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Regulation
No. 1100-2-8162

31 December 2013

INCORPORATING SEA LEVEL CHANGE
IN CIVIL WORKS PROGRAMS

1. Purpose. This Regulation provides United States Army Corps of Engineers (USACE) guidance for incorporating the direct and indirect physical effects of projected future sea level change across the project life cycle in managing, planning, engineering, designing, constructing, operating, and maintaining USACE projects and systems of projects.
2. Applicability. This Regulation applies to all USACE elements having Civil Works responsibilities and is applicable to all USACE Civil Works activities. This guidance is effective immediately and supersedes all previous guidance on this subject.
3. Distribution Statement. This publication is approved for public release; distribution is unlimited.
4. References. Required and related references are at Appendix A. A glossary is included at the end of this document.
5. Geographic Extent of Applicability.
 - a. USACE water resources management projects are planned, designed, constructed, and operated locally or regionally. For this reason, it is important to distinguish between global mean sea level (GMSL) and local (or “relative”) mean sea level (MSL). At any location, changes in local MSL reflect the integrated effects of GMSL change plus changes of regional geologic, oceanographic, or atmospheric origin as described in Appendix B and the Glossary.
 - b. Potential relative sea level change must be considered in every USACE coastal activity as far inland as the extent of estimated tidal influence. Fluvial studies that include backwater profiling should also include potential relative sea level change in the starting water surface elevation for such profiles, where appropriate. The project vertical datum must be the latest vertical reference frame of the National Spatial Reference System, currently NAVD88, to be held as constant for tide station comparisons, and a project datum diagram must be prepared per EM 1110-2-6056.

6. Incorporating Future Sea Level Change (SLC) Projections into Management, Planning, Engineering Design, Construction, and Operation and Maintenance of Projects.

a. Research by climate science experts predict continued or accelerated climate change for the 21st century and possibly beyond, which would cause a continued or accelerated rise in global mean sea level. (See Appendix B)

b. The resulting local relative sea level change (SLC) will likely impact USACE coastal project and system performance. As a result, managing, planning, engineering, designing, operating, and maintaining for SLC must consider how sensitive and adaptable 1) natural and managed ecosystems and 2) human and engineered systems are to climate change and other related global changes.

c. Planning studies and engineering designs over the project life cycle, for both existing and proposed projects, will consider alternatives that are formulated and evaluated for the entire range of possible future rates of SLC, represented here by three scenarios of “low,” “intermediate,” and “high” SLC. These alternatives will include structural, nonstructural, nature-based, or natural solutions, or combinations of these solutions. Alternatives should be evaluated using “low,” “intermediate,” and “high” rates of future SLC for both “with” and “without” project conditions. The historic rate of SLC (as described in Appendix B) represents the “low” rate. The “intermediate” and “high” rates are based on the following:

(1) The “intermediate” rate of local mean sea level change is estimated using the modified National Research Council (NRC) Curve I and equations 2 and 3 presented in Appendix B (see Figure B-10) and is corrected for the local rate of vertical land movement as discussed in Appendix B.

(2) The “high” rate of local mean SLC is estimated using the modified NRC Curve III and equations 2 and 3 in Appendix B (see Figure B-10) and is corrected for the local rate of vertical land movement as discussed in Appendix B. This “high” rate exceeds the upper bounds of IPCC estimates from both 2001 and 2007 to accommodate the potential rapid loss of ice from Antarctica and Greenland, but it is within the range of values published in peer-reviewed articles since that time (see Figure B-1).

(3) The low, intermediate, and high scenarios at NOAA tide gauges can be obtained through the USACE on-line sea level calculator at <http://www.corpsclimate.us/ccaceslcurves.cfm>.

d. Once the three rates have been estimated, the next step is to determine how sensitive alternative plans and designs are to these rates of future local mean SLC, how this sensitivity affects calculated risk, and what design or operations and maintenance measures should be implemented to adapt to SLC to minimize adverse consequences while maximizing beneficial effects. Alternative plans and designs are formulated and evaluated for three SLC possible futures. Alternatives are then compared to each other, and an alternative is selected for

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recommendation. The approach to formulation, comparison, and selection should be tailored to each situation. The performance should be evaluated in terms of human health and safety, economic costs and benefits, environmental impacts, and other social effects. There are multiple ways to proceed at the comparison and selection steps. Possible approaches include:

(1) Working within a single scenario and identifying the preferred alternative under that scenario. That alternative's performance would then be evaluated under the other 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.


