Procedures to Evaluate Sea Level Change; Impacts, Responses and Adaptation; U.S. Army Corps of Engineers' Approach

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Abstract

The U.S. Army Corps of Engineers, (USACE) has embarked on a comprehensive approach to climate change that is flexible enough to incorporate new knowledge and changing conditions. A tiered analysis is recommended for the inclusion and assessment of sea level change impacts on a project and the project alternatives. Inherent in this approach is the understanding that review and decision points exist after each analysis tier that allow the engineers and planners to reassess the required data and analysis. 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. In essence, what is being assessed at the strategic decision context level is whether there is potential for significant or catastrophic consequences to life safety, property, critical infrastructure, and ecosystems. The second tier of the screening process determines project area exposure and vulnerability by looking at three categories: project area characterization, capacity/resilience, and loading/processes. The third tier addresses project alternative development and evaluation under SLC. Through nonstationarity, thresholds and tipping points identify key milestones in the project timeline when impacts are expected to be realized.

1. INTRODUCTION

In response to the water-related risks posed by climate change, the U.S. Army Corps of Engineers, (USACE) has embarked on a comprehensive approach that is flexible enough to incorporate new knowledge and changing conditions. Adequately incorporating potential sea level change (SLC) into the planning and engineering process will improve the resilience of project systems and will maximize sustainability over time. The USACE goal is to develop practical, nationally consistent, legally justifiable, and cost effective measures, both structural and nonstructural, to reduce vulnerabilities and improve the resilience of our water resources infrastructure. Analytical perspectives will be developed to determine the appropriate investments in maintenance, operations improvements, reallocation, major rehabilitation, and new construction.

The Corps' most recent update to sea level change guidance was in 2011 in the form of an Engineering Circular, EC 1165-2-212, "Incorporating Sea-Level Change Considerations in Civil Works Programs". (USACE, 2011) The guidance was developed with help from top sea-level science experts at NOAA's National Ocean Service and the US Geological Survey. The

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Engineering Circular 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. How those curves are assessed within the alternative formulation and evaluation will depend on the strategic decision context of the project and the assessment of project area vulnerability.

The next step in the guidance, the U.S. Army Corps of Engineers’ Engineering Technical Letter (ETL), outlines the recommended planning and engineering implementation approach for addressing impacts of projected sea level change at Corps projects. The guidance development has utilized an interdisciplinary team that includes representatives from all the different regions of the Corps of Engineers, other key federal agencies dealing with infrastructure and systems, and outside experts. ETL tools focus on specific methods for implementing multiple-scenario planning and carrying out a tiered screening and analysis of three sea level change scenarios which identify key thresholds and tipping points within the system. A hierarchy of decisions is recommended to support an appropriate level of analysis. Issues that climate change poses for the USACE are in many ways common to all infrastructure agencies and organizations. Therefore, the guidance recognizes the essential role of collaboration with other federal agencies as well as state and community partners.

Key Concepts. Understanding some general concepts that will be discussed and applied throughout this paper will be helpful in implementation.

a. Nonstationarity. New understanding of the dynamic nature of coastal and hydrologic processes has brought with it the realization that stationarity, though it has been a fundamental assumption in engineering design, must be reassessed when considering future global and climate changes. We can no longer rely on observed historical observations and trends alone as we consider plausible future conditions.

b. Framework for robust analysis. Due to the uncertainty and variability of future sea-level changes and their associated impacts, we must employ a robust framework that is flexible and adaptable to multiple future scenarios. Emphasis is placed both on how the project operates within a larger system and how project decisions now can influence future conditions through unintended consequences or cascading impacts. Robustness here is considered to be the ability of a system to continue to perform satisfactorily under changing conditions and over a wide range of conditions.

c. Scaled analysis and decision-making. Scaling recommended actions to the decision being taken and its potential consequences (i.e., decision scaling) helps us make sense of the issues climate change poses and helps to characterize the appropriate level of effort for analysis and design.

d. Screening tools. A key component of a scaled decision-making process is effective use of early screening levels. This approach utilizes a risk-informed decision matrix format to direct the planning and design approach and the level of analysis.

e. Adaptation Horizon. Infrastructure often stays in place well beyond its design life, which means that the latter years, often those beyond the design service life, are years in which climate impacts are increasing. Using a longer planning horizon that includes both the realistically expected service life and changing climate impacts over this period, enables us to improve robustness and resilience compared to shorter time frames.

f. Scenario Analysis. Planning and design require a coherent, internally consistent description of plausible future states. Due to the uncertainty of future changes in climate, it is necessary to examine a range of possible scenarios. This allows a bracketing of possible cases for exposure and performance for the project alternatives. This process should also identify unacceptably high levels of risk.

g. Cumulative and System Effects. Our infrastructure operates in a system, 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. Understanding the relationships between critical systems and infrastructure may point to novel solutions that improve resilience. Five critical infrastructure categories include transportation, electricity, telecommunications, water supply, and wastewater.

h. Tipping points and thresholds. Identifying thresholds beyond which performance is affected or significantly changed is an important way to understand current and future vulnerability. It is especially important to note thresholds for which the performance of the system can deteriorate rapidly once the threshold is exceeded (a tipping point). Understanding thresholds can inform urgency and timing of action, range of feasible actions, as well as larger system effects.

i. Stability and performance functions. Each project and system of projects can be assessed in terms of stability against the design loading as well as its ability to perform the project function expected under these loadings. Stability and performance may have variable sensitivity to the incorporation of a changing sea level.

j. Consequence. Consequences are the end result or effect caused by some event or action, and may be beneficial, neutral, or detrimental. A detrimental consequence is often referred to as an impact. Consequences may be expressed descriptively, categorically (e.g., high, medium, low) or quantitatively (monetary value, number of people affected). Developing a good understanding of consequences is important in decision-scaling.

Within the larger context of climate change analysis, it should be considered that infrastructure planned and built with past climate and weather in mind may not be adequate for future resilience and operation. Figure 1 below illustrates how a changing climate can influence the reliability of the adopted long-range plan for significant infrastructure as well as the potential consequences over the future life cycle.

