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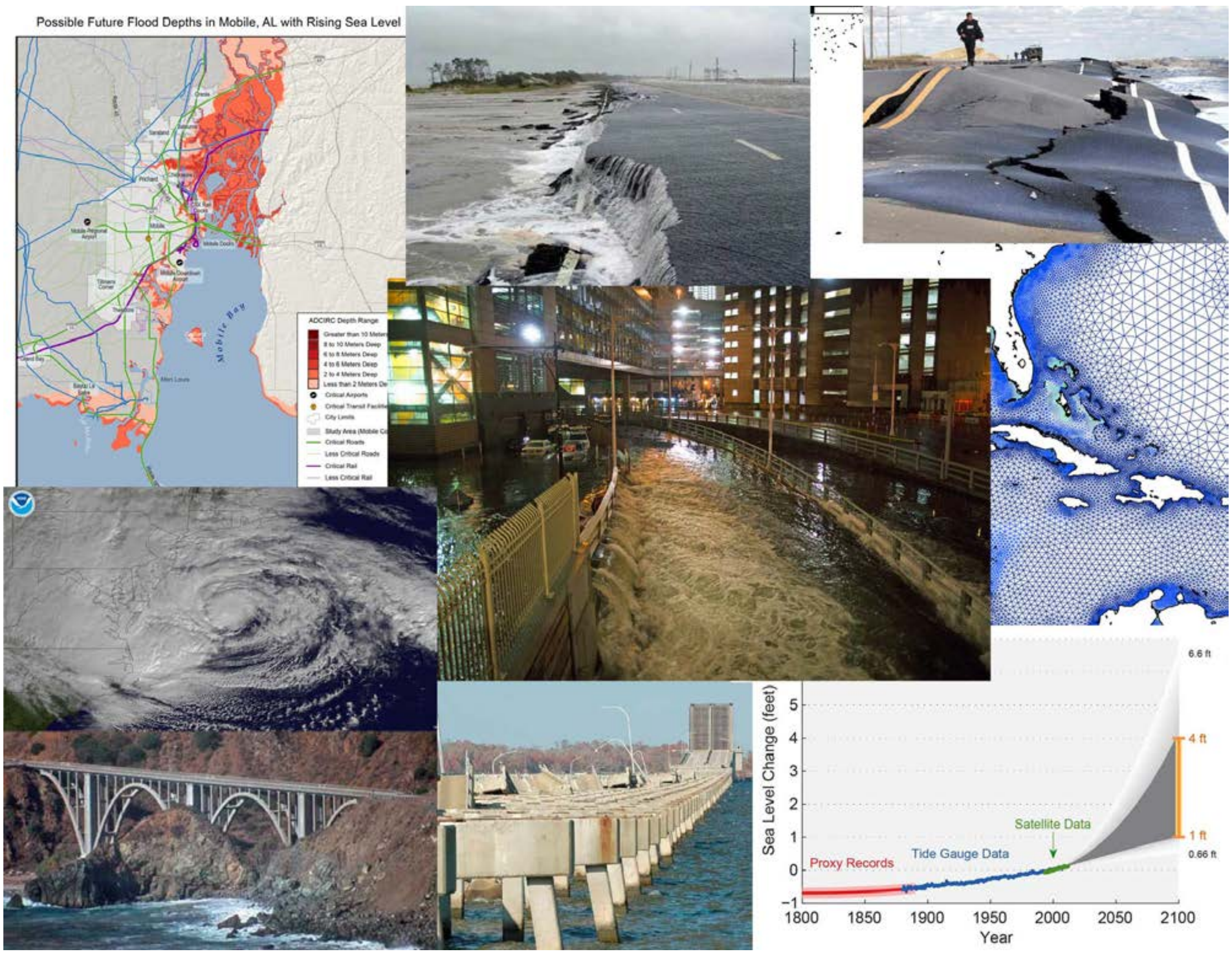

Highways in the Coastal Environment: Assessing Extreme Events

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<tr><td colspan="4">16. Abstract
This manual provides technical guidance and methods for assessing the vulnerability of coastal transportation facilities to extreme events and climate change. This is a standalone supplement, a "Volume 2," to the existing, primary FHWA Hydraulic Engineering Circular (HEC) manual: "Highways in the Coastal Environment," HEC-25 (2nd ed., FHWA 2008). The focus of this supplement is quantifying exposure to sea level rise, storm surge, and waves considering climate change. It is anticipated that there will be multiple uses for this guidance including risk and vulnerability assessments, planning activities, and design procedure development.

The critical coastal processes controlling the vulnerability of transportation assets to extreme events are identified by region along with some available methods for modeling them and the likely impacts of climate change. Global sea level rise, including projections of future sea levels, is emphasized because of its importance.

Tools for developing vulnerability assessments for coastal transportation infrastructure are described within the framework of engineering risk. Storm damage mechanisms, often exacerbated by sea level rise and climate change, are described. Adaptation approaches for coastal transportation infrastructure are also described.