(2) Comparing all alternatives against all 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 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.

(3) Reformulating after employing approaches (1) or (2) to incorporate robust features of evaluated alternatives to improve the overall life-cycle performance.

e. Plan selection should explicitly provide a method to address uncertainty, describing a sequence of decisions allowing for adaption based on evidence as the future unfolds. Since Civil Works projects typically have an actual physical life far beyond the period of economic analysis, careful consideration of adaptability is an important consideration in project formulation and development. Decision makers should not presume that the future will follow any one of the SLC scenarios exactly. 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.

FOR THE COMMANDER:

2 Appendices:
APPENDIX A: References
APPENDIX B: Technical Supporting Material
Glossary


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APPENDIX A

References

A-1. Required References.

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ER 1105-2-100

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EM 1110-2-6056

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c. Other Publications.

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A-2. Related References.

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APPENDIX B

Technical Supporting Material

B-1. Background on Sea Level Change.

a. In the preparation of this document USACE has relied 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 as a water resources management agency. USACE has been proactive, however, in working closely with science agencies to develop actionable science that can inform planning and engineering decisions. USACE climate change adaptation guidance will be periodically reviewed and revised as new information becomes available.

b. USACE water resources management projects are planned, designed, constructed, operated, and maintained locally or regionally. SLC 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 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., CCSP 2009). 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 the 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.

(1) Global Sea Level Change. Global (eustatic) SLC 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 from total salinity; and most recently, 3) changes in the heat content of the world's ocean, 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. Thus, 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 to occur at an accelerated rate and is the topic of much of the discussion in this document. NOAA (2010) contains detailed information on GMSL; other publications provide a similar discussion (Church et al. 2007, NRC 2012).

(2) 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 both global and local SLC caused by changes in 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 SLC 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 chapter, 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-2. Determination of Historic Trends in Local MSL.

a. The planning, design, construction, operation, and maintenance of USACE water resource projects in and adjacent to the coastal zone must consider the potential for future accelerated rise in GMSL to affect the local MSL trend. At the same time, 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 SLC may have had on regional coastal resources and problems in the past.

b. 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 stations operated by NOAA/NOS in the U.S. (see <http://www.co-ops.nos.noaa.gov/index.shtml>). 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. The Permanent Service for Mean Sea Level (PSMSL), which is a component of the U.K. Natural Environment Research Council's National Oceanographic Centre, has been collecting, publishing, analyzing, and interpreting sea level data from the global network of tide stations since 1933. Global sea level data can be obtained from PSMSL via their website (<http://www.psms.org>). PSMSL should be considered as a source of information for non-U.S. stations that are not represented by NOAA-NOS. Using PSMSL data, NOAA-NOS also provides sea level trend estimates for stations identified by the Global Sea Level Observing System (GLOSS) community using the same methodology used for all U.S. stations (http://tidesandcurrents.noaa.gov/sltrends_global.shtml). Note that the periods of record for PSMSL gauges vary; some gauges have shorter periods of record than are recommended for relative SLC trend analysis. Figure B-1 illustrates the following conclusions:

(1) Most of the Atlantic and Pacific coasts of the lower contiguous 48 states have had sea level rise trends between 0 and 3 mm/yr (or 0 and +0.3 meters per century) (green symbols).

(2) The highest rates of local MSL rise in the U.S. have occurred along the Gulf Coast in the Mississippi River delta region at 9–12 mm/yr (or 0.9–1.2 meters per century) (red symbols), with significant rises in Texas and the mid-Atlantic (3–6 mm/yr or 0.3–0.6 meters per century).

(3) On the other hand, most stations in Alaska exhibit a falling trend of local MSL. Local mean sea level is falling relative to the land in many glacial fjords in Alaska because of local land vertical rebound after loss of the weight of the glaciers.