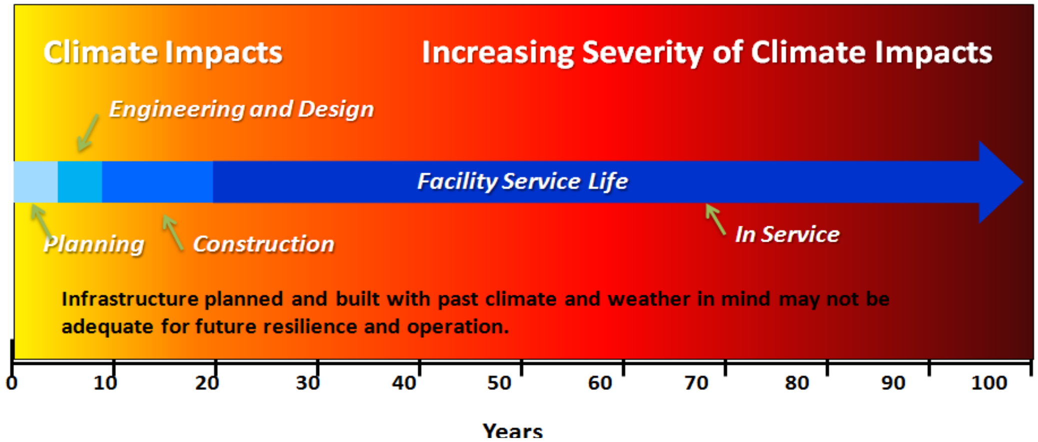

Figure 1. Water resources infrastructure timeframes vs. climate impacts. (Savonis, 2011)

2. UNDERSTANDING SEA LEVEL CHANGE

In the preparation of the guidance, USACE has relied entirely on climate change science performed and published by agencies and entities external to USACE. The conduct of science as to the causes, predicted scenarios, and consequences of climate change is not within the USACE mission. The USACE is a user of the best available and actionable climate science knowledge. This guidance will be periodically reviewed and revised as the accepted consensus changes.

2.1 Non-stationary Processes

Climate change undermines stationarity, a basic assumption that historically has facilitated management of water supplies, demands, and risks. The assumption of stationarity allows planners and engineers to assume that hydrologic or coastal processes vary within an unchanging envelope of natural variability, so that the past accurately represents the future. Stationarity was a basic assumption made during the early- to mid-20th century era of Federal infrastructure building, when engineers designed water resources projects using what would now be considered relatively simple tools on the basis of short observed hydrology records. Lacking sophisticated dynamic process models and computational techniques, two primary factors enabled them to design and construct the many projects still in operation today: 1) inherent conservatism in design and 2) stationarity.

Conservatism in design (e.g., factors of safety) has been replaced in many cases by risk-based design. While alleviating issues associated with the economic cost of conservatism, risk-based design is highly dependent on projections of future conditions and the inherent uncertainty of the system. Today, there is growing recognition that, despite its successful application in the past, the assumption of stationarity may no longer be valid.

2.2 Changes in Global Mean Sea Level.

At any location, changes in local mean sea level (MSL) reflect the integrated effects of global mean sea level (GMSL) change plus local or regional changes of geologic, oceanographic, or atmospheric origin. 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 (IPCC 2007a). One impact of continued or accelerated climate warming is thus continued or accelerated rise of GMSL.

Because the USACE method entails a scenario-based approach, it may be useful to consider an upper bound on 21st century eustatic sea-level rise. Several peer-reviewed publications have proposed maximum estimates of GMSL rise by year 2100. Although the authors use different physical bases to arrive at the estimates, none of them proposes a 21st century GMSL rise greater than 2 meters. Figure 2 illustrates the minimum and maximum GMSL change expected by year 2100, along with author or publication. Based upon these bodies of research, it seems reasonable that a credible upper-bound for 21st century GMSL rise would be about 2 meters. This by no means suggests that 21st century GMSL rise cannot exceed 2 meters, but a maximum of 2 meters is reasonable at this time.

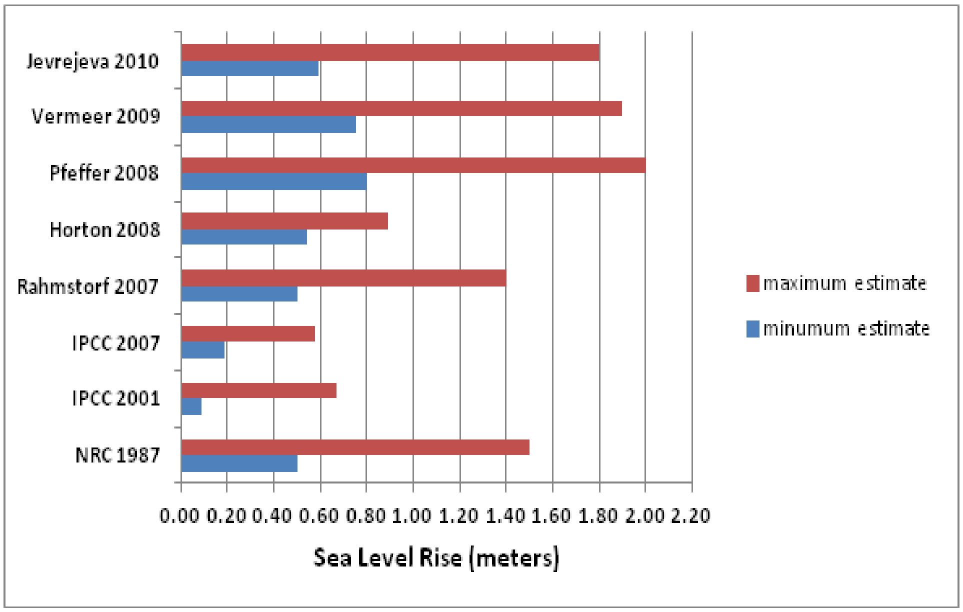

Figure 2. Comparison of maximum and minimum estimates of global SLR by year 2100. (Gill, 2011)

2.3 Changes in Local and Regional MSL

For USACE projects, the changes that are of interest are the local or regional changes. Sea-level change can cause a number of impacts in coastal and estuarine zones, including changes in shoreline erosion, inundation or exposure of low-lying coastal areas, changes in storm and flood damages, shifts in 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., CCSP 2009).

Geologic factors are a primary component of local sea-level change. Vertical land movement can occur due to tectonics (earthquakes, regional subsidence or uplift), compaction sedimentary strata, crustal rebound in formerly glaciated areas, and withdrawal of subsurface of fluids. Networks of long-term Continuously Operating Reference Stations (CORS) are being monitored by the National Geodetic Survey (NGS) of the National Atmospheric and Oceanic Administration (NOAA). Where co-located with tide gauges, these stations will begin to provide direct estimates of local vertical land uplift or subsidence.

