existing projects, the evaluation of SLC impacts to ecosystem resources can be as simple as mapping the physical location of ecosystem benefits or habitat resources of interest against the projected elevation of mean high higher water (MHHW) and considering whether resources of concern could likely

self-maintain over SLC rates expected over this time period. For projects in the planning phase, this evaluation may be done qualitatively during an initial screening of alternatives and then more quantitatively as a normal part of the alternative formulation, evaluation, and selection process.

Table F-7. Examples of SLC qualitative and quantitative analysis tools.

Level 1 **Qualitative analysis**	**Level 2** **Semi-quantitative analysis**	**Level 3** **Quantitative analysis**
Best professional judgment Conceptual ecological models Scenario analysis	GIS overlay analysis of projected benefits and high water lines (bathtub mapping analysis); estimates and comparisons of maximum vertical accretion rates to SLC Ecological benefits assessment model coupled with future boundary conditions that incorporate SLC	2D/3D hydrodynamic/salinity model coupled with ecosystem benefits model Storm surge model Sedimentation/erosion model and ecosystem simulation model Coupled hydrodynamic/ecological models Coastal wetland evolution models such as SLAMM

(2) The ecological, regional, and national significance of the targeted resource should be evaluated by the PDT as part of establishing the strategic decision context. All projects, regardless of size or status (operational or planning phase), should undergo Tier 1 assessment. For restoration or mitigation projects that are small (<$10 million), impact assessments at Tier 1 may be sufficiently robust to proceed to a decision point regarding sustainability. PDTs should consider the use of more quantitative and complex tools for projects of significant size (>$100 million) that are either located in geographic areas of high or very high vulnerability or consist of habitats or other ecosystem features that may be highly vulnerable and highly valuable.

(3) Table F-7 shows some examples, listed in order of complexity, of typical analytical approaches. PDTs are encouraged to investigate the possibility of using existing evaluation tools developed by other government and non-government organizations. The Ecosystem-Based Management Tools Network (http://ebmtoolsdatabase.org) is one web-based source of assessment tools that can be applied to SLC analysis. Examples of the application of several of these methods are provided in Section F-6. The reader should also consult USACE (2011) for an overview of ecological forecasting tools and USACE (2012) for an overview of risk and uncertainty in making ecological forecasts.

(4) It is important to note that although habitat benefits are the primary benefits of ecosystem restoration projects, many projects also provide benefits in other USACE mission areas. Consideration of these is outside the scope of this appendix, but ideally they should be evaluated in order to capture all project benefits.

(5) For Tier 1 assessments for ecosystem types occurring over a broad geographic region, it might be possible to infer the vulnerability for project ecosystems to SLC or its effects from trends at other locations. Additionally, the range of responses at other sites may provide

example feature and condition analogies useful in guiding plan formulation for SLC, as well as for adaptive management. Features and conditions of failing ecosystems would be appropriate to avoid in planning future projects, as well as adapting or retrofitting existing projects.

(6) For Tier 2 assessments, impacts may be assessed using flooded area maps generated using geographical information systems (GIS). Baseline or existing condition maps can be generated with current mean sea level (MSL) and MHHW plus 1–6ft (0.3–1.8m) of SLC. Potential habitat vertical accretion and erosion rates over this range of elevations should be estimated. The alternative features and benefited areas (if available) can be spatially located on these maps relative to areas anticipated to be inundated due to SLC. The evaluation of benefit loss for each alternative might be done using a GIS intersection of the benefit area maps and the flooded area maps with SLC. This may be particularly helpful if the alternatives are substantially different with regard to the locations of the features or benefited area. Where alternatives all have similar feature and benefit locations, the PDTs will have to rely on other information, such as freshwater and sediment delivery capacity, preliminary operating schemes, etc., in order to assess benefit loss. These "bathtub" maps give an idea of potential habitat loss under the assumption of static topography and bathymetry. In reality, topography and bathymetry are always in flux at the site-specific scale due to land accretion, subsidence, erosion, and historic SLC. In evaluating benefit loss, the project team should consider whether the area generating benefits has been reduced or merely relocated as a consequence of SLC. For instance, a wetlands area may no longer provide estuarine salinity benefits as sea level and salinity increase; however, freshwater wetlands farther upland could provide those benefits as they transition to estuarine conditions. Similarly, freshwater wetlands adjacent to the coast may transition to saltwater wetlands, while adjacent farmland may transition to freshwater wetlands as increased groundwater stages inhibit agricultural productivity. In these two cases it is apparent that the SLC impact analyses should include a review of natural and man-made topographic features such as terraces, scarps, and levees. Additionally, site-specific assessments of soil biogeochemical conditions (oxidation, sulfide content, etc.) and accretion rates as influenced by saltwater intrusion and increased inundation should be considered, along with landscape changes via shoreline erosion and interior pond formation.

(7) For Tier 3 assessments, the hydrologic models, ecological models, and benefit assessment tools used to evaluate the final array of alternatives may be capable of incorporating SLC estimates into the model boundary conditions. If this is the case, the evaluation of SLC scenarios on project benefits is simply done by incorporating SLC scenarios into the hydrologic model boundary conditions and post-processing the hydrologic and ecosystem benefit results.

(8) The paleoecological or historical record may document coastal ecosystem evolution during past times when local SLC rates or other conditions were comparable to those forecast for the future. The PDT should determine whether paleoecological or historical ecology studies have been conducted in the project vicinity. If not, site-specific paleoecology or historical ecology studies could be conducted to inform SLC plan formulation.

(9) For USACE planning documents, each alternative should be evaluated under each time frame to determine the percentage of benefits the alternative is able to maintain for the historic, intermediate, and high SLC scenario curves. To further distill the SLC impact analysis, the PDTs may evaluate the alternatives' overall sensitivity to SLC by combining the results of each

time frame and scenario to get one score for comparison purposes. PDTs should refer to the *Trade-off Analysis Planning and Procedure Guidebook* published by the Institute of Water Resources (Yoe 2002) for guidance on score formation and evaluation.

(10) To facilitate the review and interpretation of the overall analysis, narrative descriptions of the logic used to arrive at estimates of achievable benefits should accompany the assessment. In addition to the findings of the analysis, this narrative should include extensive discussion of the uncertainty in the data. If the project has flood protection or water supply aspects that are not addressed in the project benefits analysis, the PDT needs to evaluate the impact of sea level rise on these secondary project benefits. Details on how to conduct analyses for these additional non-ecosystem benefits are provided in separate appendices.

(11) While the SLC impact analysis is to be incorporated into the overall plan selection process used to identify and select the preferred plan, the project team should keep in mind that the SLC impact analysis is not the deciding factor—it is just one of the factors to consider in the selection of the Tentatively Selected Plan (TSP).

g. Frequency and Timing of SLC Analysis.

(1) For authorized projects, PDTs should consider performing re-assessments in response to storm events or the publication of revised SLC projections or when needed to evaluate the effectiveness of adaptation measures.

(2) Given the uncertainty about how restored habitats will adapt to SLC, SLC impacts to project benefits should be monitored in the normal course of project operation. This information will be useful in determining when adaptive measures should be put in place or when the SLC evaluation process should be re-initiated. For authorized projects, a potential source of funding for SLC assessments may be Operations and Maintenance (O&M) money, since SLC can affect project operations and performance. For projects in the planning process, the PDTs should include funding for periodic re-assessments of SLC impacts in the project authorization document. In general, re-assessments every 10 years should be sufficient for most regions of the U.S.; however, in areas with significant land subsidence, a more frequent re-assessment schedule may be warranted.

F-6. Ecosystem Restoration SLC Examples. Examples of a hypothetical adaptive restoration project—an application of Level 1 (qualitative) SLC analysis, an application of Level 2 (semi-quantitative) SLC analysis, and a Level 3 (quantitative) SLC analysis—are provided below. Most of the examples come from existing USACE planning documents. These examples can be obtained from the USACE District offices that prepared the associated reports.

a. Adaptive Restoration Example for Biscayne Bay Coastal Wetlands Project. The Biscayne Bay Coastal Wetlands (BBCW) project is a new project located in southern Miami-Dade County (Figure F-2). The project is intended to improve near-shore bay salinity conditions, reduce salinity within tidal wetlands, and rehydrate freshwater wetlands through the diversion of fresh water from canals into lands adjacent to Biscayne Bay. The project is expected to cost approximately $180 million and is part of the larger Comprehensive Everglades Restoration Plan that was authorized by Congress in 2000.

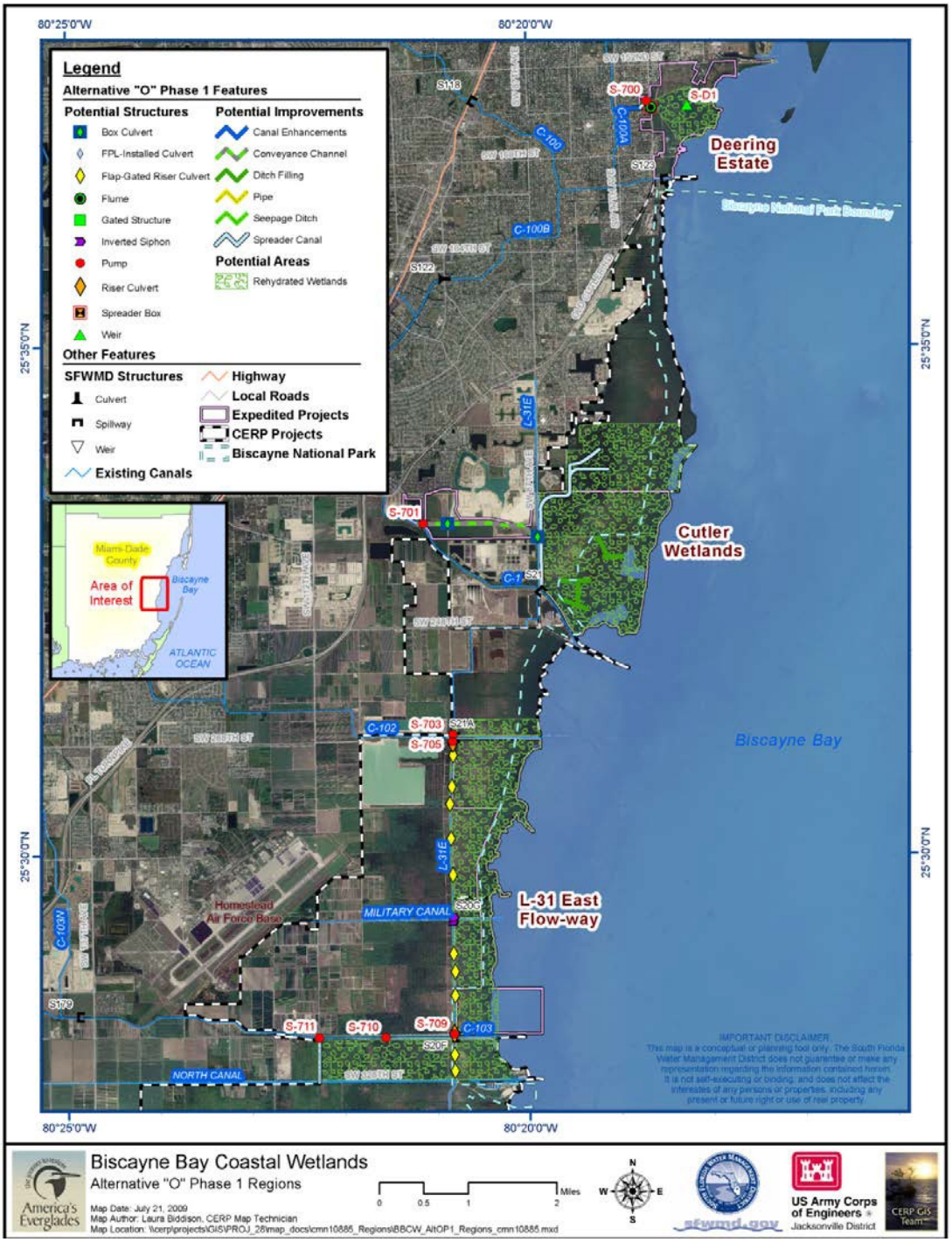


Figure F-2. Biscayne Bay Coastal Wetlands project area in Miami, Florida.

(1) Tier 1: Strategic Decision Context.

(a) Table F-8 shows an inventory of the resources within the project study area, as well as an evaluation of the risk from SLC. Increased mean sea level is expected to adversely affect the tidal wetland habitat and the freshwater habitat by altering the salinity balance in these areas.

Near-shore areas will be impacted by increased depth of inundation and increased salinity. Failure of the project will result in a decrease in the local fishery (pink shrimp, sea trout) as well as a decrease in habitat quality, which will affect valued species (oyster, American crocodile, wood stork, blue heron, roseate spoonbill), some of which are listed as threatened and endangered species. The project does not include any features intended to provide flood protection, so failure of the project would not increase human health risk or directly affect infrastructure investments.

Table F-8. Resource inventory and SLC vulnerability assessment for BBCW project.

Built and natural conditions and features	**Summary details**	**Risk from SLC***
Tidal wetlands	30,000+ acres of tidal wetlands within study area. Most of the tidal wetlands are vegetated with mangroves. Invasives such as Australian pine and Brazilian pepper trees are present in areas that were ditched and drained for farming or mosquito control.	2
Freshwater wetlands	10,000+ acres of freshwater wetlands within study area and at elevations below 5ft (1.5m) NAVD88. Much of these wetlands are degraded due to invasive vegetation and insufficient hydroperiod.	3
Near-shore habitat	Salinity conditions in the first 1,000 m of bay adjacent to shore is critical habitat for juvenile fish, pink shrimp, and oysters.	1
Endangered species	T&E species include American crocodile, roseate spoonbill, and indigo snake. Juvenile crocodiles require low-salinity water in tidal wetlands. Spoonbills require shallow freshwater pools for feeding.	2
Secondary project purpose (i.e., flood protection)	Tidal wetlands adjacent to bay serve flood protection function by decreasing wave energy and dampening tide magnitude.	3
Structural features	L-31E levee is an existing structure that divides the freshwater wetland zone from the tidal wetland zone. This levee is currently functional and limits salinity impacts to freshwater wetland areas. The high-rate SLC scenario overtops this levee within 50 years.	2
Sedimentary sources	Natural sources of mineral sediments are very limited in this area. Mangroves generate organic sediments at rates similar to historic SLC rates; however, accretion is not likely to be sustainable under the high SLC scenario.	2
Land use	Land use in the vicinity of the project is residential on the north end of the project and agricultural on the southern end of the project. Higher mean sea level will result in more flooding of these areas.	2
Groundwater elevation	Groundwater stages are lowered during the dry season to facilitate agricultural operations west of the project lands. Higher mean sea level will result in saltwater intrusion into the surficial aquifer.	3
Surface water hydrology	C-1, C-100, C-102, and C-103 canals provide drainage and water supply to the project area. In water supply mode, these canals resupply the surficial groundwater aquifer and help limit salinity intrusion. Higher mean sea level compromises the ability of gravity flow outlet structures to operating during high tide events. Flood protection is compromised.	3

* 3 = high, 2 = medium, 1 = low, X = not present

The project is located partially in and directly adjacent to Biscayne Bay National Park and Biscayne Bay Aquatic Preserve, so the success of the project is of interest to multiple Federal (NOAA, DOI), state (Florida Department of Environmental Protection), and local (Miami-Dade Permitting Environment and Regulatory Affairs Department) agencies. Future adaptation of the project to SLC impacts is likely to involve landward migration of tidal and freshwater wetlands habitat. At present, this is possible, since much of the land inland from the project features is now used for agriculture and can be cost-effectively converted back to wetland habitat. Inland areas are now protected by a hurricane levee (L-31E), and it is likely that overtopping of this levee will become more frequent and therefore the periods between overtopping events will become shorter, resulting in salinity impacts to vegetation becoming permanent rather than ephemeral. Habitat conversion from freshwater vegetation to salinity-tolerant vegetation is generally not reversible.

(b) Based on the project setting information, the consequence of project failure is considered to be medium. This rating is largely based on (1) the presence of threatened and endangered species within the project area, (2) the ability of habitats to migrate inland, and (3) the existence of similar habitat outside the project area that would also be subject to similar impacts from SLC.

(2) Tier 2: Project Area Exposure and Vulnerability. Project area vulnerability is evaluated by reviewing project information, establishing the areal extent subject to the 100-year high SLC curve, evaluating the loading processes, and determining the resiliency of valued ecosystem components to SLC-related stressors.