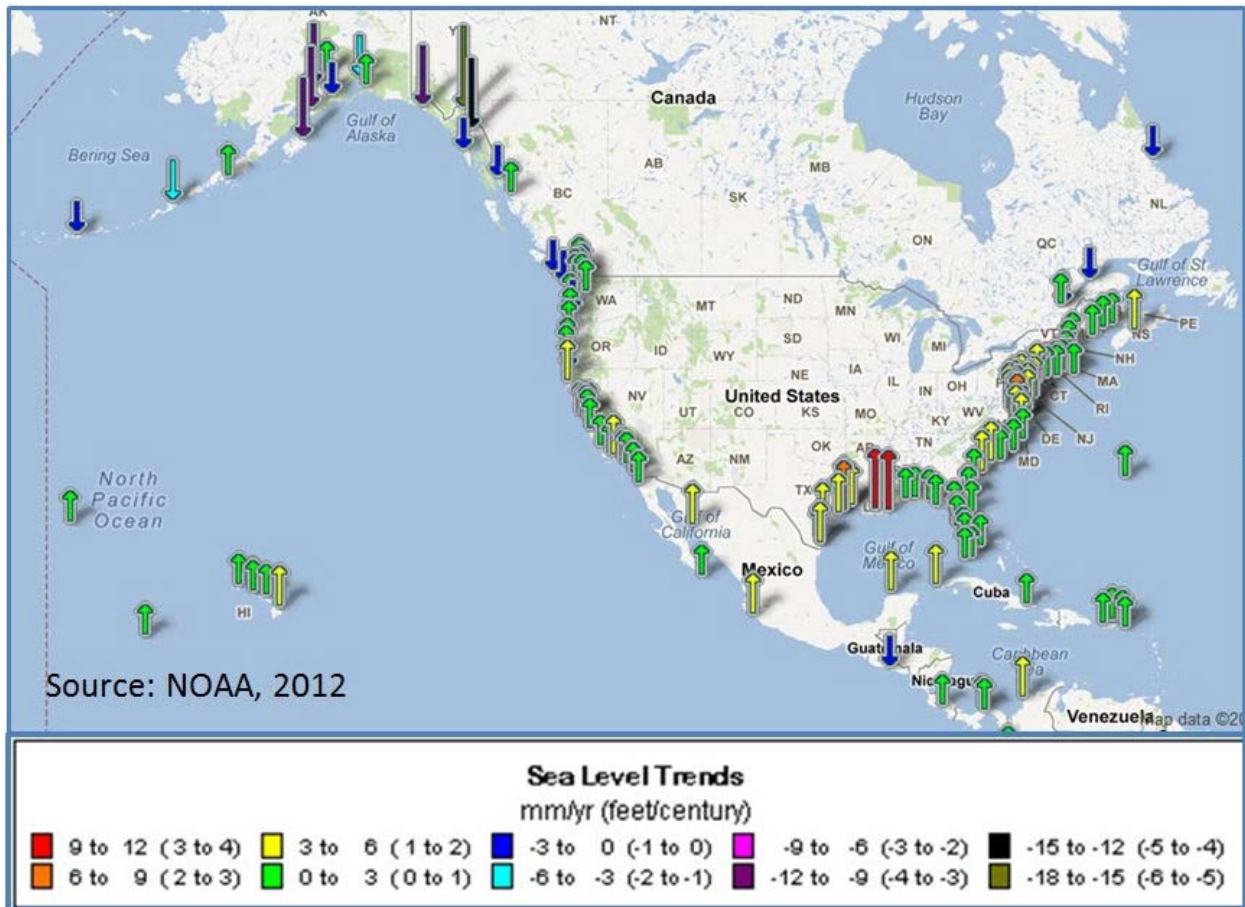


Figure B-1. Mean sea level trends for U.S. tide stations computed by NOAA for 128 long-term water level stations using a minimum span of 30 years of observations at each location. See <http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml> for updated information.

c. It is important to consider the length of tide station record required to obtain a robust estimate of the historic relative mean SLC. The length of the record is important because inter-annual, 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.

d. The Manual on Sea Level Measurement and Interpretation (Intergovernmental Oceanographic Commission 1985, 2012) suggests that a tidal record should be of at least of 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). Figure B-2 (from Zervas et al. 2009) shows the relationship between period of record and the standard error of the trend for selected U.S. tide stations. Note the significant decrease in standard error approximately at the 40- or 50-year period of record. Record lengths shorter than 40 years in duration could have significant uncertainty compared to their potential numerical trend values of a few millimeters per year. 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.