Atmospheric factors can also affect local or regional water levels. Decadal-scale phenomena include El Niño-Southern Oscillation (ENSO) in the Pacific and North Atlantic Oscillation (NAO) in the Atlantic, among others (see IPCC 2007a for a more complete discussion). Climate change may also alter the frequency and severity of tropical storms which could secondarily influence sea level. This is currently the subject of scientific research.

2.4 Determination of Historic Trends in Local MSL.

USACE project planners and engineers must be aware of the historic trend in local MSL, because it provides a useful minimum baseline for projecting future change in local MSL. Awareness of the historic trend of local MSL also enables an assessment of the impacts that sea-level change may have had on regional coastal resources and problems in the past.

Historic trends in local MSL are best determined from tide gauge records. The NOAA Center for Operational Oceanographic Products and Services (CO-OPS) provides historic information and local MSL trends for tidal gauges operated by NOAA-NOS in the US. NOAA CO-OPS has been measuring sea level for over 150 years, with tide stations operating on all U.S. coasts through the National Water Level Observation Network. 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 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 3 presents data from NOAA tide gauges for U.S. coast sites. (NOAA CO-OPS)

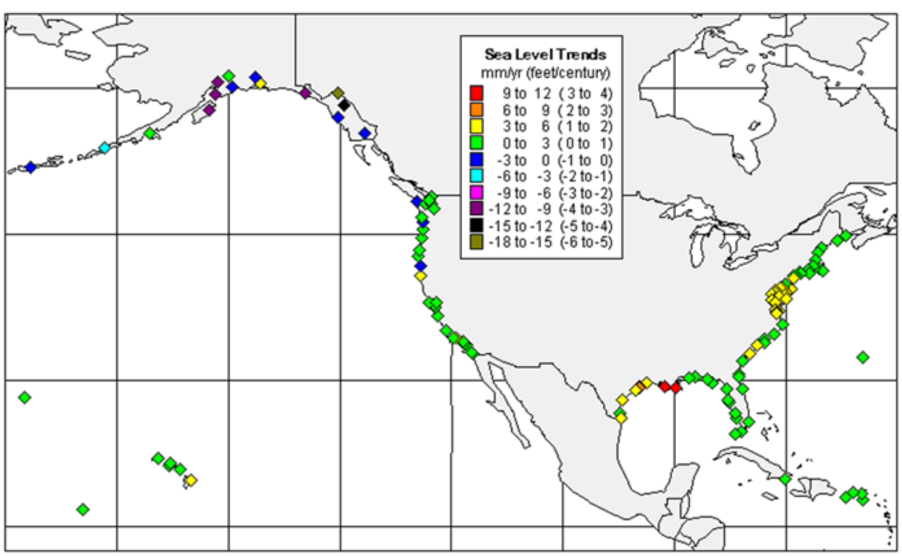

Figure 3. Mean Sea Level Trends for U.S. Tide Stations (NOAA)

Most U.S. tide stations experienced a rise in local MSL during the 20th Century. The predominance of green and yellow symbols along much of the Atlantic and Pacific coasts of the continental US represent tidal gauges with local MSL trends between 0 and +0.6 meters per century. The highest rates of local MSL rise in the U.S. have occurred along the Gulf Coast (red symbols). On the other hand, most stations in Alaska exhibit a falling trend of local MSL.

2.5 Estimating Future Change in Local MSL.

In USACE activities, analysts shall consider what effect changing relative sea-level rates could have on design alternatives, economic and environmental evaluation, and risk. The analysis 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 potential future acceleration of GMSL. Designs should be formulated using currently accepted design criteria. Figure 4 illustrates the comparison of the three sea level rise curves for a Corps of Engineers project area in La Jolla, California. (USACE, 2009)

The lowest blue curve is the extrapolated historical trend curve, which is an extrapolation of the data shown in the inset box, obtained from the local NOAA tidal gauge. This curve is primarily controlled by regional sea level change projection and land uplift or subsidence. The updated Engineering Circular, 1165-2-212 modified the start date of the sea level rise projection curves to conform with the current NOAA National Tidal Datum Epoch 9 consistent with USACE datum guidance. The start year utilized for the development of the updated SLC curves is 1992.

The red intermediate curve is estimated using the modified 1987 National Research Council (NRC) Curve 1. (National Research Council, 1987) These values are added to the local rate of vertical land movement. The blue and green markers that bound this line indicate the 2007 IPCC SRES low and high estimates (SRES = special report on emissions scenarios, a subset of 6 of the IPCC projections). The purple line in figure 4 provides the modified NRC Curve 3, representative of the high curve and the upper bound. Those values are added to the local rate of vertical land movement. This “high” rate exceeds the upper bounds of IPCC estimates from both 2001 and 2007 to accommodate potential rapid loss of ice from Antarctica and Greenland, but is within the range of peer-reviewed articles released since that time.

2.6 Magnitude and Frequency of Change.

In order to achieve a true perception of future vulnerability, the incorporation of SLC (or other climate factors) will need to describe the change from two general perspectives: magnitude and frequency. Identifying the potential magnitude of water level changes at the project site due to sea-level change begins with the future projection of local sea-level change as described in the three sea-level change curves and as shown in the example in figure 4. Note that with the exception of the extrapolation of the historic trend given by the low curve, the rate of change is projected to increase with time. This factor is important when considering potential project area changes in the future and available response time. 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. Epochs of analysis recommended include 20 years, 50 years, and 100 years.

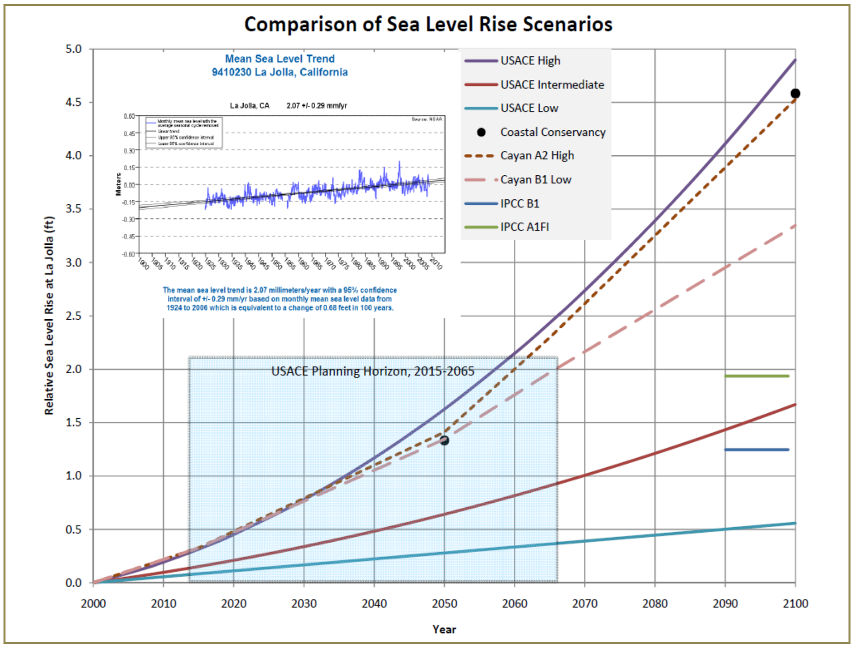

Figure 4. Example of Comparison of the three sea level rise curves at a project site. (USACE, 2009)