(a) Project Area Description. The project area is located south of Miami, Florida, and is composed of three regions (Deering Estates, Cutler Wetlands, and L-31E Wetlands). Along the coastline, the ground elevation is typically below 5ft (1.5m) NAVD 88, with the exception of a coastal dune ridge that ends at the northern end of the project area (Cutler Wetlands). The project benefits are associated with enhancing hydration of freshwater wetlands, reducing salinity within saltwater wetlands, and reducing salinity conditions within the near-shore area. The near-shore zone is defined as the sub-tidal area out to 1,000 m from the shoreline. This area is considered to be prime nursery habitat for juvenile fish, oysters, and shrimp. The tidal wetland zone is the land subject to frequent inundation due to the tidal cycle. The western edge of the tidal wetland zone is the L-31E storm protection levee. The freshwater wetland acreage is located west of the L-31E levee, although there is remnant freshwater acreage in the Cutler Wetlands area. In the southern part of the project area (L-31E Wetlands), active farmland is located west of the freshwater wetlands. Because of the low uniform topography of the area and the extensive farmlands, the potential for habitat migration is high in the L-31E portion of the project area. In the Cutler Wetlands and Deering Estates areas, residential and light commercial land uses will limit the potential for habitat migration as mean sea level increases.

(b) Capacity for Resilience. A project area's capacity for resilience is a function of project purpose, physical characteristics, topography, and sensitivity, as well as the available buffer for adjustments. The BBCW project area is very flat, with an average elevation of less than 5ft (1.5m) NGVD88. The L-31E storm protection levee runs along the eastern boundary of the project area and presently divides the tidal wetlands along the shoreline from freshwater wetlands and agricultural fields to the west of the levee. With the exception of the storm protection levee, the topography and agricultural land use are favorable for gradual migration of

habitat inland as sea level rises. Overall, the project area appears to be fairly resilient, given the potential for habitat migration as sea level changes under historic or moderately increased rates.

(c) Loading and Processes. Once the project area's resilience, resources, and systems are categorized, the level of project area loading and critical processes relevant to the project performance need to be identified. The intent is to bracket SLC within the overall loading parameters and define the level of sensitivity to SLC.

– The surficial aquifer in the project study area is highly transmissive, which means that a higher mean sea level will immediately result in increased groundwater stages as well as increased saltwater intrusion. The tidal range for Miami-Dade County is approximately 2.0ft/0.6m, with high tide at approximately 1.0ft (0.3m) NAVD88 and low tide at –1.0ft (0.3m) NAVD88. Typical wave heights within Biscayne Bay are less than 1ft (0.3m). The Florida Statewide Regional Evacuation Study Program estimates that the storm surge for a Category 1 Tropical Storm is 5.0ft/1.5m. Category 3 and Category 5 storm surges are estimated at 11.4 and 16.5ft (3.5 and 5.0m), respectively. Based on this information, it appears that a Category 1 storm event would result in a storm surge that would flood the entire project study area. The USGS Coastal Vulnerability map for the project study area indicates that the region is highly susceptible to impacts from increased sea level. (The USGS assessment focuses on the physical impacts of increased mean sea level rather than biological or chemical impacts; nonetheless, the USGS vulnerability maps are good indicators of habitat vulnerability to SLC.)

– At present the freshwater wetland habitat located just west of the L-31E levee has not been permanently affected by storm surge events, as these events are infrequent and of short duration. Even the Category 5 storm event that occurred in 1992 did not result in permanent damage to freshwater wetlands located west of the L-31E levee. However, as the mean sea level increases, the frequency of levee overtopping will increase, and the impact to freshwater wetland vegetation will become more apparent. The first tipping point is likely to be an increase of MSL of approximately 1ft (0.3m), resulting in the mean lower low water (MLLW) level line moving west to the base of the L-31E levee. With this increase in sea level, it is unlikely that mesosaline (5–18 PSU salinity) conditions will be sustainable in the tidal wetlands east of the L-31E levee. With an increase of 2ft (0.6m) in mean sea level, the MLLW will be approximately half the height of the levee. At this elevation, saltwater intrusion into the surficial aquifer will begin to adversely affect the freshwater wetlands located west of the levee. Farmers west of the levee will experience decreased productivity because of saltwater intrusion and because they will be increasingly unable to keep the root zone dry during the growing season. The easternmost farmland will begin to be abandoned and convert into disturbed wetlands. (This phenomenon has occurred for lands east of the L-31E levee where acreage farmed in the 1940s to 1960s has reverted to wetlands due to SLC-related increased flooding, among other factors.)

– As the sea level rises, mangrove forest will move westward towards the L-31E levee alignment. Near-shore shallow estuarine habitat that is targeted for salinity improvement by this project will slowly move west towards the L-31E levee as MSL rises. Whatever peat soils exist east of the L-31E levee will decompose and disappear as saltwater intrudes into remnant graminoid marsh not previously impacted by tidal flows. At higher sea level conditions, freshwater wetlands west of the L-31E levee will transition to saltwater wetlands.

– Many tidal creeks have already disappeared in coastal wetlands as a result of sediments trapped by opportunistic plants that have rooted in the creek beds as water flow has diminished. Restoring water flows through the saltwater wetlands will help maintain open watercourses. Sea level rise is expected to modify the patterns of connectivity through Everglades coastal wetlands and increase sediment loads (Davis et al. 2005). This phenomenon is also likely to occur in the Biscayne Bay coastal wetlands. In addition to SLC, climate change may result in more extreme weather events. If SLC is accompanied by an increase in tropical storm intensity and frequency, the rate of soil accumulation may increase and partially offset higher MSL conditions. [Hurricane Wilma resulted in an approximately 5-cm accumulation of sediment deposits in the Everglades mangrove zones in 2005 (Whelan 2009).] Also, increased mean sea level conditions in Biscayne Bay are likely to moderate hyper- and hypo-salinity events in the near-shore zone, as there will be more ocean water available for dilution.

– Under higher rates of SLC, the increase in groundwater stages and in surface water depths will result in a loss of flood protection for the area. The open/close operating criteria at coastal canal structures may be modified as water managers attempt to counteract the effects of SLC on flood protection and salinity control. The SLC-related increase of groundwater stage in the western part of the project area could increase hydration to the freshwater wetlands to the extent that the water management practices need not be significantly modified to continue to provide the same level of flood protection west of the L-31E levee.

– Overall, the project study area is considered to be highly vulnerable to SLC, given the transmissive aquifer, the relatively low topographic relief, and the potential impact of salinity on vegetation. Mitigating this vulnerability is the potential accommodation space available for habitat migration with SLC.

(3) Tier 3: Alternative Development, Evaluation, and Adaptability. The restoration benefits projected for this project are associated with the rehydration of freshwater wetlands, salinity maintenance in the saltwater wetland area, and moderated salinity conditions in the near-shore area adjacent to the saltwater wetlands that border Biscayne Bay. To accomplish the project goals, the PDT developed five with-project alternatives that incorporate features such as reservoirs, stormwater treatment areas, diversion pumps, spreader canals, and gated culverts. These features are intended to take water from the existing canal network and distribute it to wetlands east and west of the L-31E coastal storm protection levee. All of the alternatives are similarly located in proximity to the existing coastline and are expected to be similarly impacted by SCL. Given this fact, the SLC analysis for the project was performed by first analyzing the impact of SLC on the most favored alternative (Alternative O, Phase 1) and then determining if the other alternatives would be more or less impacted by SLC.

(a) SLC Scenarios for the Project Area. USACE planning guidance calls for evaluating the effects of SLC under multiple scenarios, including analysis of sea level rise at low, intermediate, and high levels at 20, 50, and 100 years following the completion of construction. Relative sea level rise has been calculated by the Jacksonville District for the low, intermediate, and high scenarios at 5-year intervals based on the historic sea level rise as measured at the NOAA Key West tide station. Relative SLC in this part of Florida is equivalent to eustatic SLC because the land elevation is generally stable. The results of this analysis are presented in Figure F-3 and Table F-9.

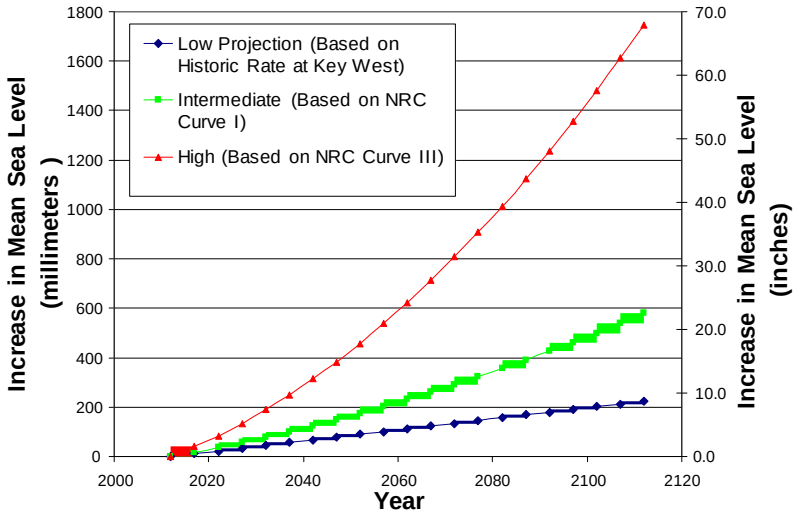


Figure F-3. Projected relative sea level rise at BBCW project features (assuming that construction was completed in 2012).

Table F-9. Relative sea level rise at 5-year intervals for low, intermediate, and high projections. The low projection was based on the historic rate at Key West, the intermediate projection was based on NRC Curve I, and the high projection was based on NRC Curve III. (The base year for these estimates is 1986 based on prior NRC guidance. The latest USACE protocol calls for using 1992 as the base year for these calculations).

Year of analysis	Sea level rise (mm)			Sea level rise (in.)		
	Low	Intermed.	High	Low	Intermed.	High
2012	0	0	0	0.0	0.0	0.0
2017	11	18	40	0.4	0.7	1.6
2022	22	37	84	0.9	1.4	3.3
2027	34	57	134	1.3	2.2	5.3
2032	45	78	189	1.8	3.1	7.4
2037	56	100	248	2.2	4.0	9.8
2042	67	124	313	2.6	4.9	12.3
2047	78	149	383	3.1	5.9	15.1
2052	90	175	458	3.5	6.9	18.0
2057	101	202	538	4.0	8.0	21.2
2062	112	230	623	4.4	9.1	24.5
2067	123	260	712	4.9	10.2	28.0
2072	134	291	807	5.3	11.4	31.8
2077	146	322	907	5.7	12.7	35.7
2082	157	356	1012	6.2	14.0	39.9
2087	168	390	1122	6.6	15.3	44.2
2092	179	425	1237	7.1	16.7	48.7
2097	190	462	1357	7.5	18.2	53.4
2102	202	500	1482	7.9	19.7	58.4
2107	213	539	1612	8.4	21.2	63.5
2112	224	579	1748	8.8	22.8	68.8

(b) Evaluation of SLC Impacts to Alternative O, Phase I.

– The effect of SLC on BBCW habitat will vary, depending on the location and elevation of the affected lands and to some extent the placement of the project features. Alternative O, Phase 1 project components are located east of the Homestead portion of the L-31E Levee, in the Cutler Wetlands, and at Deering Estates in the north. The dividing line between the freshwater wetland habitat and the saltwater wetland habitat is generally considered to be the L-31E levee, although some remnant freshwater wetland habitat exists in the Cutler Wetlands east of L-31E. Elevation cross sections of the project area are shown in Figures F-4 and F-5. Maps of the L-31E and Cutler Wetlands components with MSL and MSL+2ft (0.6m) SLC are shown in Figures F-6 through F-9. Based on the topography and sea level conditions shown in these figures, it appears that SLC will impact the saltwater wetland habitat east of the L-31E levee to the greatest extent.

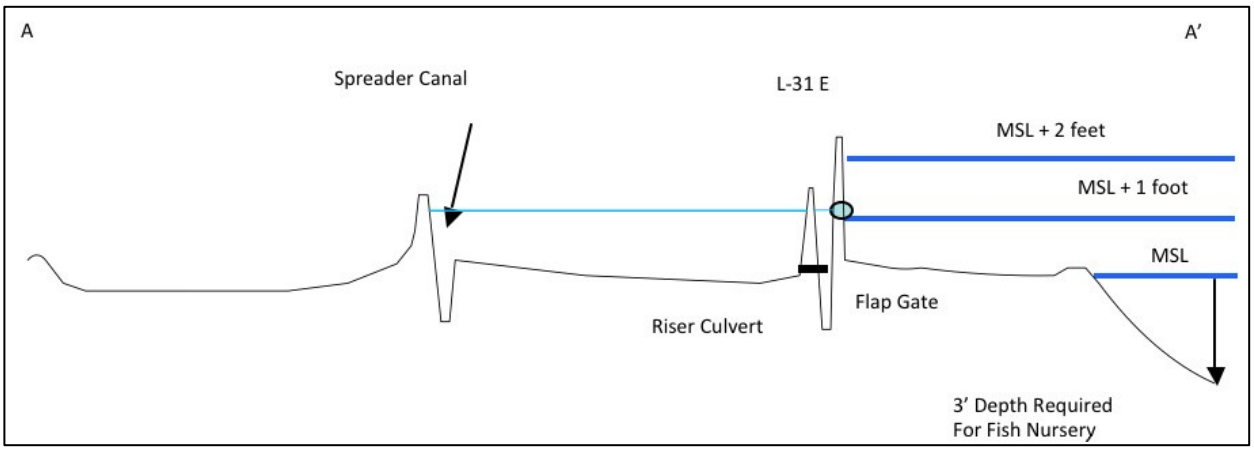


Figure F-4. Homestead Wetlands (Cross section A–A´).

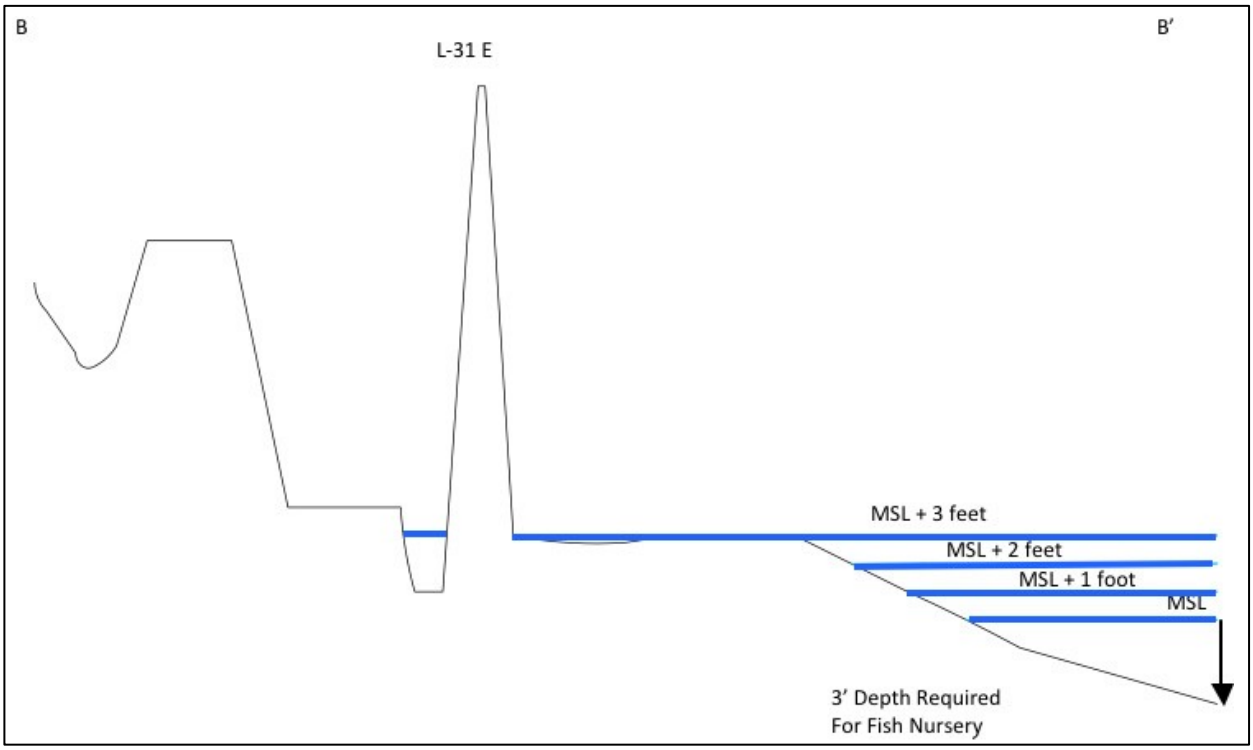


Figure F-5. L-31E Cutler Wetlands (Cross section B–B´).