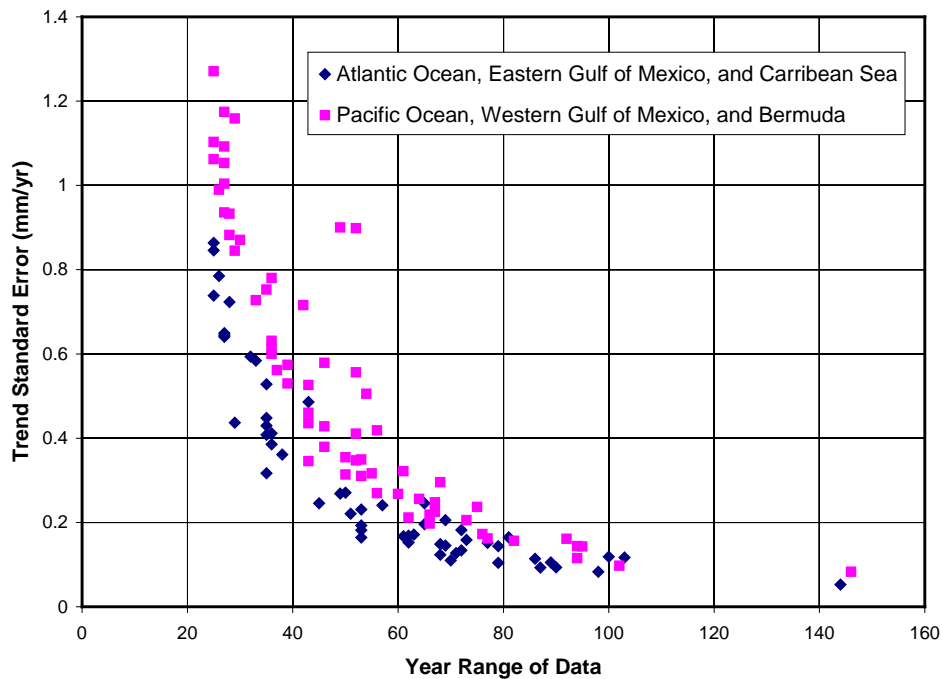


Figure B-2. Standard error of linear trend of sea level change vs. period of record for U.S. tide stations. (From Zervas et al. 2013.)

e. 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 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.

f. Confidence Limits. Current information on the magnitude and confidence limits based on standard error of the estimate of trends for NOS tide stations is available online at <http://tidesandcurrents.noaa.gov/sltrends/slrmap.html>. Figure B-3 shows the Atlantic coast.