Once the range of projected changes in sea level are identified for the project site, the influence of that change on local extremes can be evaluated. Figure 5 illustrates projected changes in both low and high extremes at an example site in Massachusetts. Sea Level Change values are predicted 100-year values plus one uncertainty to provide a conservative estimate of SLC for each scenario. Annual Exceedance Probabilities (AEP) are provided by NOAA CO-OPS (http://tidesandcurrents.noaa.gov/est/index.shtml). The three columns show projected water level extremes using existing NOAA tidal and storm surge data as well as potential regional sea level rise, both low estimates and high estimates. Contrast the potential shift in datum for the existing, low SLC and high SLC columns. The low SLC estimate shifts the datum approximately 1 ft (0.3 m) while the higher SLC estimate shifts the datum over 6 ft (>2m). These plots are intended to show the adjustment relative to present day MLLW (1983-2001 NTDE).

Figure 5 does not include additional loading parameters such as wave run-up and open coast storm surge or extreme sudden changes such as rapid subsidence due to earthquake. While the tendency may be to focus on the changes in extreme highs for the project area and in many cases, the extreme high will represent the controlling loading case, the shift in extreme lows can also be of importance depending on the project purpose. For example, ecosystem, water supply and drainage projects will be impacted by a shift in the normal and extreme lows. Also note that over the 100 year adaptation planning horizon, NOAA will have updated the tidal epoch reference plane on 19 year intervals. As seen in figure 5, the respective change from the existing condition at the project site can be significant.

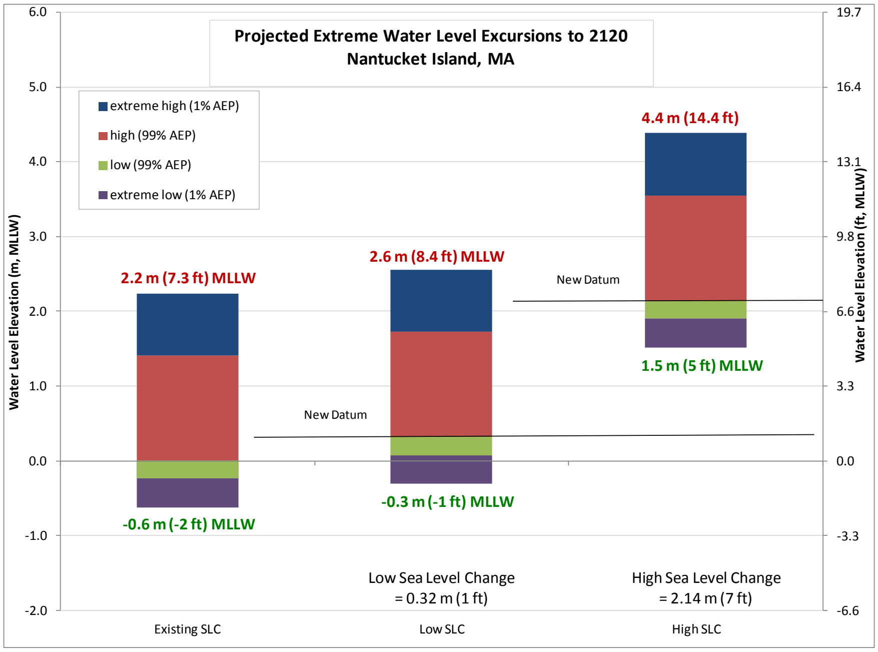

Figure 5. Illustration of future potential changes in water level extremes at a project site.

The second area of primary concern in terms of defining future project area vulnerability involves assessing the potential increased frequency of water level events or loading conditions. Future storm tides will reach higher elevations than past storms and will do so more frequently, impacting both flooding and structural loading. Figure 6 illustrates this concept for an application at Annapolis, Maryland. 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. (Kriebel, 2012) Key elements of this plot are identification of a vulnerable threshold and the increases in the frequency of extreme events relevant to that threshold. How each project area and range of alternatives respond 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.

2.7 Overall Process or Performance Driven Impacts and Other Factors

A thorough physical understanding of the project area and project purpose are required in order to effectively assess the project sensitivity to sea-level change. Some Corps of Engineers 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. Potential catastrophic failure of a levee or floodwall would fall into the latter category. Some projects may have aspects of both types of impacts, i.e. stability issues for the reliability of the infrastructure (extreme event driven) and performance issues regarding the expected project performance (process- or performance- driven). Examples of the second category might be frequency or return interval of overtopping and flooding or changes in ecosystem characteristics due to modified hydraulics.