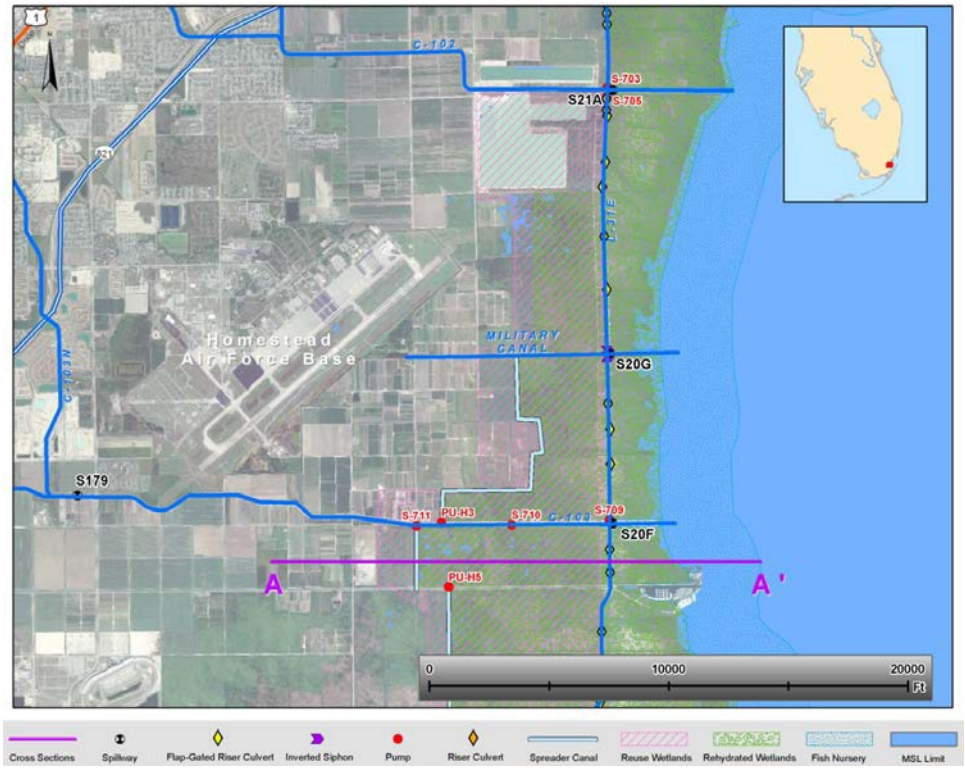


Figure F-6. Homestead Wetland area as impacted by MSL.

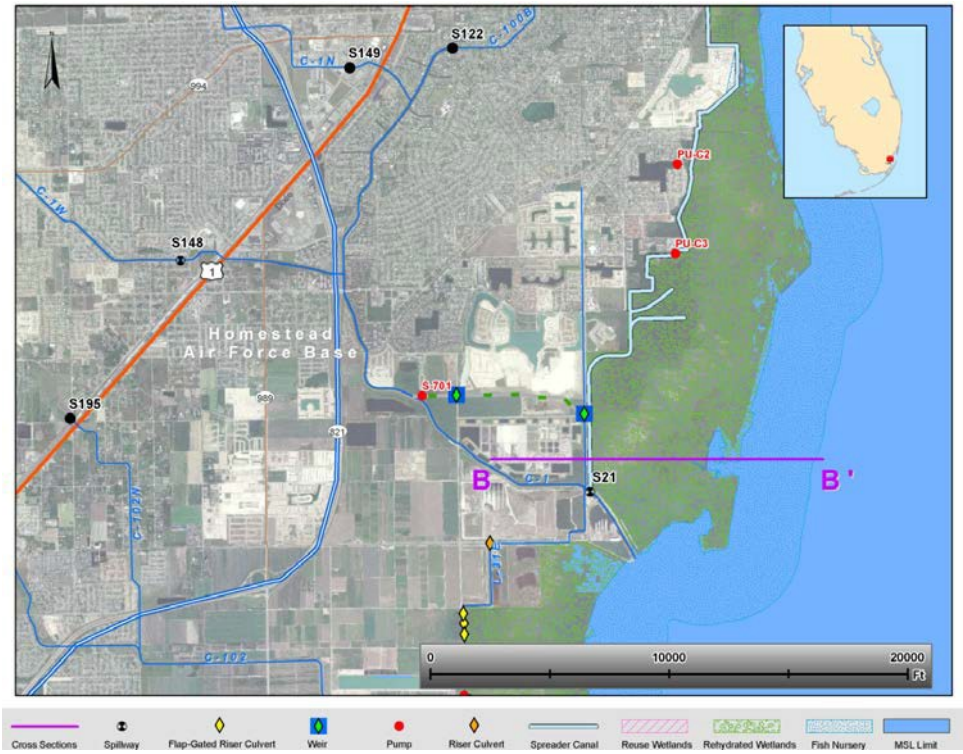


Figure F-7. Cutler Wetland area as impacted by MSL.

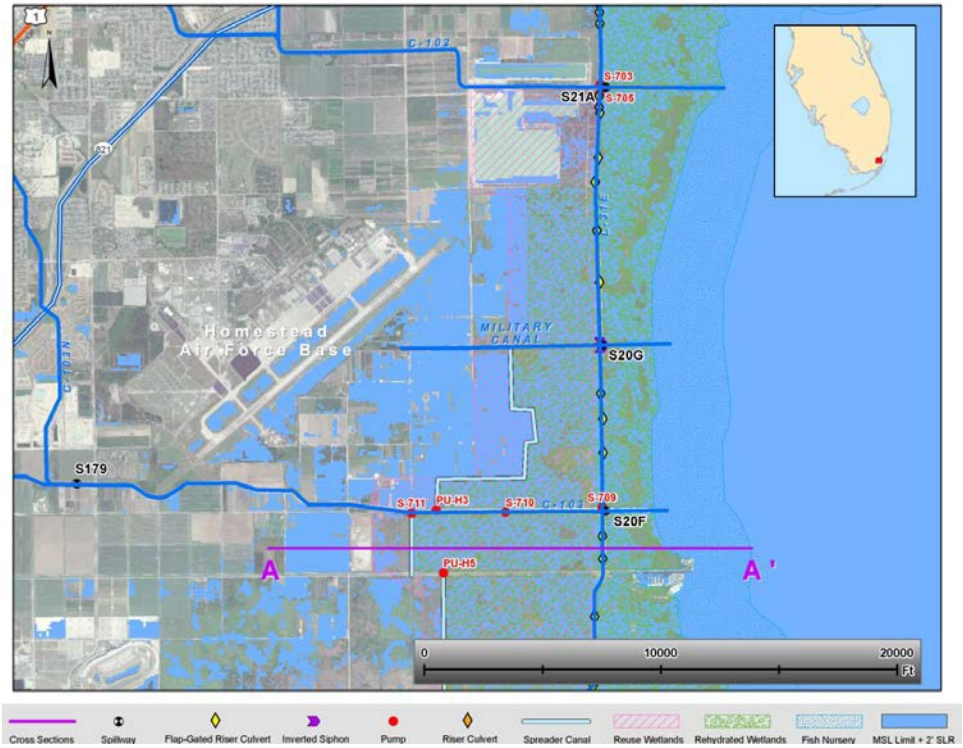


Figure F-8. Homestead Wetland area as impacted by MSL+2ft (0.6m) SLC.

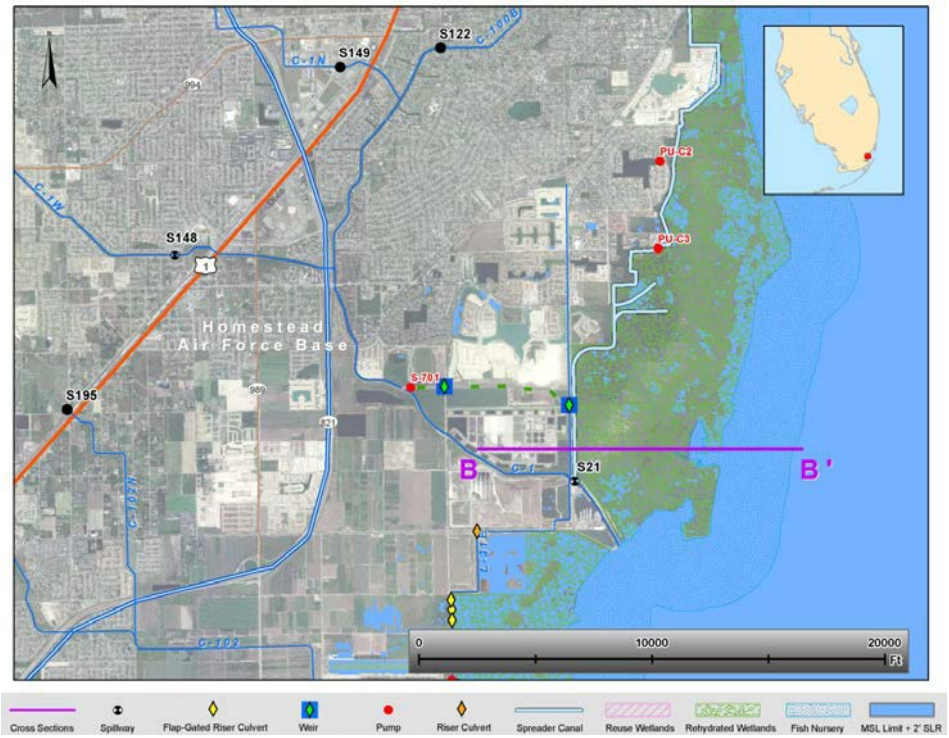


Figure F-9. Cutler Wetland as impacted by MSL+2ft (0.6m) SLC.

– To assist in evaluating the likely effect of sea level rise on project benefits, the areas where the freshwater and saltwater rehydration benefits are expected to occur were mapped. For saltwater wetland-related project benefits, the degree to which the flooded area covers the benefitted zone under different MSL plus SLC projections is used to indicate how benefits are likely to be reduced by sea level rise. The maps of the L-31E Wetland components show that 24 in. of SLC will result in substantial flooding of the lands between L-31E and Homestead Air Reserve Base. These lands are where most of the freshwater wetland benefits are assumed to occur. Freshwater wetland benefits are assumed to be 50% impacted when SLC approaches 24 in. These freshwater wetlands will begin to transition to saltwater wetland habitat because of an increase in the salinity of surface water and shallow groundwater.

– The estimate of the effects of SLC on the near-shore salinity benefits resulting from this project is less quantitative than that for the saltwater wetland benefits. Given the gentle slope of the saltwater wetlands east of L-31E, SLC is expected to result in the translocation of estuarine nursery habitat westward as MSL increases. At higher SLC projections, the L-31E levee may act as a boundary that limits the further translocation of near-shore nursery habitat.

– Using the methodology described above, qualitative assessments of the SLC impact to project benefits are discussed for three SLC projections for three different points in time. Table F-10 shows the distribution of project-related restoration benefits across the three component areas and three ecozones. The reduction in ecozone benefits was estimated using the GIS maps and cross sections shown in Figures F-4 through F-9. For relative increases in SLC of less than 1ft (0.3m), simple interpolation was done to estimate the loss of project benefits. Note that GIS

maps of the Deering Estates component were not generated for this analysis. The SLC-related benefit reductions for the Deering Estates component were estimated to be similar to those expected at Cutler Wetland.

Table F-10. Approximate distribution of ecosystem benefits (measured in habitat units) across the three component groups for Alternative O, phase 1.

Region	Freshwater ecozone	Saltwater ecozone	Nearshore ecozone	Total
Deering	6	191	177	374
Cutler	0	3089	1387	4476
L-31E	277	3116	1387	4779
Total	283	6396	2950	9629

– Figures F-4 and F-5 show elevation cross sections from Homestead Wetlands and Cutler Wetlands. The location of the benefited areas relative to the flood conditions for MSL and MSL+2 foot conditions are shown in Figures F-6 through F-9 for the Homestead Wetlands and the Cutler Wetlands. These figures were used to estimate benefit losses and are included here for illustrative purposes so that readers can imagine where each combination of SLC scenario and time period might fall. Table F-11 summarizes the percentage of benefits available under five critical SLC scenarios. After 20 years, the low projection for SLC will have no impact on project benefits. The intermediate projection for SLC at 20 years, which is equivalent to the low projection at 50 years, will result in minimal reduction of project benefits. A 7- to 9-in. increase in MSL will likely result in less than 10% reduction in overall project benefits. A 23- to 25-in. increase in MSL (2ft/0.6m scenario) will result in a significant reduction in both the freshwater and the saltwater wetland benefits. This is particularly true for the L-31E Homestead saltwater wetlands, which are shown to be significantly impacted by 2ft/0.6m of SLC in Figure F-8. The Cutler Wetlands area will experience less impact under 2ft/0.6m of SLC, given the higher average land elevation in this area. The impact on SLC on salinity benefits in the near-shore zone under the 2ft/0.6m scenario is expected to be minimal because the zone of optimal salinity conditions will move upland (westward) over time. Under the low SLC projection of 2–4 in. at 20 years, it is possible that deposition in the near-shore, mudbank, and mangrove areas will match SLC so that there would be minimal change in the average embayment depth. Under the moderate to high SLC projections, there may be some change in the total area where salinity conditions are optimal for some mesohaline and oligohaline species. Because of the topography in the saltwater wetland area, particularly in the Cutler Wetland area, it is unlikely that mesohaline and oligohaline areas will be substantially eliminated by SLC under any scenario in 20 years. At the higher SLC estimates, some reduction in the severity and duration of hypersaline conditions in Biscayne Bay proper is likely because the rate of exchange of bay water with ocean water will increase. Freshwater wetland benefits are assumed to be 50% impacted at the high projection in 50 years because approximately half of the target wetlands are within 1 mile of the L-31E levee. Under the moderate to high SLC projections, there may be some change in the total area where salinity conditions are optimal for some mesohaline and oligohaline species. Analyzing the effect of SLC at 100 years is a requirement as part of the

SLC guidance; however, it is important to recognize that the anticipated project benefits are based on a 50-year planning horizon. Thus, any benefits lost to SLC after 50 years would have accrued in the absence of SLC after the anticipated life of the project.

Table F-11. Sea level change impact to Alternative O, Phase 1, project performance.

Increase in mean sea level (in.)	Scenarios	Project performance: % of benefits remaining			
		Freshwater wetland benefits	Saltwater wetland benefits	Near-shore salinity	Total project benefits
2	20-year low	100	100	100	100
3–4	20-year intermediate, 50-year low	100	94	100	96
7–9	20-year high, 50-year intermediate, 100-year low	100	88	100	92
23–35	50-year high, 100-year intermediate	48	46	88	59
69	100-year high	0	0	0	0

– Figure F-10 shows the expected benefit response pattern as it is impacted by sea level rise. The response curves in this figure are based on the assumption that it takes 10 years to build up to the expected maximum habitat improvement. The expected impacts to the three ecozones that result from the 20-year and 50-year high sea level rise scenarios are shown by the decline in annual benefit performance after 10 years. Linear interpolation is used to estimate the benefit performance between the inflection points. In this analysis, there is not expected to be an impact to near-shore benefits at 20 years, but at 50 years, these benefits are estimated to be reduced by approximately 12%. At 20 years, the saltwater wetland benefits are estimated to be reduced by approximately 12%, while at 50 years, these benefits would be reduced by approximately 54%. There is not expected to be an impact to freshwater wetland benefits at 20 years, but at 50 years, these benefits are estimated to be reduced by approximately 52%. The average annual project benefits for Alternative O, Phase 1 are expected to be reduced by sea level rise by 17% over the 50-year life of the project, compared to the annualized benefit estimates for future conditions not impacted by sea level rise.

– An analysis of SLC impacts on each of the plans included in the final array of project alternatives has been prepared by using the likely preferred plan (Alternative O, Phase 1) as the basis for determining relative impact. This was done because all of the planning alternatives are expected to experience similar impacts from SLC, as they include similar features located in the same general area relative to the existing coastline. A short discussion of each of the final alternatives follows. [Maps and full descriptions of each of the project alternatives can be found in USACE (2011a).]