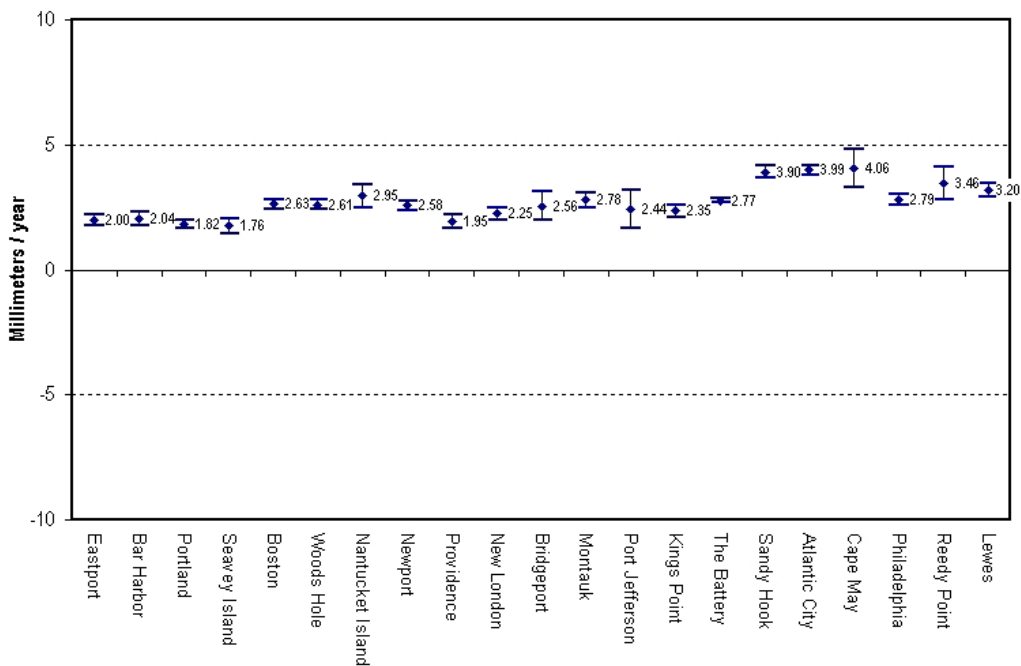


Figure B-3. Magnitude and confidence limits of trends for northern Atlantic coast NOS tide stations. [Zervas (2009), <http://tidesandcurrents.noaa.gov/sltrends/index.shtml>].

B-3. Regional Sea Level Change. Regional SLC rates should be evaluated as well as rates of local SLC and global SLC. The estimate of trends for NOS tide stations available online at <http://tidesandcurrents.noaa.gov/sltrends/slrmap.html> provides 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 or land isostatic rebound and deformation. 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. The graphical products from the satellite altimeter missions also demonstrate the regional variability of SLC. Although the average for the entire globe is approximate 3.0 mm/yr, there is significant regional variability, with some areas exhibiting neutral or even negative sea level trends. For the U.S., this is the case for much of the West Coast and Gulf of Alaska, for instance. Although the satellite altimeter average global rate is often used to suggest recent acceleration in rates of global sea level rise, the actual local or regional rate may be much different. Areas that could experience regional rates different than global rates include the northern Gulf of Mexico, the Gulf of Maine, and the Gulf of Alaska.

B-4. Estimating Future Change in Local MSL.

a. 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 that shall be based on an extrapolation of the historical tide gauge rate, and intermediate and high rates that include future acceleration of GMSL. The analysis may also include additional intermediate rates, if the project team desires [e.g., the high rate from Parris et al. (2012)]. The sensitivity of each design alternative to the various rates of SLC shall be considered. Designs should be formulated using the wide body of currently accepted design criteria for each applicable mission area.

b. Uncertainty Over Time. The use of sea level rise scenarios as opposed to individual scenario probabilities underscores the uncertainty in how local relative sea levels 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. The 1987 NRC report recommended that feasibility studies for coastal projects consider the high probability of accelerating GMSL rise and provided three different scenarios. NRC (1987) described these three scenarios using the following equation:

$$E(t) = 0.0012t + bt^2 \tag{1}$$

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 . 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 (2007a), results in this equation being modified to be:

$$E(t) = 0.0017t + bt^2 \quad (2)$$

(1) The three scenarios proposed by the NRC result in global eustatic sea level rise values, by the year 2100, of 0.5 meters, 1.0 meters, and 1.5 meters. Adjusting the equation 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 of 1983–2001), instead of 1986 (the start date for equation 1), 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. 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. 2011).

(2) Manipulating equation (2) 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 (3):

$$E(t_2) - E(t_1) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2) \quad (3)$$

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). 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 fifty-year life and is to be constructed in 2013, $t_1 = 2013 - 1992 = 21$ and $t_2 = 2063 - 1992 = 71$.

(3) The low, intermediate, and high scenarios for NOAA tide gauges can be obtained through the USACE on-line sea level calculator at <http://www.corpsclimate.us/ccaceslcurves.cfm>.

(4) Figure B-4 illustrates an example of the three sea level rise curves for a location in Grand Isle, Louisiana.