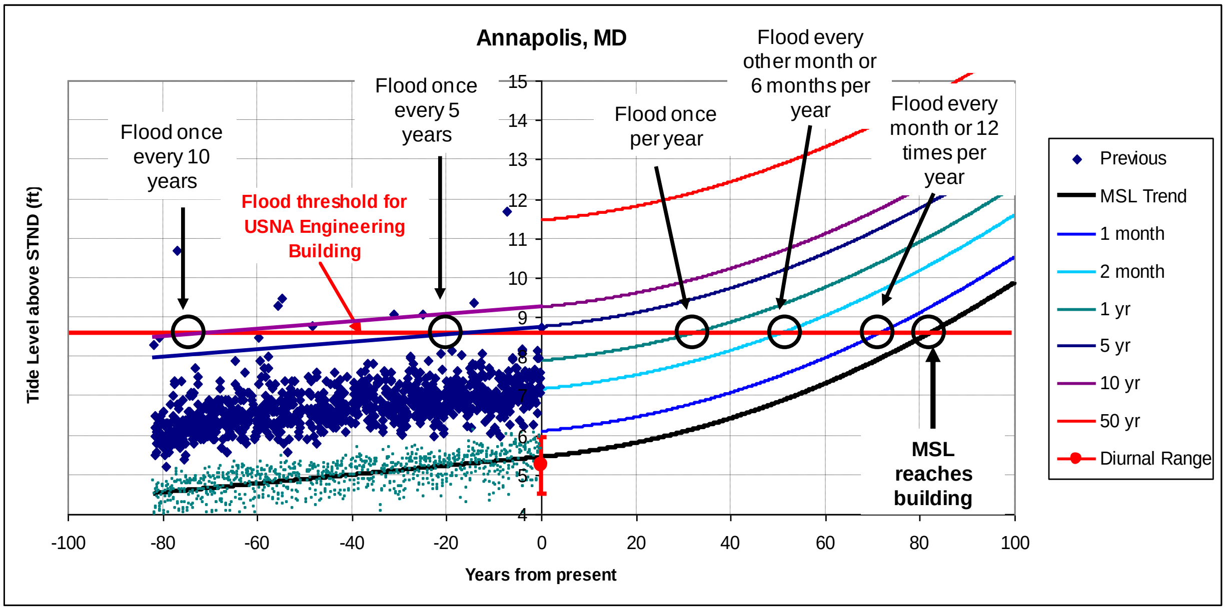

Figure 6. Illustration of impacts on frequency of loading events related to SLC. (Kriebel, 2012)

Each project area may also include exposure to other climate change factors (e.g. storm wave frequency and intensity) as well as significant inter-connections with systems within the project area. In these cases, sea-level change will need to be assessed in terms of its cumulative effect with other factors on project stability and performance. One loading alone may not exhibit significant impacts, however, multiple parameters can result in a failed system. This is particularly true if the project area is already stressed in some manner or has low resilience to changes. All of the factors discussed above will vary with region.

3. INCORPORATING SEA LEVEL CHANGE IN PLANNING AND ENGINEERING

Since we cannot identify a single most-likely future condition when considering climate change or other broadly uncertain drivers, methods are needed to compare performance across multiple future scenarios. Scenario analysis is proposed for those problems that have large uncertainties with large potential consequences. Scenarios are not forecasts, but are plausible future states that are used to examine potential outcomes and to assess the performance of existing USACE projects. It is important to note that this SLC approach does not rely on a theory or a number to be applicable. The approach is to provide a flexible and robust framework which can be modified as needed and new information is obtained.

The degree to which SLC is addressed within the study 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 life cycle. Throughout the process it will be determined how sensitive alternative plans and designs are to the range of potential future rates of changes in sea level. Further assessments 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. We must consider sensitivity relative to human health and safety, economic costs and benefits, environmental impacts, and other social effects.

The three general types of project alternative approaches with respect to timing of actions are anticipatory, adaptive, and reactive strategies shown in figure 7 over the project timeline. The anticipatory strategy implements features and design robustness now, for example, increasing design parameters for engineered features. Another example of an anticipatory action would be to acquire additional lands for wetland migration or future structure construction and/or expansion. The adaptive management strategy uses sequential decisions and implementation based on new knowledge. For this strategy, implementation occurs prior to SLC impacts and requires advance planning to maintain the ability to adapt. The reactive strategy can be planned or ad-hoc, but in either case no actions would be implemented until the impacts of SLC begin. It is important to note that no one strategy is, in and of itself, a better strategy. Additional information regarding project area sensitivity, potential consequences, available response time as well as benefit / cost tradeoffs are needed to decide the best approach.

Figure 7. Conceptual comparison of different project alternative strategies

Figure 8 illustrates the basic stages of screening recommended for a project incorporating SLC in the analysis. Each additional stage of analysis is developed based on its ability to improve the decision-making. The key pieces of information utilized to make infrastructure decisions include impacts to social, environmental, policy, benefit-cost, and residual risk for a project. Early on 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 selection of a sea level rate to design for is less critical. However, if alternative response differs significantly for different rates of change, special care should be taken in the analysis so that the residual risk, both in terms of costs and impacts, is captured.

Some key questions relevant to SLC to be incorporated in the analysis:

- Does inclusion of different rates of SLC affect the decision that is being made?
- What is the relative scale of the potential impact of SLC in the project area within the larger context of natural variability of processes?
- Are all alternatives expected to be affected equally by SLC?
- What is the range of SLC over which an alternative will be adaptable?
- Do some alternatives require additional preparation in order to plan for their implementation under SLC?
- What is the expected range of cost of the project alternatives?
- When might you expect to see SLC impacts in the project area and what might the magnitude of those impacts be?
- How much lead time might be needed for the alternative range?
- How might the potential extreme loading conditions in the project area affect impacts and what are the potential impacts if we are wrong?