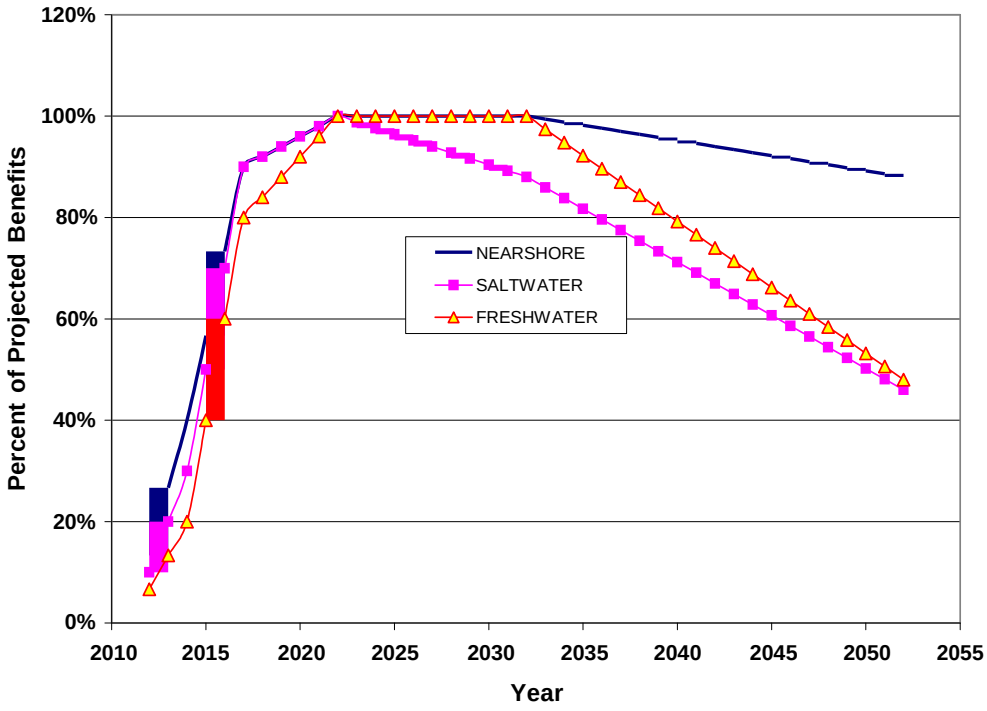


Figure F-10. Effect of sea level rise on projected benefit stream for Alternative O, Phase 1.

- Alternatives YB and Q: These two alternatives generate more freshwater wetland benefits and fewer saltwater wetland and near-shore salinity benefits than Alternative O, Phase 1. SLC conditions less than approximately 24 in. would likely result in less impairment to overall project benefits for these two alternatives compared to Alternative O, Phase 1. Conversely, some of the project-related freshwater wetland rehydration (and the associated project benefits) would likely occur in the absence of the project as a result of increased groundwater stages caused by sea level rise. This is particularly true for the higher SLC projections, because maintaining the existing level of flood protection will be difficult given the porous nature of the underlying Biscayne Aquifer. For SLC in excess of 24 in., the freshwater wetlands restored by these alternatives will likely begin to transition to saltwater wetlands, particularly in areas directly west of the L-31E levee.

- Alternative O: For SLC less than 24 in., this alternative would experience less impairment to the predicted benefits than Alternative O, Phase 1, because a larger proportion of the benefits would come from freshwater wetland restoration. For SLC above 24 in., this alternative would begin to lose freshwater wetland benefits for rehydrated areas directly adjacent to the L-31E levee as these wetlands begin to transition to saltwater species.

- Alternative M: This alternative generates almost all of its benefits east of the L-31E levee. In the L-31E wetlands area, the alternative does not include pumps to move water over or through the levee. This means that project benefits are particularly at risk because higher sea level conditions will reduce the flow rate through culverts in L-31E.

Thus, under any SLC condition, the benefits from this alternative would be reduced to a greater extent than for any of the other with-project alternatives.

- Alternative O, Phase 1: This alternative is the basis for all relative comparisons of SLC impacts to with-project alternatives.

- No Action Alternative: As sea levels rise, the critical habitat where oligohaline and mesohaline salinity conditions exist in the saltwater wetlands and mangroves east of the L-31E levee will shrink relative to the existing conditions. Freshwater wetland areas will likely experience some beneficial rehydration as a result of moderate SLC due to the increased groundwater stage; however, at levels above 24 in. of SLC, freshwater wetlands in areas south of the C-1 canal and adjacent to the L-31E levee are likely to begin to transition to saltwater species as flood protection efforts begin to fail.

(c) Alternative Adaptation and Design Considerations.

– The SLC impact analysis performed for this project relies on the assumption that targeted habitats will migrate inland as SLC occurs. While this is likely to be the case for the initial increase in mean sea level, eventually the habitats will migrate onto farmlands that are not now under public ownership. Public ownership is not a prerequisite to habitat migration, because some farm owners experiencing higher mean sea levels that impact their land uses will eventually abandon their lands rather than fight increased flooding and salinity impact. However, public ownership will facilitate habitat migration by limiting the placement of barriers such as farm levees. Since long-term maintenance of benefits provided by this project are predicated on the assumption that habitats will migrate inland and that lands will be available for this, the project delivery team should incorporate SLC adaptation into the project adaptive management plan.

– To reduce the risk associated with project implementation, flexibility in the design and operation of features can be incorporated into the project during the planning engineering and design (PED) phase. For instance, pump station equipment, culverts, and distribution canals can be designed to accommodate higher headwater and tailwater elevations. Impoundment levees can be designed for higher tide and storm surge conditions. Future modifications of the project features or operations to counteract the impact of sea level rise should be focused on preserving and maintaining project benefits as well as existing coastal habitat. Project modifications that both preserve project benefits and enhance flood protection are preferred if they are available. Features planned and operated for one purpose can be repurposed as SLC begins to affect water management needs in the future. For instance, the planned S-705 pump station that is located at the intersection of the C-102 canal and the L-31E levee can be repurposed to help maintain a hydraulic barrier of fresh water in the L-31E borrow canal. Similarly, as SLC contributes to marginal decreases in the C-103 canal system's ability to provide flood protection due to increased tailwater conditions at S-20F, the project's S-710 and S-711 pump stations can be used to assist in removing some of the marginal increase in flood flows from the C-103 canal. Rather than compromise the project, such a modification would likely enhance the freshwater wetland habitat downstream of these two pump stations.

– More extreme methods of preserving the targeted habitat, such as breaching the existing L-31E levee and constructing a new one farther inland, are outside of the scope of the BBCW project at this time; however, they may be considered in the future as a method of ensuring the future existence of near-shore and tidal wetland habitat in the project area.

(d) Residual Risk. As with the predictions of future rates of SLC, there is uncertainty in the estimates of effects to project-related ecosystem benefits because of the accuracy and reliability of the datasets and methodology used in this analysis. The MSL flood prediction maps are based on topographic data that are known to be accurate to within 0.5ft (0.15m). The land elevation is assumed to be static over the 20-, 50-, and 100-year periods; however, topographic change is likely to occur in the saltwater wetland areas as a result of SLC and other natural processes. The performance metrics used to evaluate the alternatives considered for this project were developed for static sea level conditions. These metrics did not incorporate some of the processes and functions known to vary with increased mean sea level. Preserving project benefits relies on the eventual migration of targeted habitats into inland areas presently utilized as farmland, but not all of this land is now in public ownership. Additionally, there is uncertainty about how long it will take before migrated habitats become substantially productive. Despite these limitations and inherent uncertainties, the analysis is presented here since it is the most reliable information available at this time.

(4) Conclusion.

(a) This analysis looked at the effect of sea level rise on the benefits predicted for the selected Alternative O, Phase 1. The results indicate that within the 20-year planning horizon, less than 10% of the project ecosystem benefits are likely to be at risk from SLC. At the end of the 50-year planning horizon, the benefits attributed to the selected plan may be diminished by as much as 40% as a result of sea level rise. Limited impacts to project benefits are anticipated at the low and moderate SLC projections at 50 years. Under the high SLC scenario at 100 years, the project benefits will not occur. As mentioned above, the project is justified based on a 50-year project service lifespan. The effects of SLC on project benefits that occur after the 50-year project service lifespan should be treated the same as benefits that occur after the project service lifespan. In other words, effects that occur after the 50-year project service lifespan should not be considered for plan selection or determination of project viability. The effects observed after the 50-year project service lifespan, however, can inform the PDT regarding the long-term sustainability of the project in that location.

(b) A qualitative comparison of SLC impacts to benefits accorded other project alternatives was done. This analysis showed that the selected plan will likely experience a greater percent reduction in overall benefits compared to the alternatives that focus on freshwater wetland rehydration (Alternatives YB and Q); however, these alternatives would not provide as much preservation of the critical oligohaline and mesohaline habitat located east of the L-31E levee. In comparison to the No Action Alternative, the selected plan will provide more protection to oligohaline and mesohaline habitat located east of the L-31E levee. The selected plan should perform the same as the No Action Alternative in terms of the effects to most of the freshwater wetland habitat west of the levee.

b. Level 1 Analysis Examples.

(1) Puget Sound Nearshore Ecosystem Restoration Project. For this project, a qualitative analysis of SLC impacts was prepared to discuss the potential ramifications of SLC on project management measures. Level 1 SLC qualitative analysis was considered the appropriate level of analysis, given that the project was in the feasibility stage. The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP), located in coastal Washington State, qualitatively considered the effects that projected future SLC could have on the management, planning, design, construction, operation, and maintenance of Federal coastal projects. The PSNERP PDT evaluated the relative sensitivity of the 21 near-shore management measures (described in the main body of the Management Measures Technical Report) to the projected range of sea level rise for the Puget Sound region. The qualitative assessment relies on the referenced data and conclusions of qualified scientific experts, which have been developed over many years. A copy of the SLC analysis for this project can be obtained from Planning Division at the Seattle District of USACE.

(2) Broward County Water Preserve Area. For this project, a semi-quantitative assessment of SLC impacts was used to describe future SLC impacts to project performance. A Level 1 SLC analysis approach was considered to be sufficient because the project study was well underway before the implementation of recent SLC guidance. The Broward County Water Preserve Area (BCWPA) project is located approximately 20 miles inland from the Atlantic coastline of southeastern Florida. This project is potentially subject to sea level rise impacts because of the relatively flat topography of the region. The restoration benefits projected for this project are associated with the rehydration of freshwater wetlands and the improvement in the quality of water diverted from local drainage and water supply canals. A semi-quantitative analysis of SLC impacts was conducted for the Project Implementation Report (PIR) using best professional judgment regarding the potential for decreased project benefits that might result from reduced flood control capacity in the local drainage network. The impacts analysis was carried out late in the planning process, so the assessment focuses on the selected plan. A copy of the SLC analysis for this project can be obtained from Planning Division at the Jacksonville District of USACE.

c. Level 2 Analysis Example. For the C-111 Spreader Canal Western Features project, a semi-quantitative assessment of SLC impacts was used to describe future SLC impacts to project benefits. A Level 2 SLC analysis approach was considered to be sufficient because the project study was well underway before the implementation of recent SLC guidance. The C-111 Spreader Canal Western Features project is located in southern Miami-Dade County. The project will be subject to sea level rise impacts because the project features are located directly adjacent to Florida Bay and the coastal zone of Everglades National Park, which are both tidally influenced. This project is justified solely based on ecosystem benefits such as near-shore salinity control, tidal wetland rehydration, and freshwater wetland rehydration. Per USACE guidance, a sea level rise impacts analysis was conducted for the project implementation plan. The impacts analysis was carried out late in the planning process, so the assessment focuses on the selected plan. The analysis was done by mapping coastal land elevations and future mean sea level (MSL) projections at MSL+1ft (0.3m), MSL+2ft (0.6m), MSL+3ft (0.9m), MSL+4ft (1.2m), and MSL+5ft (1.5m) against a map of areas where project benefits were expected to

accrue. Estimates of project benefit impacts were made based on a comparison of targeted benefit acreage and inundated acreage at each future sea level projection. This SLC analysis is included in the *C-111 Spreader Canal-Western Features, Integrated Project Implementation Report and Environmental Impact Statement* available from the Jacksonville District of USACE.

d. Level 3 Analysis Examples.

(1) Medium Diversion at White Ditch. The goal of this ecosystem restoration project is to maintain and restore wetlands in the lower Mississippi River delta by creating a river diversion through a canal called White Ditch to a degrading wetland area in the lower Mississippi River delta. A Level 3 screening tool was used to incorporate sea level rise and subsidence processes with wetland creation through river diversions. The tool, the SAND2 model, developed by ERDC-EL, is spreadsheet based and fairly simple to use. The model develops wetland-acres-created projections based on sediment and nutrient input assumptions that create a wetland acre based on a typical wetland bulk density. A starting condition in the receiving area where freshwater and sediment are diverted is depth based and will change over time based on the relative sea level rise (RSLR) rate chosen. The receiving area is considered to be a degraded wetland habitat with patches of open shallow water to completely open shallow water at a certain average depth baseline, which is adjusted over time based on the desired RSLR rate (reflecting eustatic sea level and subsidence processes in the receiving area). As the process inputs accumulate sediment and nutrient inputs from the river diversion, wetland acres fill the receiving area shallow open water depth cells, and the wetland habitat acres are accounted for in the spreadsheet model over time. The wetland creation is offset by the gradual RSLR rate impacting the area needed to fill in the receiving area, mimicking the habitat stressors responsible for wetland loss. The somewhat simplistic model produces an accounting of potential wetland acres based on the inputs of sediment and nutrients. The model can also account for climate stressors by changing the water, sediment, and nutrient inputs to reflect drought and flood periods. Other stressors such as wind and wave action and hurricanes are not represented in the model but do account for catastrophic wetland loss on an episodic nature. As such, the model produces an upper limit of potential habitat created and provides a valuable screening tool to assess a number of potential alternatives during plan formulation. A copy of this SLC analysis is included in the *Authorization Report for the Medium Diversion at White Ditch* available from the New Orleans District of USACE.

(2) Application of Sea Level Affects Marsh Model (SLAMM).

– The SLAMM is an example of a tool that directly incorporates multiple physical and chemical processes into the evaluation of sea level effects on coastal habitat. The SLAMM integrates potential future scenarios of global sea level rise with data inputs such as area-specific NOAA tidal data, detailed wetland information from the U.S. Fish and Wildlife Service's National Wetlands Inventory, regional light-imaging detection and ranging (LiDAR) data, and USGS digital elevation maps to project potential habitat changes. One of the benefits of the SLAMM model is that it integrates multiple processes and data sets in an attempt to maximize realism. For example, it can assess the extent to which seawater inundation contributes to the conversion of one habitat type to another by looking at elevation, habitat type, slope, sedimentation and accretion, erosion, and the extent to which the affected area is protected by

dikes or other structures. In addition, SLAMM accounts for relative changes in sea level for each study site. Relative sea level rise is calculated as the sum of the historic eustatic trend, the site-specific rate of change of coastal elevation due to subsidence, changes in natural sediment loads, rates of marsh accretion, and the accelerated sea level rise, depending on the future scenario chosen. Within SLAMM, there are five primary processes that affect wetland fate under different scenarios: inundation, erosion, overwash, saturation, and accretion (Glick et al. 2010).

– Two examples of applying the SLAMM model are provided as web links. Neither of these examples comes from USACE documents; however, they are provided here because the SLAMM model can be easily adapted to USACE's SLC assessment requirements. The first example is for the application of the model to marshlands located in Cook Inlet in Alaska. This area is subject to regional land uplift, so sea level rise impacts are limited. The second example application of SLAMM is for Grand Bay National Estuarine Research Reserve located near Moss Point, Mississippi. This area is subject to regional land subsidence, so sea level rise impacts are significant. Information on SLAMM is available at the following web sites:

- Application of Sea Level Affecting Marshes Model (SLAMM) to Alaska's Cook Inlet (http://www.fws.gov/slamm/Alaska%20SLAMM%20Summary%20Report-1.ashx.pdf)
- Application of SLAMM model to Western Gulf Coast (http://warrenpinnacle.com/prof/SLAMM/GrandBayFinal.pdf).

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX G

Example Project: Incorporating Sea Level Change into the Analysis and Design of a Coastal Storm Damage Reduction Project

G-1. Introduction.

a. This appendix provides an example of how this guidance can be applied to a Coastal Storm Damage Reduction (CSDR) project. Portions, or all, of the example may be applicable to other project areas, depending on their vulnerability to SLC and other project-specific factors. Similarly, another project area may require analysis in addition to that described here. This example is designed to provide further description of several methods outlined in Appendix D.

b. The example project area is located on a barrier island fronting the Atlantic Ocean in northeast Florida. The example assumes that the project is in the feasibility study stage. However, the methods described are also applicable to projects being re-evaluated or studied for SLC impacts to project performance.