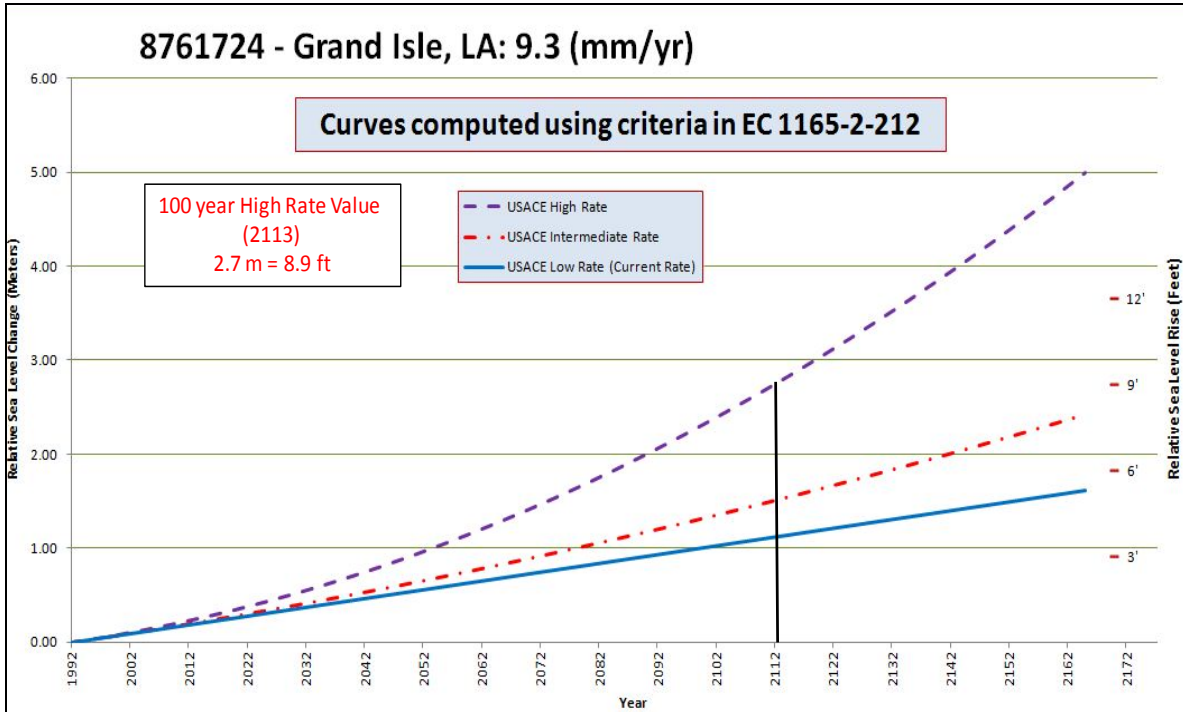


Figure B-10. Example USACE SLC curves for Grand Isle, Louisiana.

GLOSSARY

Terms and Abbreviations

Coastal

As used in this ER, locations with oceanic astronomical tidal influence, as well as connected waterways with base-level controlled by sea level. In the latter waterways, influence by wind-driven tides may exceed astronomical tidal influence. Coastal areas include marine, estuarine, and riverine waters and affected lands. (The Great Lakes are not considered “coastal” for the purposes of this ER.)

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 Sea Level (LMSL). The current vertical datum used in the United States is the North American Vertical Datum of 1988 (NAVD 88), which replaced the National Geodetic Vertical Datum of 1929 (NGVD 29) (formerly referred to as the Sea Level Datum of 1929). For tidal datums, see below.

Eustatic sea level rise

A change in global average sea level brought about by an increase in the volume of the world ocean (IPCC 2007b).

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 2007b).

Local (i.e., “relative”) sea level

Sea level measured by a tide gauge with respect to the land on 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 2007b). Relative sea level change will also affect the impact of any regional SLC.

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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 sea floor following the reduction of the load of an ice mass, for example, since the last glacial maximum (~21,000 years ago). The rebound is an isostatic land movement (IPCC 2007b).

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 to changes in bathymetry. Regional sea level change as used here does not include local geologic effects, such as subsidence or tectonic movement.

Risk

A measure of the probability and severity of undesirable consequences (including, but not limited to, loss of life, threat to public safety, environmental and economic damages).

Sea level change

A change in the mean level of the ocean.

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 so recorded gives the observed secular changes of the relative sea level (IPCC 2007b).

Tidal datums

A standard elevation defined in terms of a certain phase of the tide. Tidal datums are local datums and should not be extended into areas which 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 bench marks.

Uncertainty

The result of imperfect knowledge concerning the present or future state of a system, event, situation, or (sub) population under consideration. There are two types of uncertainty: aleatory and epistemic. Aleatory uncertainty is attributed to inherent variation that is understood as variability over time and/or space. Epistemic uncertainty is 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.