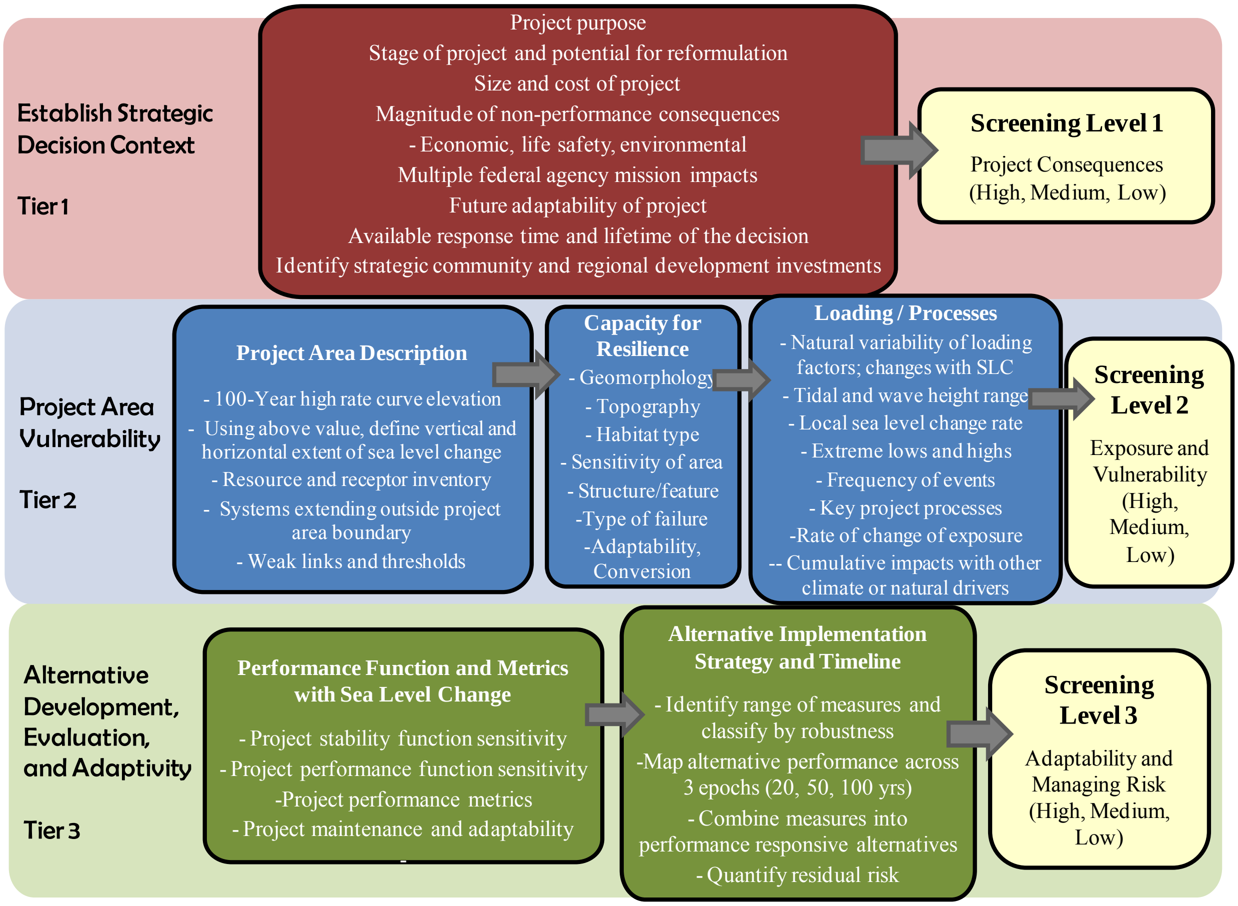

Figure 8. Screening process for analyzing and incorporating SLC in the planning process.

3.1 Tier 1 - Establish a Strategic Design Context.

A tiered analysis is recommended for the inclusion and assessment of SLC impacts on the project and the project alternatives. Inherent in this approach is the understanding that review and decision points exist after each analysis tier that allow the engineers and planners to reassess the required data and analysis which is sufficient to answer the essential problem statements and risk questions of the study. 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 active focus on risk-based scoping to define pertinent water resources needs, opportunities, and the appropriate level of detail for conducting investigations.

The essence 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. The project purpose and the stage of the project in the life cycle is the first defined term. Projects can range from reconnaissance studies which will determine the existence of a federal interest to an examination of potential vulnerabilities and future operations and maintenance requirements for existing infrastructure. The size and cost of the project as well as the potential magnitude of non-performance consequences provides a level of impact definition.

Non-performance consequences can include excessive maintenance requirements, increasingly frequent flooding, loss of essential ecosystem habitat, impacts on operations of project and a corresponding reduction in provided services, life safety, or an unacceptable level of uncertainty regarding project performance and costs. Cumulative system impacts or impacts to other federal agency missions should also be identified at this stage. Also important at this stage is a description of the possible adaptability of the project as well as the lifetime of the decision being made. 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.

Other projects which involve new structures or significant layout modifications of existing structures, projects which are an essential component of a larger system or community, 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. While the establishment of the strategic decision context is important to determining the most appropriate and cost-effective study plan, all projects will still need to go through the second tier or Project Area Vulnerability phase to determine the actual exposure and vulnerability of the project area. Due to the shifted and nonstationary 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 verify expected impacts.

3.2 Tier 2 – Project Area Exposure and Vulnerability to Sea Level Change

Within Tier 2 of the project approach, the project area's vulnerability to SLC will be assessed. The Project Area Vulnerability stage includes 3 primary components as shown in figure 8: (1) project area characterization, (2) capacity for resilience, and (3) loading and processes. As with all USACE studies, the description of the future without project (FWOP) condition is the foundation for any analysis or additional work. All of the information and data required to move through the first two levels of the flowchart in figure 8 should be readily available for the initial screening stage. 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.

3.2.1 Project Area Description.

In order to simplify the initial steps of this phase of the study and yet still capture the real areas of potential risk for use in the initial screening, some bracketing and risk assessment steps are recommended. 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 sea level change impacts. 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 1 is an example of such an inventory table that provides a snapshot of the potential magnitude and severity of consequences due to SLC within 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. Potential system and cumulative effects should be explored.

The analysis doesn't yet focus on a specific alternative, but on the project area and the critical resources it depends on. The idea behind looking at the entire system around a study area is that you may be able to protect coastal infrastructure for 50 years, however the critical resources that infrastructure depends on: e.g., roads, storm drainage, may be impacted before that time. The assumption should not be made that those critical resources will remain in place or fully functioning. Similarly a navigation project can provide services for a number of years, but the hinterland to which the service benefits are provided may be impacted/modified by SLC. The discussion during this stage should include the identification of weak links in the project performance or benefit framework.

Table 1. Example of Inventory & Forecast Conditions, Qualitative Matrix which describes study area's and parallel system's susceptibility to SLC. (USACE, 2009)

Critical Resources in Study Area	**Density of Resource (3=high, 2=medium, 1=low, X=none present)**	**Relevant Notes**	**Risk from SLC (3=high, 2=medium, 1=low, X=none present)**
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 10-15 feet. Estuary and other wetland partially surrounds the study area.	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

3.2.2 Capacity for Resilience.

Resilience is defined as the ability of a system to recover from the effect of an extreme load that may have caused harm. This step should summarize the resilience characteristics of the project area which will differ by project type. A project area's capacity for resilience is a combination of project purpose, physical characteristics, topography, and sensitivity as well as available buffer for adjustments or adaptations. For example, in the case of coastal storm damage reduction projects, a natural shoreline can range from a wide beach, high dune-protected backshore to a sediment-starved, low dune area. Similarly, while some structures are relatively flexible under increased loading or easily adaptable, others can fail catastrophically and are difficult to adapt. Concrete flood walls may be an example of the second category of non-flexible structures.

3.2.3 Loading and Processes.

Once the project area 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. Regionally, the significance of sea level change 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. Figure 9 shows a general diagram illustrating how SLC might relate to other loading magnitudes and uncertainties in a project area. Keep in mind that several of the parameters shown in Figure 9 illustrate the potential natural variability of cyclic loading that occurs with respect to a given datum (surge, waves, tides) and a couple parameters serve to shift that datum line either up or down (vertical land movement, SLC). This effect is also shown in figure 5, illustration of future potential changes in water level extremes at a project site.