G-2. Tiered Analysis Based on Potential Risk of Sea Level Change. A tiered analysis is recommended to determine the risk of potential SLC and to incorporate the results into the plan formulation process. Incorporating potential SLC into the SMART planning process will require an active focus on risk-based scoping to define pertinent needs, opportunities, and appropriate level of detail for conducting investigations. In particular, close attention is needed at the beginning of each study to screen planning and scoping decisions. A risk-based approach to study execution facilitates the appropriate study layout and selection of tools such that time and money are spent cost effectively and efficiently. The tiered analysis process is shown in Figure 9. The six-step planning process detailed in the *Planning Guidance Notebook* (ER 1105-2-100) incorporates this tiered approach.

G-3. Tier 1 – Establish Strategic Decision Context.

a. The first step in the process outlined in Figure 9 is to establish a broad understanding of how SLC may impact the study area. Currently, there is no constructed Federal CSDR project in the study area. The example feasibility study is implemented under the Flood Risk Reduction business line, Hurricane and Storm Damage Reduction mission area. Reduction of storm damage to infrastructure and maintenance of existing environmental and recreation benefits are the focus of the study. Life safety is minimally considered because it is assumed that the study area can be evacuated prior to significant storm impacts. The shoreline in the study area has been, and continues to be, developed without the presence of a dedicated Federal CSDR project. It is therefore assumed that development of the study area will continue to occur with or without a CSDR project in place.

b. A CSDR project may feasibly reduce storm damage caused by SLC over a certain period, but it may not protect against the impact of elevated sea levels on other systems or resources on which the project area relies. For example, the infrastructure in the study area relies

on gravity storm drainage. As sea level rises, the potential for reduced drainage and subsequent flooding increases. Any CSDR project formulated by this study would not decrease this potential. Other systems and resources that the study area may depend on, and that would not necessarily benefit from a CSDR project, include electrical power and sanitary sewer systems.

c. To evaluate SLC impacts to infrastructure, critical resources, and residents of the study area, a qualitative matrix was developed (Table G-1). Resources evaluated in the matrix were based on those identified by the USACE Coastal Systems Portfolio Initiative (CSPI). CSPI describes the resource risk in a project area relative to the density of the resource, the population density that the resource serves, or, in the case of environment/habitat and recreation, the value placed on the resource. See http://cspi.usace.army.mil for more information.

d. The qualitative matrix shown in Table G-1 evaluates the resources on which the study area depends. In addition to the CSPI evaluation criteria, Table G-1 evaluates the vulnerability to resources from potential SLC, or sea level rise (SLR) in the case of the study area. The average vulnerability from SLR is 1.2, which represents a relatively low vulnerability of resources. This indicates that SLR is not a major contributor to overall resource vulnerability within the 50-year period of analysis.

e. Overall, the initial analysis above indicates that the project area's vulnerability to SLC is relatively low and that potential SLR is not a major contributor to future damages over the 50-year planning horizon. However, elevations within the project area (the Atlantic Ocean side of the island) are some of the highest on the barrier island, about 15–20ft (4.6–6.1m) above mean sea level (MSL). The profile of the island slopes downward from these elevations to the landward side (the marsh side), where the lowest elevations of infrastructure are approximately 2–10ft (0.6–3.0m) above current MSL. The island profile is shown in Figure G-1. Areas on the marsh side of the island will likely be impacted by inundation more frequently than on the ocean side as sea level rises, especially during extreme high tide events.

f. A relatively low risk from SLC to the project area combined with high uncertainty over potential accelerations in the rate of SLC led to an adaptive management strategy.

Table G-1. Qualitative matrix showing vulnerability of resources from potential SLC.

Resource	Risk rating from CSPI*	Description	Vuln. from SLR*	Description
Residential and commercial structures	2	Mostly residential (single-family homes) and commercial structures. Approximately 50% of the project area is currently protected by revetment or seawall of varying quality. Most ground floor elevations of structures are 14ft/4.3m above existing Mean Sea Level (MSL).	1	Projected high SLC scenario would not place MSL near infrastructure within 50-year planning horizon and would increase the flood frequency very minimally. Typical surge experienced in project area from large coastal storms is 2–4ft (0.6-1.2m). This indicates that SLR is not a major contributor to future damages over the 50-year planning horizon.
Environment and habitat	3	Beach/dune habitat. Narrow, steep beach backed by average 18.5ft (5.6m) high dunes. Where no dune exists, revetments or seawalls of varying quality have been constructed.	2	Beach berm and dune system is located between 10.5 and 18.5ft (3.2 and 5.6m) above MSL. Subaerial habitat is located throughout this system.
Infrastructure (roads, water/sewer lines, boardwalks, navigation structures)	2	Water/sewer lines, septic tanks, revetment and dune walkovers exist. State Road A1A is approx. 14ft (4.3m) above MSL. Most other infrastructure not impacted until water level, including storm surge, reaches above this point. The 10-year return period storm tide level is equal to 4ft (1.2m).	1	By the end of the 50-year planning horizon, State Road A1A remains adequately elevated above MSL under any SLC scenario. A 12ft (3.7m) difference would remain between MSL and A1A.
Critical facilities (police, fire, schools, hosp., nursing homes)	1	Low density of critical facilities	1	Elevation of most critical facilities remains above MSL under any SLC scenario by the end of the 50-year planning horizon.
Evacuation routes	3	State Road A1A is main north/south evacuation route, located approximately 14ft (4.3m) above MSL.	1	At end of the 50-year planning horizon, State Road A1A remains adequately elevated above MSL under any SLC scenario. Even under high SLC scenario, a 12ft (3.7m) difference would remain between MSL and A1A.

Recreation	3	Significant recreational use of beaches and fishing pier	1	Beach berm is approximately 10.5ft (3.2m) above current MSL. Recreational use of beach is high. Fishing pier deck is approximately 25ft (7.6m) above current MSL. Projected high SLC scenario would not impact pier within 50-year planning horizon.
		Average =	1.2	Low vulnerability

* 3 = high, 2 = medium, 1 = low, X = not present

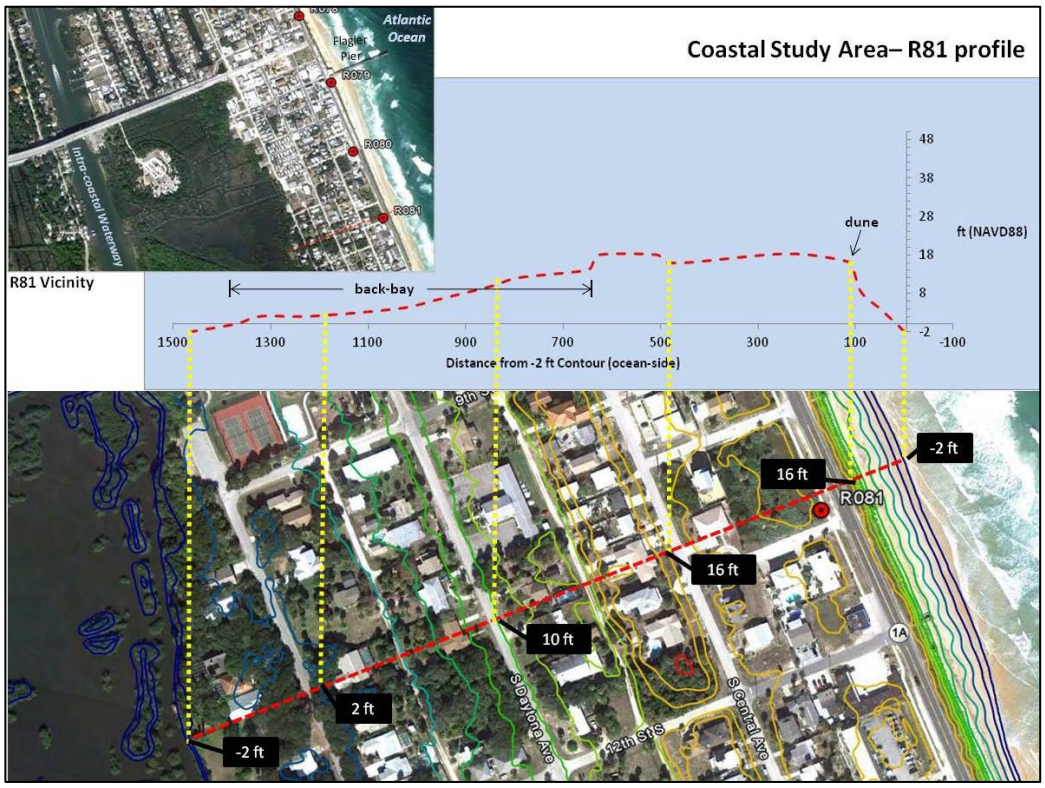


Figure G-1. Project area profile.

G-4. Tier 2 - Project Area Vulnerability to SLC.

a. This guidance provides a methodology for determining a range of SLR estimates based on the local historic SLR rate, the construction (base) year of the project, and the design life of the project. Three estimates are required by the guidance: a baseline estimate representing the minimum expected SLC, an intermediate estimate, and a high estimate representing the maximum expected SLC. From Equation B-3 in Appendix B, the baseline, intermediate, and high SLR values were estimated for the project area.

Based on historical sea level measurements taken from National Ocean Service (NOS) gauge 8720218 at Mayport, Florida (Mayport Bar Pilots Dock), the historic SLR rate was determined to be 2.4 mm/year

(0.0079 ft/year). The project base year for potential construction was specified as 2014. The period of analysis was

projected to be 50 years, and SLC estimates were calculated for 100 years. Following calculations outlined in the Appendix B, the average baseline, intermediate, and high SLR rates were found to be 0.0079 (2.4 mm), 0.0161 (4.9mm), and 0.0428 (13mm) ft/year, respectively (Figure G-2).

b. Problems for the study area, which are typical for CSDR projects around the U.S., include threat of infrastructure damage, loss of habitat and current recreation from effects of waves, erosion, and inundation caused by coastal storms. Opportunities exist to reduce infrastructure damage and maintain existing habitat and recreation. Rising sea level is a component of overall damages caused by erosion, inundation, and wave attack that contribute to problems in the study area. SLC does not necessarily constitute a new problem but potentially exacerbates those problems already identified. Existing condition data pertinent to this SLC assessment are included in Table G-2.

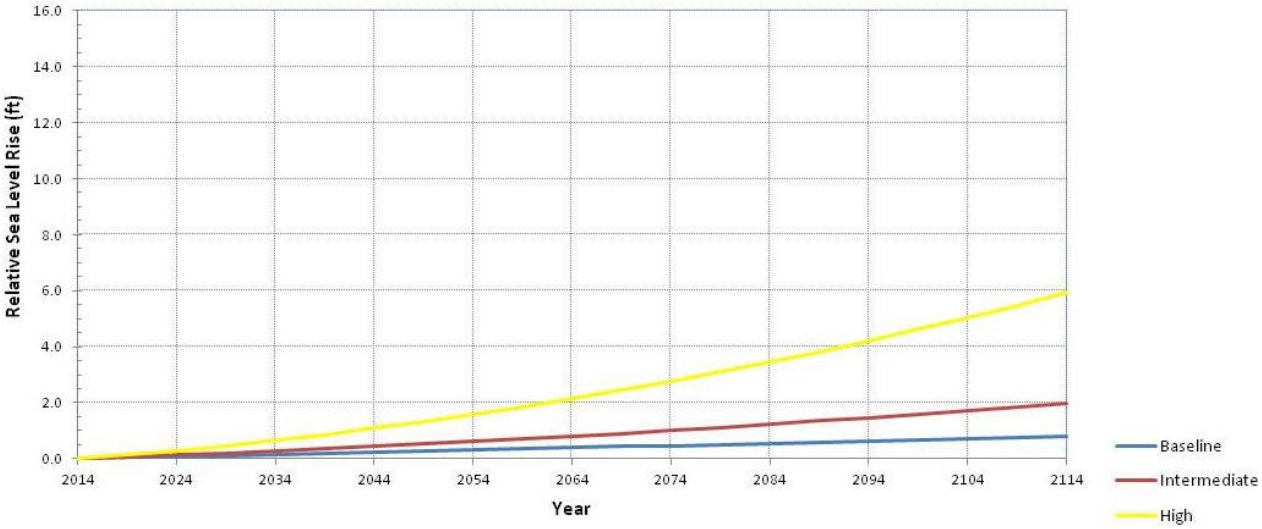


Figure G-2. Relative sea level rise over 100 years for the project area.

Table G-2. Existing conditions pertinent to SLC assessment.

Project Location: Florida, barrier island on northeast Atlantic coastline

Pertinent Data: elevations are averages of reaches

	Project location	Flagler County, FL
	Analysis initiation date	2014
	Project area length	9.03 miles (shoreline length)
	Project area width	from MHW line to 400 feet inland
	Natural berm width	0 ft (no "flat" berm)
	Natural foreshore slope	0.4
	Natural berm height	11.0 ft NAVD88 11.46 ft MSL
	Upland height	14.5 ft NAVD88 14.86 ft MSL
	Natural dune height	19.0 ft NAVD88 19.46 ft MSL
	measured SLR	2.40 +/- 0.31 mm/yr (0.0076 ft/yr)
	NOS gage 8720218 - Mayport, Florida	
Relative SLR rates:	**baseline**	+2.40 mm/year (0.0079 ft/year)
	intermediate	+4.90 mm/year (0.0161 ft/year)
	high	+13.05 mm/year (0.0428 ft/year)

Tides (Atlantic Ocean)

semi-diurnal	
mean range	4.2 ft
spring tide	5.1 ft

Combined Total Storm Tide Values for Various Return Periods

Return Period TR (years)	Combined Total Storm Tide Level* above NAVD88 (ft.) Middle Profile (R-55)	Relative to MSL (ft.)
500	15.67	16.13
200	12.87	13.33
100	10.77	11.23
50	8.37	8.83
20	5.37	5.83
10	3.87	4.33

*Includes contributions of: wind stress, barometric pressure, dynamic wave set-up and astronomical tide.
0 ft NAVD88 = 1.03 ft NGVD

Original data from Beaches and Shores Resource Center, Florida State University in NGVD

NOS bench mark #8720686	Ft Matanzas			
MHW	1.231	meters	4.04	feet
NAVD88	0.807		2.65	
MSL	0.667		2.19	
MLLW	0			
NOS bench mark #8720757	Bings Landing, Matanzas River - back-bay side of barrier island			
MHW	0.491	meters	1.61	feet
NAVD88	0.334		1.10	
MSL	0.284		0.93	
MLLW	0			

c. The guidance suggests using the high SLC curve to define the study area. In the project area, the ocean-front area from MHW to 400ft (121.9m) inland should adequately cover the area impacted by erosion, inundation, and wave attack through a 50-year period of analysis under the high SLC scenario. The majority of the ocean-front area is fronted by 18ft (24.7m) high dunes relative to NAVD88, according to surveys carried out by the Florida Department of Environmental Protection (FDEP) at coastal range monuments. These surveys typically extend from the dune crest toward the ocean and do not cover the middle or backbay side of the barrier islands. However, LiDAR data from 2009 were available for the entire barrier island and were used to create Figure G-3. The elevations determined by LiDAR are not as precise as from the FDEP surveys. The LiDAR measurement for the dune crest at R-81 is 16 ft (4.9 m) NAVD88, whereas the surveyed elevation is 18ft (5.5m) NAVD88, a 2ft (0.6 m) difference. The LiDAR data were used in Figure G-3 because they are more conservative and represent the only survey that includes the backbay side of the barrier island.

d. A key question when assessing the vulnerability of the project area to SLC is when the critical thresholds will be crossed, if at all, by potential SLC. The lower portion of Figure G-3

shows two thresholds depicted by horizontal dashed lines, one on the seaward side of the barrier island on which the project area is located and one on the marsh side of the island, outside of the project area.

e. Throughout the project area, the dune crest height represents a critical threshold. State Road A1A (1A in Figures G-3 and 4) is located at roughly this elevation, and most infrastructure, including single-family homes and businesses, is located at or above this elevation, as seen in Figure G-3. Some infrastructure on the marsh side of the island, outside of the project area, is located below this elevation.

f. Mean Sea Level (MSL) is 0.46ft (.14m) lower than 0 ft NAVD88 on the ocean side of the island. Table G-2 shows the 50-year storm tide elevation to be 8.37ft (2.6m) NAVD88. The combined total storm tide includes contributions of wind stress, barometric pressure, dynamic wave set-up, and astronomical tide. Water elevations during such storm events could reach the top of the dunes (16ft/4.9m NAVD88 in Figure G-1) once the sea level increases by about 7ft (2.1m) (8.37ft/2.6m storm tide + 7ft (2.1m) sea level increase + 0.46ft (.14m) MSL/NAVD88 differential ≈ 16ft/4.9m). This estimate does not consider erosion of the dune height, which could occur over time. However, based on past local practice, it can be reasonably assumed that efforts will be made to maintain the dune at its current elevation to protect Highway A1A. At the end of 50 years, the sea level may increase by 2ft (0.6m) under the high SLC scenario, 5ft (1.5m) below the threshold. This indicates that SLR is not a major contributor to future damages in the project area over the 50-year planning horizon.

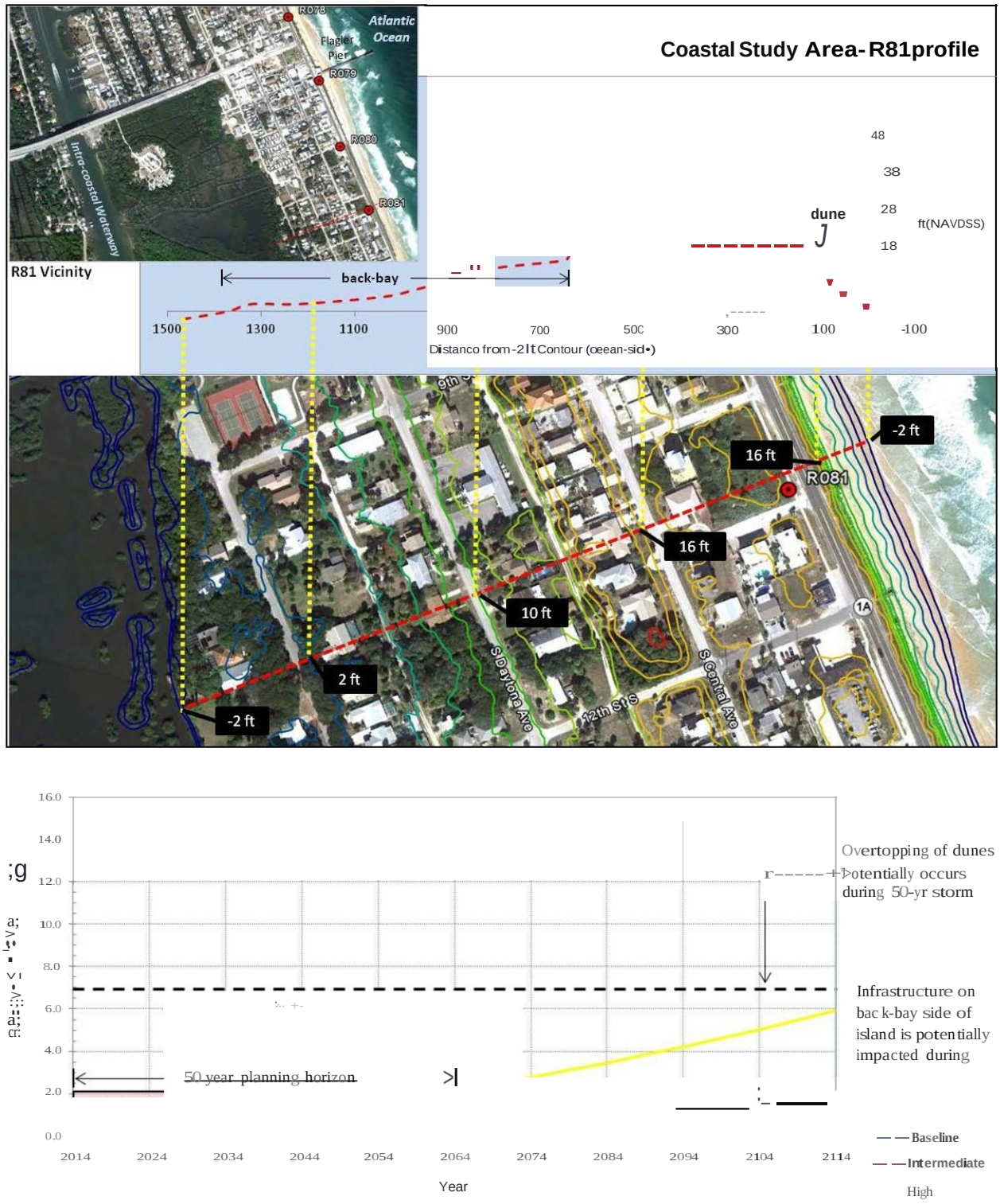


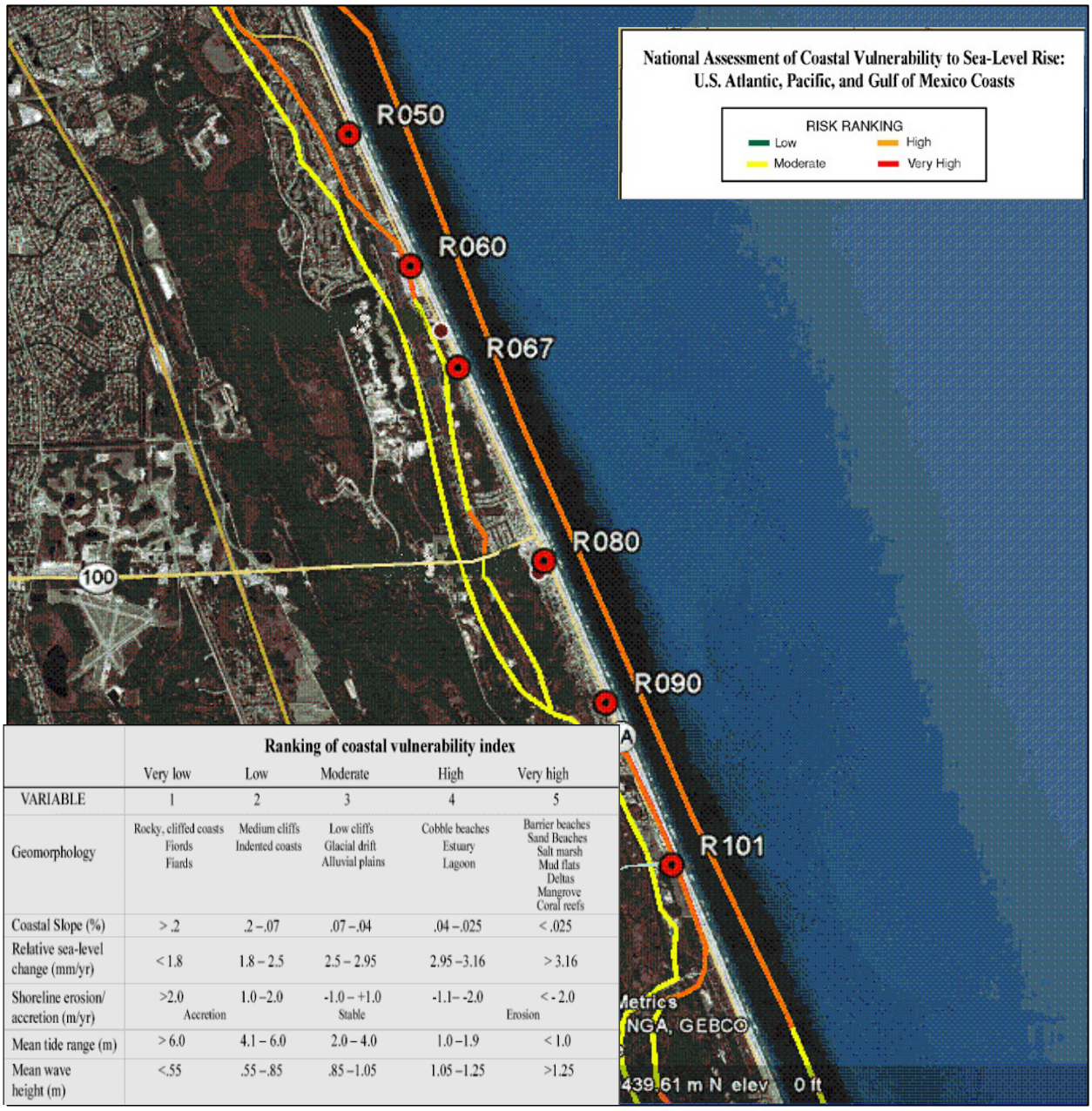
Figure G-3. Project area profile and threshold analysis.

Figure G-4. Atlantic Ocean, beach, and reveted dune system fronting State Road A1A in the project area.

h. The guidance directs that systems outside the project area should also be evaluated for vulnerability to SLC. The vulnerability of the back side of the island was evaluated to inform the sponsor and to determine if there would be impacts to the project area. The project area does not heavily rely on any systems on the back side of the island, such as storm drains. Although the main hurricane evacuation route off the island is located on the back side, it is sufficiently elevated. The MSL on the back side of the island is approximately 0.16ft (0.05m) lower than NAVD88. The infrastructure on the backbay is generally built above 2ft (0.6m) NAVD88 (2.16 MSL), as seen in Figure G-3. This side of the island is mainly affected by tides, not surge, because of its distance from coastal inlets and the resulting sheltering from most factors contributing to combined total storm tide. The tidal range on the back side of the island is smaller than on the ocean side. NOS gauge #8720757 at Bings Landing, Matanzas River, recorded tide levels relevant to the marsh side of the barrier island from October 2003 to September 2004. The mean tide range was 1.47ft/0.45m, with a mean higher high water (MHHW) level of 0.66ft (0.2m) NAVD88. The infrastructure could be periodically impacted once the sea level increases by about 1.2ft (0.4m) (0.66-ft MHHW + 1.2ft (0.4m) sea level increase + 0.16ft/0.05m NAVD88/MSL differential ≈ 2ft/0.6m). The low and medium scenarios are not expected to increase by this much within the 50-year planning horizon, as seen in Figure G-3. However, the high scenario is predicted to surpass this threshold in just over 30 years. If the SLR rate increases to the high scenario, infrastructure on the back side of the island could be

impacted during higher high tide events (spring tide events), depending on current and future construction to protect against elevated water levels such as seawalls and bulkheads. SLC should be monitored to provide adequate lead time to plan for impacts in the case of accelerated SLC.

i. The existing Coastal Vulnerability Index (CVI) developed by the U.S. Geological Survey (USGS) is a useful indicator of the project area's natural vulnerability to SLC. The USGS used six input parameters to assess the CVI for geographic areas along the Nation's shoreline. Parameters used include geomorphology, coastal slope, relative SLC, shoreline erosion and accretion, mean tide range, and mean wave height (Thieler and Hammar-Klose 2000a,b). Population and infrastructure type, or density, are not parameters used in the assessment. Figure G-5 shows that the CVI for the study area is rated as moderate to high because the area is part of an erosional barrier island surrounded by sandy beaches and salt marsh.



	Ranking of coastal vulnerability index				
	Very low	Low	Moderate	High	Very high
VARIABLE	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts Fiords Fiards	Medium cliffs Indented coasts	Low cliffs Glacial drift Alluvial plains	Cobble beaches Estuary Lagoon	Barrier beaches Sand Beaches Salt marsh Mud flats Deltas Mangrove Coral reefs
Coastal Slope (%)	> .2	.2 – .07	.07 – .04	.04 – .025	< .025
Relative sea-level change (mm/yr)	< 1.8	1.8 – 2.5	2.5 – 2.95	2.95 – 3.16	> 3.16
Shoreline erosion/ accretion (m/yr)	>2.0 Accretion	1.0 – 2.0	-1.0 – +1.0 Stable	-1.1 – -2.0	< - 2.0 Erosion
Mean tide range (m)	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	< 1.0
Mean wave height (m)	<.55	.55 – .85	.85 – 1.05	1.05 – 1.25	>1.25

Figure G-5. USGS CVI.

j. As described in the main text and Appendix B, a threshold analysis similar to those done by Dr. Kriebel of the U.S. Naval Academy could be very useful for visually demonstrating how an established threshold, such as the existing ground floor of a building that has been inundated by past high water events, will be exceeded more frequently as sea level rises.

k. The extreme water level analyses highlight an important effect of SLR: because of increasing water levels, future storms will reach higher elevations and will produce greater flood damage than past storms of the same magnitude. A fitting analogy is, “If you raise the floor of a basketball court, you’ll see more dunks.” In an era of rising sea levels, the number and severity of flood events that cross a threshold will increase, leading to more severe damages per storm but also

more damaging storms in a given time, even if there is no change in storm climatology from the present.

l. These analyses are based on monthly high water elevations recorded at NOS tide gauges. Some of these gauges are located inside inlets or are otherwise protected from open ocean waves and surge and are therefore not recording the total water elevation that may be reached at a CSDR project area. The effects of surge, wave run-up, or other water elevation additions should be incorporated into the analysis if possible.

G-5. Tier 3 - Alternative Development Considering SLC. The guidance suggests that areas where SLC provides a relatively small contribution to overall impacts should rely on mostly qualitative SLC impact analysis with limited quantitative analysis. A combination of the two will be used to formulate alternatives.

a. Initial Management Measure Screening

(1) Coastal risk reduction can be achieved through a variety of approaches, including natural or nature-based features (e.g., wetlands and dunes), nonstructural interventions (e.g., policies, building codes, and emergency response such as early warning and evacuation plans), and structural interventions (e.g., seawalls and breakwaters). Natural and nature-based features can attenuate waves and provide other ecosystem services (e.g., habitat, nesting grounds for fisheries). However, they also respond dynamically to processes such as storms, both negatively and positively, with temporary or permanent consequences. Nonstructural measures are most often under the jurisdiction of state and local governments (and individuals) to develop, implement, and regulate, and they cannot be imposed by the Federal government.

(2) Management measures are the building blocks of alternatives. For this example, eight nonstructural and twelve structural measures were screened against the four Planning Accounts: National Economic Development, Environmental Quality, Other Social Effects, and Regional Economic Development. The effects of SLC and the measures' adaptability to these changes were considered under the National Economic Development (NED) account. This is an example of how the tiered analysis recommended by the guidance can be incorporated into the six-step planning process. Table G-3 was used as part of the planning process under Step 3 – Formulating alternative plans.

(3) For brevity, Table G-3 only shows a sample of the initial management measures screened. Each measure was subjectively given a score of zero for not meeting criteria, one for partially meeting criteria, and two for fully meeting criteria. All four criteria were given equal weight for this preliminary screening to assess how a measure stacks up across all of the Federal objectives. For additional screenings, more weight could be given to the NED account, because any CSDR project should maximize NED benefits. With all four criteria being equal, a measure can receive a maximum of eight points, which would demonstrate that the measure has the potential to fully meet the Federal objectives. A total of four points demonstrates that the measure partially meets the Federal objectives. Measures receiving a total of three points or less will be screened out because they less-than-partially meet the Federal objectives. Measures with four or more total points will be carried on for further evaluation. Measures that are screened out

may be re-incorporated further along in the planning process if warranted by new developments and information.

(4) As shown in the table, many measures did not address the screening criteria. These will not be carried forward to the next phase of analysis. The management measures with the greatest potential to contribute to planning objectives, Federal objectives, and consistency with planning constraints will be carried forward. The no-action measure will be carried forward as an alternative plan throughout plan formulation as a basis for comparison with other alternatives.

(5) Measures that were carried forward from the initial screening will be further evaluated as the study progresses. Table G-3 only shows a sample of the initial management measures screened, and all measures bulleted below are not shown. Measures carried forward include:

- NS-1: No-Action
- NS-8: Buyout and Land Acquisition
- S-1: Seawalls
- S-2: Revetments
- S-5: Groins
- NBI-1: Sand Covered Soft Structures
- NBI-2: Beach Nourishment
- NBI-3: Dunes and Vegetation

Only some of these measures are shown in Table G-3.

(6) Measures, used singularly or in combination with others, create alternatives, and varying scales of each create additional alternatives. An alternative may be implementable for an entire reach or for only a portion of a reach. The combination of management measures results in alternatives that merit further analysis. Combining measures into alternatives was accomplished by using engineering judgment and the Institute for Water Resources (IWR) Planning Suite, which is a USACE model that assists with formulating plans. Notably, throughout the study area, nonstructural risk reduction measures, including education efforts, maintenance of evacuation route signage, zoning codes, and setbacks, will be carried forward as elements of any complete systematic package of risk reduction measures. Many of these additional nonstructural efforts are being pursued by the project sponsor and would be performed by local entities alone.

Table G-3. Example management measure screening for the study area.