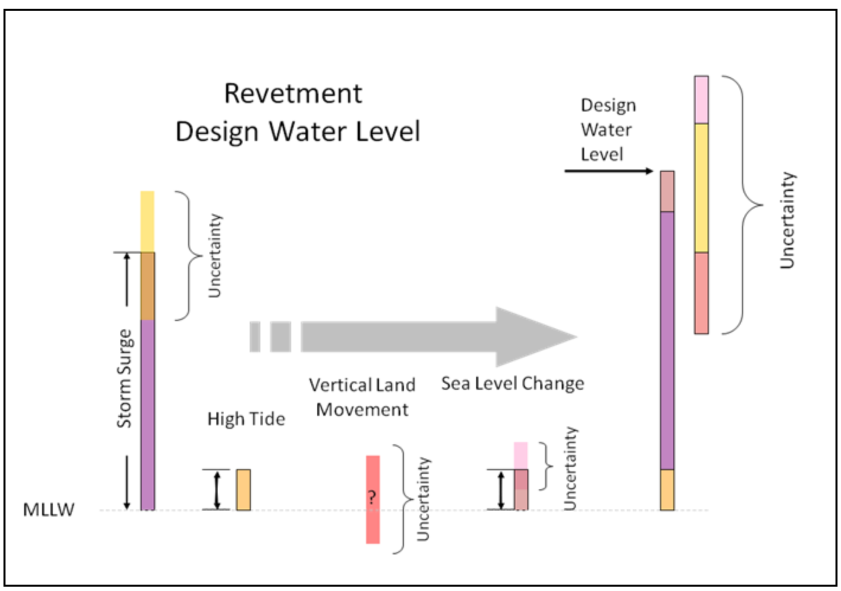

Figure 9. General diagram of how SLC relates to the other magnitudes and uncertainties of the loading parameters within a particular project area in Alaska.

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 more sensitive to percent frequency and average depth of inundation. Factors which 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. Figures 4 to 6 above illustrate typical process and framework approaches to bracketing the changes in loading with SLC.

An essential element of developing a good understanding of the project area 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 to be realized. Building on an approach being used for Shoreline Management Planning in the United Kingdom' (Defra, 2006), 3 epochs are addressed: 20 years, 50 years, and 100 years. This approach will provide a better assessment of when in the planning horizon the SLC impacts are expected to be realized. For some projects, impacts are already being experienced now at high tide periods of the month. For those projects, level of urgency would be elevated.

Figure 10 helps to visualize how the projected rate of change might alter the amount of time available for lead time prior to an action. In addition, some project actions might take more lead time than others to execute. For example, if rate of SLC was expected to threaten significant critical infrastructure or development areas, relocation or large-scale protection of those areas may involve extensive community involvement and takes years to accomplish.

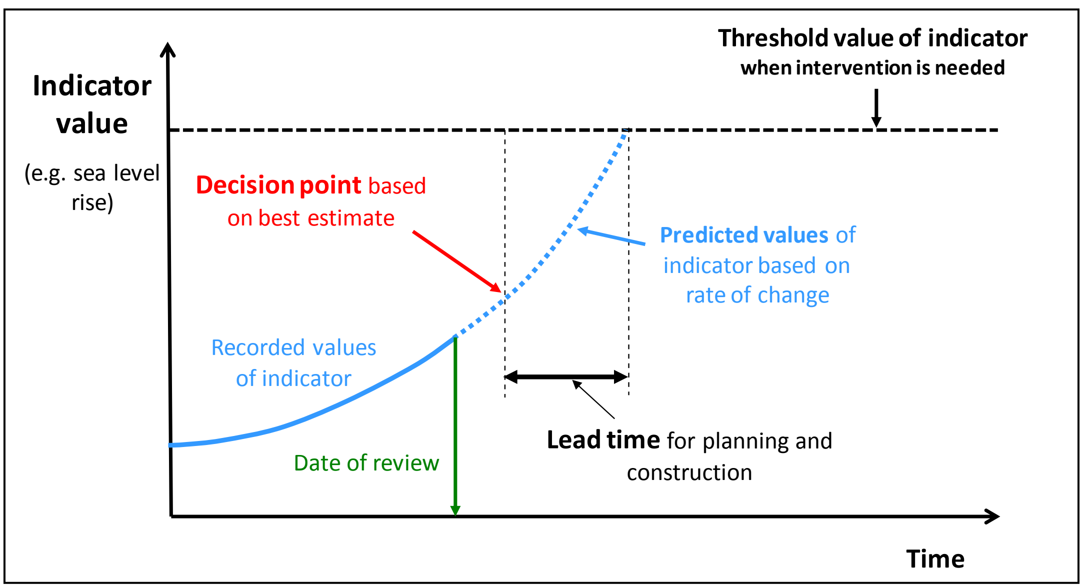

Figure 10. Impacts of thresholds and tipping points on future decision points (from United Kingdom Thames Estuary 2010 study)

After the Project Area Vulnerability assessments, the study team should be able to summarize whether 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 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.

3.3 Tier 3 – Alternative Development, Evaluation, and Adaptability

Tier 3 in the analysis addresses the formulation and evaluation of measures directed at the identified problems. Based on the project purpose and the project area vulnerability, alternatives are proposed to either protect, accommodate, or retreat from the effects of sea level change. Table 2 summarizes what possible adaptation approaches might be for different project types. This table was adapted from Nicholls and Tol (2006) and Nicholls (2011). Some mission areas have a broader range of potential options. 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 category. 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.

Table 2. Potential adaptation approaches to SLC by project type

Project Type	Protect	Accommodate	Retreat
Navigation	Upgrade and strengthen existing primary structures Expand design footprint and cross section of existing structures 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	Relocation of interior harbor infrastructure Abandonment of 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	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	Upgrade and strengthen existing structures Expand design footprint and cross section of existing structures Construct levees or polders Add secondary structures Dune/beach construction	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 levees or polders Salt water intrusion barriers	Sediment management Change water extraction Freshwater injection /diversion Modify land use Migrate landward	Modify habitat type Forbid hard defenses Abandon ecosystem

The next step is to determine how sensitive alternative plans and designs are to the rates of future local mean SLC, 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. As noted in figure 8, the general SLC-related categories of investigation at Tier 3 include 1) assessing the measure's sensitivity to sea level change, both in terms of project stability as well as 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 adds to the structure. In the case of a breakwater, increases in loading would include bigger waves attacking the structure as well as a greater overtopping rate, which has the potential to de-stabilize the leeside of the structure. Figure 11 illustrates an example of armor unit size sensitivity to SLC using the Hudson equation. 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 process-driven impact might be 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.