	Possible Measures	Federal Objectives					
		National Economic Development (NED)	Environmental Quality (EQ)	Other Social Effects (OSE)	Regional Economic Development (RED)	Total Points	Carried Forward
NS-1	No-Action	No NED benefits are realized through this measure. No damages are prevented. No project costs. Makes no attempt to keep infrastructure from being damaged. No improvement.	Potential for continued loss of the already minimal dune and dune habitat. Minimal change to other factors. Individual private shore protection measures may affect dune habitat.	Moderate risk of damage to evacuation route. Small risk to homes, businesses and the safety of residents. Beach berm may continue to erode causing a gradual loss of beach recreation. Near shore recreation will not be affected. Does not conflict with any laws.	Potential for loss of property value and tax value. Potential for decline in local business revenues.		NO
		0	1	1	0	2	
NS-4	Establish a No-Growth Program	Would only provide damage reduction benefits for potential future structures. NED benefits would be minimal as there is little room for growth east of A1A. Makes no attempt to keep existing infrastructure from being damaged, but reduces potential damage in the future, especially considering potential accelerated Sea Level Rise (SLR) rates.	No adverse effects would be created by this measure, nor would any positive benefits be realized.	Property and tax values will decrease. Risk of damage to the evacuation route remains. Beach berm may continue to erode causing a gradual loss of beach recreation. Near shore recreation will not be affected. May require changes to local law.	Potential for loss of property value and tax value.		NO
		1	0	0	0	1	
		Benefits not likely to outweigh costs in this study reach. Moving structure out of the way of danger will reduce damages to those	Moving buildings back from the dune would provide more area for dune habitat. Dune would still face potential threat of	Minimal improvements to safety for parcels where this could be implemented, but overall would not have any social effects. Risk of	Potential for loss of property value and tax value.		
NS-5	Relocation of Structures	structures, but as erosion continues other structures will continue to be at risk of being damaged. Additionally due to the current elevation of most infrastructure, SLR is not a significant contributing factor to storm damage over the period of analysis.	continued erosion.	damage to the evacuation route remains. Beach berm may continue to erode leaving little or no beach for recreation. Near shore recreation will not be affected. Relocation of historical structures may cause conflict with section 106 of the National Historic Preservation Act			NO
		0		0	0	1	
NS-6	Relocate State Highway A1A	Measure may be justified as damages to the highway would be avoided. This will reduce damages to A1A, but will not reduce damages to other infrastructure. Considering potential accelerated Sea Level Rise (SLR) rates, due to the current elevation of A1A, SLR is not a significant contributing factor to storm damage over the period of analysis.	Moving A1A inland *mov cu:mle mo1e* [illegible]	A new hurricane evacuation route would need to be established. Moving A1A will take away from the scenic qualities of the highway. Likely to be opposed by much of the community. Beach berm may continue to erode leaving little or no beach for recreation. Near shore recreation will not be affected. Does not conflict with any laws.	Businesses along A1A will suffer if the highway is relocated. Potential for loss of property value and tax value.		NO
		1		0	0	2	
S-1	Seawalls	[illegible] over the entire project area. This would provide storm damage reduction to infrastructure landward of the seawall. However adjacent properties could be made more vulnerable due to erosive effects of structures. Damage reduction could be maximized in combination with beach/dune fill to offset impacts to adjacent shoreline. Seawalls would be moderately adaptable to potential accelerated Sea Level Rise (SLR) rates.	[illegible] coo,dir>>>wo<Idnot bo signlf.co"tly altered sl'>oJido [illegible]	Likely to face objection by community and resource agencies. Could have negative effect on surrounding beaches. Reflection of wave energy off the seawall will likely intensify erosion of the recreational beach berm. Near shore recreation will not be affected. Likely inconsistent with state CZMP.	As seawall currently exist in this study reach, the regional economic w/o project conditions would not be significantly altered should a new seawall be built in the location of an existing seawall. New seawall built where no seawall exists could likely cause increased erosion of the berm which may negatively affect local tourism.		YES
		2	1	1	1	5	
S-2	Revetments	Portions of this study reach are currently reveted. Could be justified in certain areas, but not likely to be justified over the entire area of the project. This would provide storm damage reduction to infrastructure landward of the revetment. However adjacent properties could be made more vulnerable due to erosive effects of structures. Damage reduction could be maximized in combination with beach/dune fill to offset impacts to adjacent shoreline. Revetments would be adaptable to potential accelerated Sea Level Rise (SLR) rates.	As revetment currently exist in this study reach, the regional economic w/o project conditions would not be significantly altered should a new revetment be built in the location of an existing revetment. New revetment built where no revetment exists would likely have negative environmental impacts.	Likely to face objection by community. Could have negative effect on surrounding beaches. Reflection of wave energy off the revetment will likely intensify erosion of the recreational beach berm. Near shore recreation will not be affected. Likely inconsistent with state CZMP.	As revetment currently exist in this study reach, the regional economic w/o project conditions would not be significantly altered should a new revetment be built in the location of an existing revetment. New revetment built where no revetment exists could likely cause increased erosion of the berm which may negatively affect local tourism.		YES
		2	1	1	1	5	
S-3	Sand Covered Soft Structure	Could possibly be justified, would improve storm damage reduction. Would be adaptable to potential accelerated Sea Level Rise (SLR) rates.	sand would need to be maintained on top of the soft structures to ensure environmental quality. Would protect dune habitat, but could be detrimental if it became uncovered and remained that way.	would protect evacuation route and improve the aesthetics along A1A compared to the existing revetment. existing narrow beach may be maintained and nearshore recreation would not be affected. May not be permittable by the state.	Could possibly have a minor positive impact on the regional economy.		YES
		1	1	2	1	5	
S-4	Beach Nourishment	Most likely a justifiable measure. This would reduce damages to infrastructure landward of the nourishment. Would be highly adaptable to potential accelerated Sea Level Rise (SLR) rates.	Could result in temporary negative impacts to the nearshore environment. Could enhance sea turtle nesting habitat. Would need to avoid nearshore rock if present. If sand color is changed the beach may loose aesthetic quality.	Likely to be supported by a majority of the community. Improved protection of the evacuation route. The recreational beach berm would be extended. Nearshore recreation such as surfing and fishing may be affected temporarily following nourishments. Does not conflict with any laws.	Likely to have a positive effect on local tourism industry.		YES
		1	1	2	2	6	

Forward D Eliminated L.:.J Objective r; I Fully Meets L..J Objective I , I Portially Meets I I Objective Does Not Meet

b. Secondary Management Measure Screening

(1) Data on historic storms; beach survey profiles; and private, commercial, and public structures within the project area were used as input to the USACE Beach-*fx* model. The model was then used to estimate future project hurricane and storm damages. The model links the predictive capability of coastal evolution modeling with project-area infrastructure information, structure and content damage functions, and economic valuations to estimate the costs and total damages under various shore protection alternatives. This output is then used to determine the benefits of each alternative. Beach-*fx* fully incorporates risk and uncertainty and is used to simulate future hurricane and storm damages at existing and future years and to compute accumulated present-worth damages and costs. Storm damage is defined as the damage incurred by the temporary loss of a given amount of shoreline as a direct result of waves, erosion, and inundation caused by a storm of a given magnitude and probability. Beach-*fx* is an event-driven life-cycle model that estimates damages and associated costs over a period of analysis based on storm probabilities, tidal cycle, tidal phase, beach morphology, and many other factors. Beach-*fx* also provides the capability to estimate the costs of certain future measures undertaken by state and local organizations to protect coastal assets.

(2) Beach-*fx* was configured and run for each SLC scenario to estimate future without-project condition damages. The results are displayed in Figure G-6.

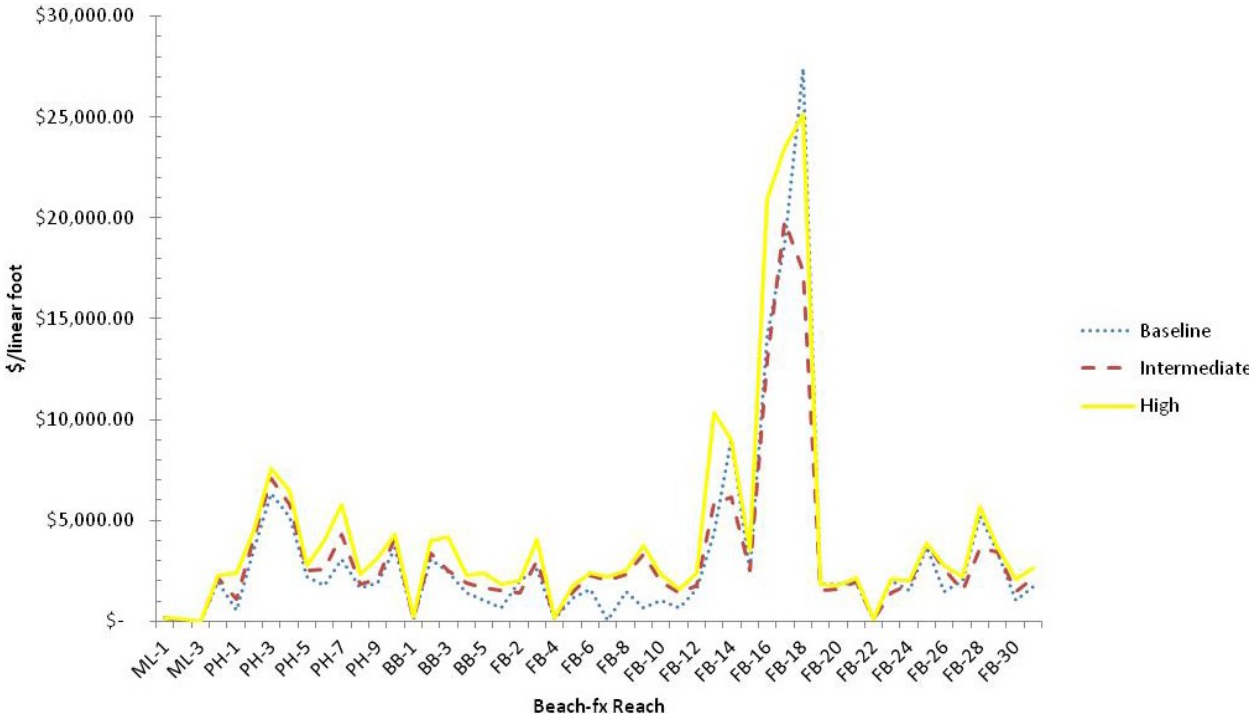


Figure G-6. Present value of future without-project damages for each SLC scenario plotted along the study area shoreline (values given per Beach-*fx* reach). Groupings of reaches are titled ML, PH, BB, and FB.

(3) In Figure G-6, the present value of future without-project damages (over 50 years) is plotted along the study area shoreline (x-axis). Damages are aggregated for sections of shoreline (Beach-*fx* reaches) that are approximately 1,000ft (304.8m) long. Interestingly, damages do not necessarily increase with an increasing rate of SLR, such as between FB-14 and FB-18. This could be due to several factors. For instance, a certain structure may be damaged multiple times over 50 years under the baseline scenario, whereas the same structure may be destroyed and removed from the structural inventory under the high scenario. Repeated damages may be more costly than the one-time destruction of the structure. This shows that decisions such as whether to repair a structure or remove it are inherently complex when forecasting a response to SLC because impacts, costs, and responses do not necessarily behave proportionally.

(4) Tabulated Beach-*fx* damage results under each future without-project SLC scenario are shown in Table G-4. The differences in damages between the SLR scenarios are insignificant, again showing that accelerated SLC rates do not necessarily translate into increased damages in the project area. Damages will depend on factors specified in the model, such as whether structures are removed from the inventory or rebuilt, depending on the degree of damage incurred during a storm event.

Table G-4. Present value of future without-project SLR damages.

	Base SLR	**Intermediate SLR**	**High SLR**	**Percent change from base rate**	**Percent change from interm. rate**
Sea level rise (ft and m/yr)	0.0079/0.0024	0.0161/.0049	0.0428/0.0130	103.80	165.84
Total damages ($)	65,303,142	65,314,126	65,522,938	0.02	0.32
Armor costs ($)	39,302,405	39,281,970	39,281,970	–0.05	0.00
Total ($)	104,605,547	104,596,095	104,804,908	–0.01	0.20

Note: Land loss estimates were not included in Table G-4.

(5) Costs per linear foot for implementation of management measures have been added to Beach-*fx* damages in Figure G-7. A project's benefit-to-cost (B/C) ratio must be greater than or equal to 1.0 for an alternative to be justified and implementable (i.e., the benefits must at least equal the costs). Benefits are synonymous with damages prevented, or the difference between without-project damages and damages resulting after implementation of an alternative. At this point in the study, alternatives have not been formulated, so no "with-project" Beach-*fx* scenarios can be run. Management measures will eventually be scaled, or combined, to form alternatives. However, damages can be used as a proxy for benefits. Using the value of without-project damages as a substitute for the benefits will overestimate the benefit provided by any measure, as this assumes that implementation of the measure results in zero damage. Therefore, if the cost of implementing a measure is equal to or less than the without-project damages, the B/C ratio can be assumed to be at least 1.0 and the measure can be justified. Figure G-7 displays rough-order-of-magnitude (ROM) costs per linear foot for measures passing the initial screening, in addition

to damages along the shoreline. Wherever damages are below a measure's ROM cost, it is assumed that the measure would not be justified along that shoreline length and the measure is screened out. Wherever damages are near or above implementation costs, it is assumed that the measure can be justified and it is carried forward.

(6) Because the costs of measure implementation may vary depending on the SLC scenario used for design, some measures have a broad cost range. Beach nourishment (NBI-2), for example, will have a higher cost for higher SLC scenarios because of a higher sand requirement, shorter renourishment intervals, and other factors. Other measures may have the same implementation cost for any scenario. Buyout and land acquisition (NS-8) would only be implemented for structures east of State Road A1A, no matter which scenario is considered. Therefore, its cost range is more narrow. NS-8 was only considered for reaches in the ML, PH, BB segments of the shoreline, because no structures exist east of State Road A1A in the FB segment.

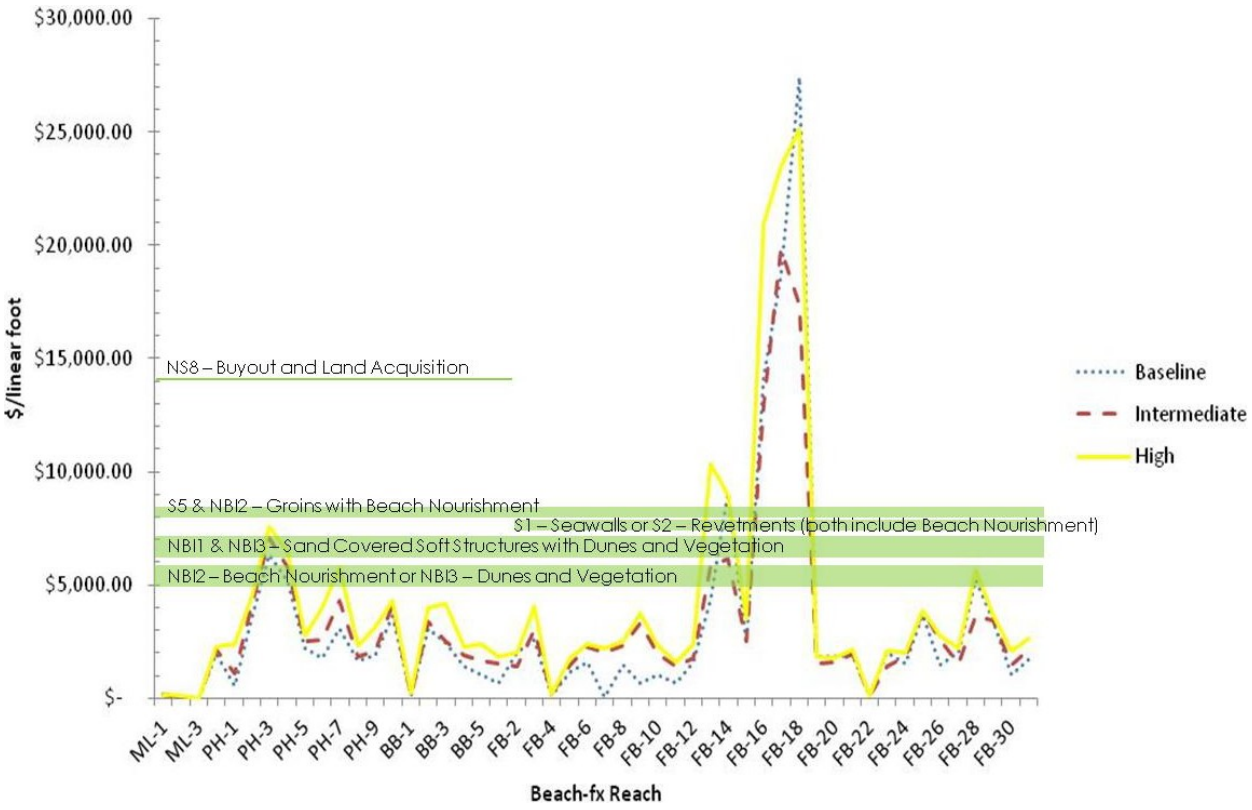


Figure G-7. Management measure costs plotted against future without-project damages along the study area shoreline.