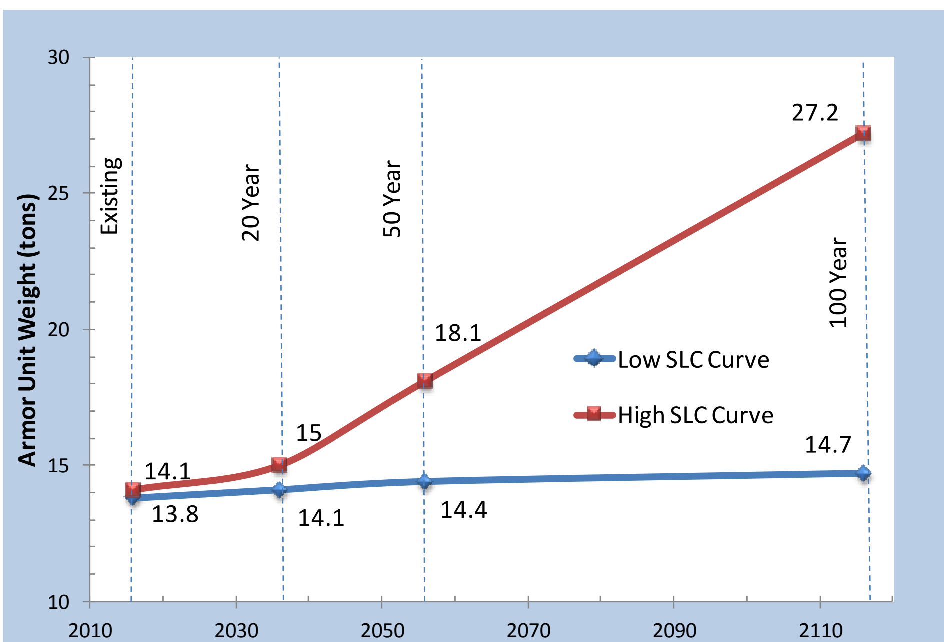

Figure 11. Sensitivity of armor unit size for low and high SLC curves using Hudson equation

3.4 Alternative Comparison and Selection Considering Sea Level Change

At this stage, 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. Once adequately screened for project conditions, including SLC, alternative plans (routes or pathways) can be developed. This may be a marked difference in the way alternative plans have been recommended in the past. 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.

Figure 12 illustrates a range of alternative pathways considered for a coastal storm damage reduction project. The horizontal dashed lines indicate at which point along each SLC curve each measure loses its viability and generates a change in pathway to another measure. Here, the viability of an alternative is assessed for a projected magnitude of SLC rather than a specific point in time. Thresholds tied to relative sea level projections indicate at what level a measure can be implemented and at what point it would no longer be viable given performance, economic, and social considerations. For this particular project, the threshold at the backside 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. A robust measure should be resilient or adaptable across all of the SLC scenarios.

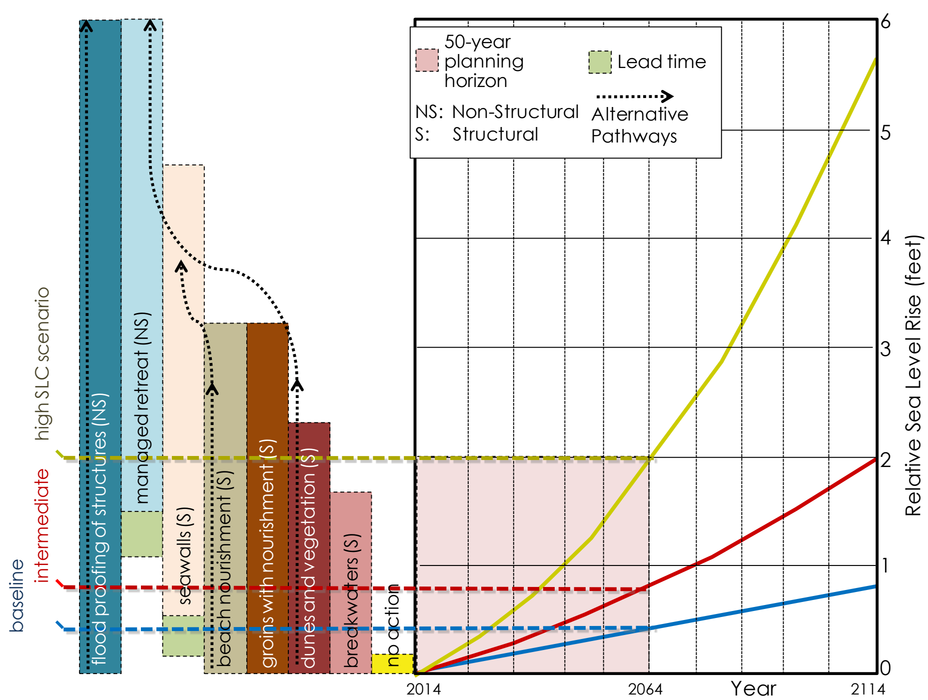

Figure 12. Example alternative pathways for a coastal storm damage reduction project (after ESPACE, 2008)

At this point in the analysis, alternatives are compared and either a recommendation is made or further analysis and re-evaluation is required. The adequacy of the measures/alternatives to address the problems and opportunities and the planning objectives are re-assessed.

4. CONCLUSIONS

USACE projects, programs and activities often involve development and management of long-lived systems. The longer the life of engineered systems and their related socio-economic 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 paper outlines the recommended planning and engineering approach at the regional and project level for addressing impacts of projected sea level change at USACE projects. The goal of this approach is to provide a method to develop practical, nationally consistent, legally justifiable, and cost effective measures, both structural and nonstructural, to reduce vulnerabilities and improve the resilience of our water resources infrastructure to sea level change.

Due to the uncertainty and variability of future sea level change, the goal of the guidance is to outline a robust framework that is flexible and adaptable to multiple future scenarios. Emphasis is placed both on how the project operates within a larger system as well as how project decisions now can influence future impacts. An essential task is to identify the potential for adaptation throughout the project life or project phasing. 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 purpose of the framework is to define the strategic importance of potential impacts both in time and space. Essential to this approach is a comprehensive knowledge of the system that the project operates within including key elevations, weak links and thresholds.

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