(7) Figure G-7 demonstrates that measures can only be justified in the central FB segment under any SLC scenario. Beach nourishment (NBI-2), dunes and vegetation (NBI-3), and soft structures (NBI-1), to a lesser degree, may be the most justifiable measures in this area. In the PH segment, these measures may only be economically justified for a half-mile length. Such a short length would likely not be feasible to construct in a fashion that would last for a reasonable

amount of time. Groins (S-5) may provide additional stabilization to beach nourishment at select locations in the FB segment. Seawalls (S-1) and revetments (S-2) with nourishment may also be justified at select locations in the FB segment.

(8) The cost for NS-8 (buyout and land acquisition), including relocation of residents, for an average beach-front residence was estimated for the PH and BB segments. Not including demolition, the cost was estimated at $14,000 per linear foot. This cost is well above any estimated damages in these reaches. Therefore, the measure will likely not be justified and is screened out.

(9) Based on this secondary screening, the FB segment will be the focus of further formulation. All management measures have been screened out for the PB and BB segments because costs would likely exceed benefits generated by providing storm damage reduction, as shown in Figure G-7.

c. Alternative Selection Considering Sea Level Change.

(1) Management measures have been combined and scaled into alternatives to a limited degree. Alternatives will be further developed by scaling the management measures in length and size for specific locations. As the alternatives are developed, the alternative evaluation criteria of completeness, effectiveness, efficiency, and acceptability will be considered, in accordance with the *Planning Guidance Notebook* (ER 1105-2-100). Completeness is satisfied by ensuring that the alternative plan includes all the necessary parts and actions to produce the desired results. Effectiveness is determined by how well the alternative plan meets objectives while considering constraints. Efficiency is determined by the cost effectiveness of an alternative plan. Acceptability is determined by evaluating the alternative plan's compatibility with local, state, or Federal law and policy, environmental constraints, and public willingness to support the plan.

(2) Alternatives not meeting the criteria will be eliminated. Alternatives that meet the criteria will be carried forward and will undergo further analysis and modeling.

(3) Alternative formulation for the central FB segment will be the focus of further formulation. Under any SLC scenario, a roughly 10,000ft (3048m) shoreline length (approximately 2 miles) from Beach-*fx* reaches FB-11 through FB-20 would potentially receive damages significant enough to justify multiple alternatives (Figure G-7). Alternatives carried forward for this section of shoreline include:

- NS-1: No-Action
- S-1: Seawalls with Beach Nourishment
- S-2: Revetments with Beach Nourishment
- S-5: Groins with Beach Nourishment
- NBI-1: Sand Covered Soft Structures with Dunes and Vegetation
- NBI-2: Beach Nourishment
- NBI-3: Dunes and Vegetation

(4) The guidance directs that alternatives should be adaptable to potential SLC scenarios across the planning horizon. The alternatives above, as well as current or planned measures being taken by the local sponsor to provide storm damage reduction, are shown in Figure G-8.

(5) In Figure G-8, different alternatives are symbolized by colored columns spanning increments of SLC. The height of the colored columns indicates each alternative's robustness and adaptability as sea level rises. Each alternative has a beginning and ending threshold. The beginning threshold may not be immediate but at some time in the future when sea level reaches a point that makes the measure acceptable for environmental, economic, social, or other reasons. The ending threshold indicates a sea level height at which the alternative no longer functions or can no longer be adapted to provide storm damage reduction. Between these thresholds, the alternative can be adapted as sea level increases. The management measures are arranged by adaptability into the future, with the most adaptable measure on the left and the least on the right. For instance, beach nourishment (NBI-2) can likely be implemented immediately in the project area, at a relative sea level equal to zero. As sea level rises, the alternative can be adapted by adding more sand to maintain the desired beach height and width. Eventually, sand sources may be depleted or be too costly, or the necessary beach dimensions may not be constructible for various reasons. The relative sea level at this point indicates the alternative's ending threshold. Note that adaptability depends on relative sea level and is independent of specific SLC scenarios. The different SLC scenarios only impact the future point in time when the relative sea level reaches an alternative's thresholds.

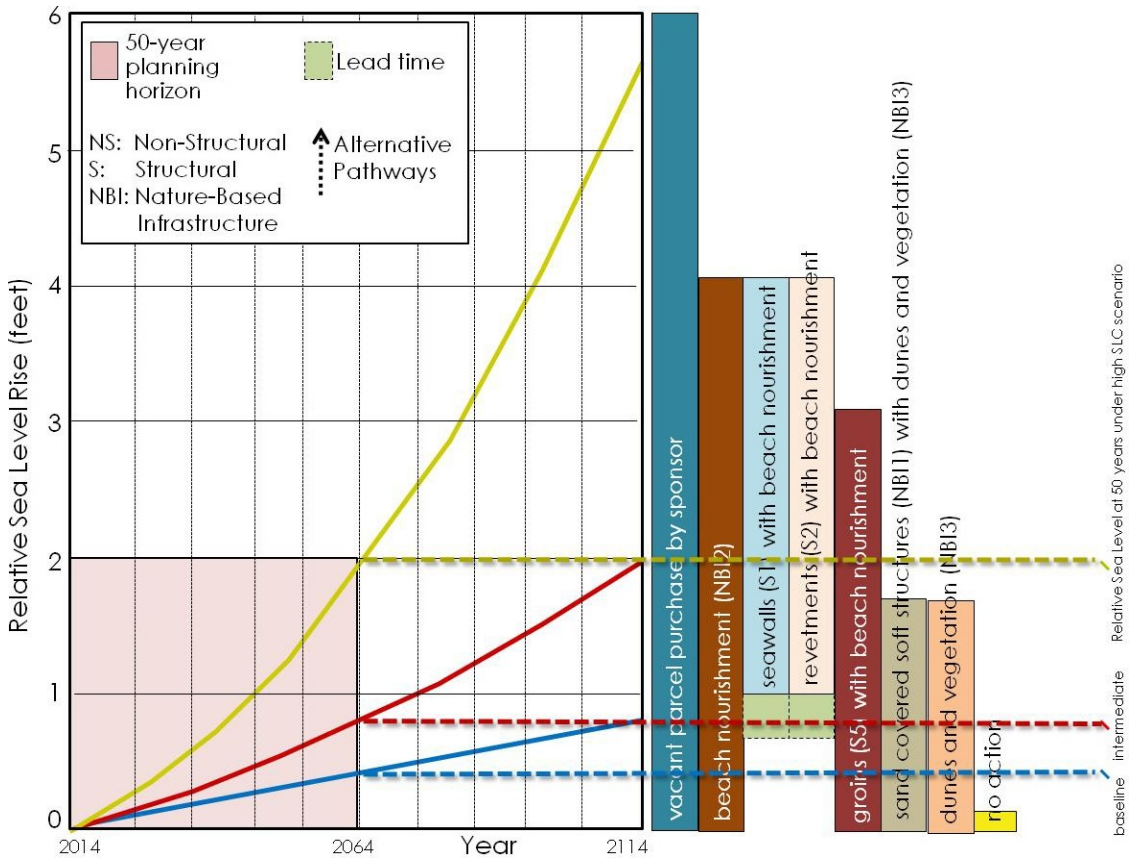


Figure G-8. Alternative adaptability to SLC scenarios.

(6) These thresholds could be developed quantitatively with model output, qualitatively, or with a combination of both. Since it has been determined that SLC is not a major contributor to damages within the 50-year period of analysis, thresholds for this study area have been developed qualitatively. Thresholds are based on experience from similar project areas and on environmental, social, and economic factors in the study area.

(7) Approximately 0.2ft (0.06m) of relative sea level rise will require shore protection measures beyond current practices (No Action). Several alternatives with beach nourishment variations are implementable with current conditions and are adaptable until the relative sea level increases by approximately 4ft (1.2m). At that point, the background erosion rate will have increased to a point where the renourishment interval is very short and uneconomical and/or the constructed berm elevation cannot be raised.

(8) Seawalls and revetments are not currently implementable because of environmental concerns, impacts to adjacent shorelines, and negative impacts to the existing beach/dune system. Seawalls and revetments may become implementable when the relative sea level increases by approximately 1.0ft (0.3m). At that time, damages to infrastructure (including State Road A1A, a hurricane evacuation route) may be significant enough to justify construction. Seawalls, revetments, and soft structures are intended to always have beach nourishment fronting them. These structures would ideally only come in contact with the ocean during the largest storm events. Therefore, their ending threshold depends on the ability to sustain beach nourishment. The function of other structural alternatives may be more dependent on the structure's crest elevation relative to sea level. Such structures may be less adaptable as sea level rises and their ending threshold is reached sooner. The effectiveness of groins depends in part on their relative elevation to sea level, and they are considered less adaptable to SLC than other alternatives considered. However, their adaptability would depend on their initial design and their allowance for future modification if necessary (anticipatory vs. adaptive or reactionary design).

(9) The project area sponsor has begun purchasing available lots east of State Road A1A and designating them as not buildable. Though not a Federally implementable alternative, this measure is included in Figure G-8 as a nonstructural alternative implemented by others. Other nonstructural measures limiting construction or condemning structures may become implementable as the relative sea level nears the upland elevation.

(10) Vegetated dunes are implementable with current conditions and are adaptable until the relative sea level increases by approximately 2ft (0.6m). At that point, no beach will exist to feed the dunes (without renourishment), and the reconstruction interval will be impractical and uneconomical. Experience from projects in Florida indicates that maintaining a sandy, vegetated dune over a soft structure is difficult. The need for relatively frequent placement of sand is uneconomical, and not maintaining the sand cover negatively impacts sea turtle nesting.

(11) Some measures that have start thresholds above a relative sea level of zero will require lead times to coordinate with agencies and the public. A lead time of 0.5ft (.15m) of relative sea level rise is applied to all such measures for this example. However, longer lead times may be required in other instances. This would allow approximately 10 years of lead time under the high SLC scenario and longer durations under the lower scenarios.

d. Recommended Alternative Considering Sea Level Change

(1) Beach nourishment (NBI-2) is adaptable across all SLC scenarios throughout the 50-year planning horizon, as shown in Figure G-8. According to ROM costs developed, it is also likely the least-cost alternative that provides the necessary benefits to the FB segment, as shown in Figure G-7. This alternative is highly adaptable to SLC. The beach berm height is naturally adjusted as sea level rises as long as there is adequate sand. For the foreseeable future, sand supplies (cost and availability) are the main factors related to this alternative's sustainability. Currently, offshore sand sources are expected to be in adequate supply to sustain the alternative in a cost-effective manner.

(2) SLC has been determined to not be a major contributor to storm damages for this project within the 50-year period of analysis. Selection of the beach nourishment alternative does not preclude future decisions regarding other forms of shore protection if SLC accelerates beyond the rates evaluated in this study. Therefore, beach nourishment (NBI-2) is the alternative best addressing the study objectives and is the alternative recommended from this analysis.

THIS PAGE INTENTIONALLY LEFT BLANK

Glossary

Annual Exceedance Probability
Annual exceedance probability (AEP) can be calculated by fitting the three parameters of the Generalized Extreme Value (GEV) probability distribution function to annual maximum or annual minimum water level data using iterative maximum likelihood estimation. The 99% exceedance probability level equals the water level expected every 1 year. The 50% exceedance probability level equals the water level expected every 2 years. The 10% exceedance probability level equals the water level expected every 10 years. The 1% exceedance probability level equals the water level expected every 100 years. Note that other probability distribution functions may be used.

Coastal
As used in this ETL, locations with oceanic astronomical tidal influence, as well as connected waterways with a base level controlled by sea level. In these latter waterways, wind-driven tides may have greater influence than astronomical tides. Coastal areas include marine, estuarine, and riverine waters and affected lands. (The Great Lakes are not considered "coastal" for the purposes of this ETL.)

Datum
A horizontal or vertical reference system for making survey measurements and computations; a set of parameters and control points used to accurately define the three-dimensional shape of the earth. The datum defines parts of a geographic coordinate system that is the basis for a planar coordinate system. Horizontal datums are typically referred to ellipsoids, the State Plane Coordinate System, or the Universal Transverse Mercator Grid System. Vertical datums are typically referred to the geoid, an earth model ellipsoid, or a local mean.

Eustatic sea level rise
A change in the global average sea level brought about by an increase in the volume of the world ocean (IPCC 2007).

Global mean sea level (GMSL)
The mean sea level for all the world's oceans. Sea level can change globally due to (1) changes in the shape of the ocean basins, (2) changes in the total mass of water, and (3) changes in water density. Sea level changes induced by changes in water density are called steric. Density changes induced by temperature changes only are called thermosteric, while density changes induced by salinity changes are called halosteric (IPCC 2007). See Figure B-5.

Local (i.e., "relative") sea level
Sea level measured by a tide gauge with respect to the land upon which it is situated. See mean sea level (MSL) and sea level change (SLC). Relative sea level change occurs where there is a local change in the level of the ocean relative to the land, which might be due to ocean rise and/or land level subsidence. In areas subject to rapid land level uplift, relative sea level can fall (IPCC 2007). Relative sea level change will also affect the impact of any regional sea level change.

Mean sea level (MSL)
A tidal datum. The arithmetic mean of hourly heights observed over the National Tidal Datum Epoch (approximately 19 years). Shorter series are specified in the name; e.g., monthly mean sea level and yearly mean sea level (NOAA 2000).

Post-glacial rebound
The vertical movement of the land and seafloor following the reduction of the load of an ice mass, for example, since the last glacial maximum (approximately 21,000 years ago). The rebound is an isostatic land movement (IPCC 2007).

Regional sea level change
An increase or decrease in the mean level of the ocean's surface over a specific region. Global sea level has regional variations, and regional sea level change may be equal to, greater than, or less than global sea level change due primarily to regional differences in ocean heating and cooling or changes in bathymetry. Regional sea level change as used here does not include local geologic effects, such as subsidence or tectonic movement.

Reliability
As used in this ETL, the capacity of a system or system component to perform its required functions under conditions that can reasonably be expected over its projected lifetime (or a shorter period, if specified).

Resilience
The ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organization, and the capacity to adapt to stress and change (IPCC 2007), interpreted by USACE (2013) as "the ability to anticipate, prepare for, respond to, and adapt to changing conditions and to withstand and recover rapidly from disruptions with minimal damage."

Risk
A measure of the probability and severity of undesirable consequences (including, but not limited to, loss of life, threat to public safety, and environmental and economic damages).

Sea level change (SLC)
A change in the mean level of the ocean.

Sustainability
As used in this ETL, the capacity of a system (ecological, human, infrastructure) to endure and to maintain well-being over time.

Tailwater effects
Upstream effects of a change in water level at the discharge point.

Tide station
A device at a coastal location (and some deep sea locations) that continuously measures the level of the sea with respect to the adjacent land. Time averaging of the sea level recorded using a tide station gives the observed secular changes of the relative sea level (IPCC 2007).

Tidal datums
A standard elevation defined by a certain phase of the tide. Tidal datums are local datums and should not be extended into areas that have differing hydrographic characteristics without substantiating measurements. In order that they may be recovered when needed, such datums are referenced to fixed points known as benchmarks.

Uncertainty
The result of imperfect knowledge concerning the present or future state of a system, event, situation, or (sub)population. There are two types of uncertainty: aleatory and epistemic. Aleatory uncertainty is the uncertainty attributed to inherent variation that is understood as variability over time and/or space. Epistemic uncertainty is the uncertainty attributed to our lack of knowledge about the system (e.g., what value to use for an input to a model or what model to use). Uncertainty can lead to lack of confidence in predictions, inferences, or conclusions.

Vulnerability
As used in this ETL, the degree to which the system or its components are susceptible to, or unable to cope with, the adverse impacts of sea level change and other coastal impacts of climate change.

THIS PAGE INTENTIONALLY LEFT BLANK