Many of the adaptations required for climate change and sea level rise are the same adaptations required for improving infrastructure resilience to extreme events with today's sea levels. Specific approaches for assessing exposure of coastal infrastructure to extreme events and climate change are presented in three different "levels of effort" ranging from use of available data to original numerical modeling. The inclusion of trained coastal scientists and engineers in the analysis team is suggested at all levels of effort. Three case studies from the existing literature on coastal vulnerability assessments to extreme events and climate change are described. Our coastal transportation infrastructure is highly exposed to extreme events today and that exposure is likely to increase with sea level rise and climate change.</td></tr>
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Table of Contents

List of Figures

List of Tables

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<u>State and Local Agencies</u>
Robert Brantly, Florida Department of Environmental Protection
Ruth Carter, Alaska DOT
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James Marino, Taylor Engineering
William McDougal, Oregon State University
Jon Miller, Stevens Institute of Technology
Jamie Padgett, Rice University
Chin H. Wu, University of Wisconsin
Harry Yeh, Oregon State University

<u>NOAA</u>
Gene R. Clark
Keith Dixon
Ellen Mecray
Jay Tanski

<u>USACE</u>
Lynn Bocamazo
Mary Cialone
John Kangas
Thomas Kendall
Jeff Melby
Jane Smith

<u>USGS</u>
Patrick Barnard
Tom Doyle

<u>FHWA</u>
Joe Balice
Daniel Byer
Michael Culp
Jeffrey Ger
Dan Ghere
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Greg Kolle
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The cover montage provides examples of coastal transportation vulnerabilities to extreme events examples of analysis tools discussed in this manual. The central photograph is seawater flooding into the Brooklyn Battery Tunnel in New York City on the night of October 29, 2012 because of storm surge from Hurricane Sandy (AP photo by John Minchillo). The other photographs, from the bottom-center clockwise are: bridge damage caused by storm surge and waves in Biloxi, Mississippi during Hurricane Katrina; the Big Creek Bridge on the Pacific Coast Highway; a NOAA satellite image of Hurricane Sandy in the Atlantic; roadway damage being caused by overflowing storm surge in Florida; and roadway damage caused by Hurricane Sandy in North Carolina (photo courtesy of NCDOT). The graphical images are: flood levels estimated for Mobile, Alabama with a specific storm and sea level rise scenario (top left); a portion of a commonly used numerical mesh of the Atlantic and Gulf coasts for computer modeling of storm surge (right middle-top); and sea level rise records and projections from the National Climate Assessment (bottom right).

Glossary

0.2-PERCENT-ANNUAL-CHANCE FLOOD: The flood that has a 0.2-percent chance of being equaled or exceeded in any given year. See 500-year flood.

1-PERCENT-ANNUAL-CHANCE FLOOD: The flood that has a 1-percent chance of being equaled or exceeded in any given year. See 100-year flood.

2-PERCENT-ANNUAL-CHANCE FLOOD: The flood that has a 2-percent chance of being equaled or exceeded in any given year. See 50-year flood.

10-PERCENT-ANNUAL-CHANCE FLOOD: The flood that has a 10-percent chance of being equaled or exceeded in any given year. See 10-year flood.

10-YEAR FLOOD: Flood level which will recur on average once every 10 years. See 10-Percent-Annual-Chance Flood.

50-YEAR FLOOD: Flood level which will recur on average once every 50 years. See 2-Percent-Annual-Chance Flood.

100-YEAR FLOOD: Flood level which will recur on average once every 100 years. See 1-Percent-Annual-Chance Flood.

500-YEAR FLOOD: Flood level which will recur on average once every 500 years. See 0.2-Percent-Annual-Chance Flood.

ADAPTATION: Preparing for the impacts of extreme events and climate change on the nation's transportation infrastructure and systems. Adaptation refers to the planning, designing, constructing, operating, or maintaining transportation infrastructure while incorporating consideration of extreme events and climate change.

ADAPTIVE CAPACITY: The degree to which the system containing the asset (road, bridge, etc.) can adjust or mitigate the potential for damage or service interruption by the hazards.

ARMOR STONE: Stone in the layer on the outside or top of a revetment or seawall.

BARRIER ISLAND: An unconsolidated, elongated body of sand or gravel lying above the high tide level and separated from the mainland by a lagoon or marsh. It is commonly between two inlets, has dunes, vegetated areas, and swampy terrains extending from the beach into the lagoon.

BATHYMETRY: The depths of water in oceans, seas, and lakes.

BAY: 1) A body of water almost completely surrounded by land but open to some tidal flow communications with the sea. 2) A recess in the shore or an inlet of a sea between two capes or headlands, not as large as a gulf but larger than a cove.

BEACH: The zone of unconsolidated material, typically sand, that extends landward from closure depths where sand is moved by waves to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation (usually the effective limit of storm waves).

BEACH EROSION: The carrying away of beach materials by wave action, tidal currents, littoral currents, or wind.

BEACH NOURISHMENT: The direct placement of large amounts of good quality sand (with characteristics similar to those of the native sand) on the beach to widen the beach.

BLUFF: A high, steep bank or cliff.

BOUNDARY CONDITIONS: Environmental conditions, e.g. water levels, waves, currents, drifts, etc. used as boundary input to numerical models.

BREAKING: Reduction in wave energy and height. In the surf zone breaking is due to limited water depth.

BREAKWATER: A structure protecting a shore area, harbor, anchorage, or basin from waves.

BULKHEAD: A structure or partition to retain or prevent sliding of the land. A secondary purpose is to protect the upland against damage from wave action.

CLIMATE: The characteristic weather of a region, particularly regarding temperature and precipitation, averaged over some significant interval of time (minimum 20 years).

CLIMATE CHANGE: 1) A significant and lasting change in the statistical distribution of weather patterns around the average conditions (i.e., more or fewer extreme weather events) over periods ranging from decades to millions of years. 2) Climate change refers to any significant change in the measures of climate lasting for an extended period of time. In other words, climate change includes major changes in temperature, precipitation, coastal storms, or wind patterns, among others, that occur over several decades or longer. 3) A non-random change in climate that is measured over several decades or longer. The change may be due to natural or human-induced causes.

COASTAL AREA: The land and sea area bordering the shoreline.

COASTAL ENGINEERING: The planning, design, construction and operation of infrastructure in the wave, tide and sand environment that is unique to the coast. A well-established specialty area of civil engineering that focuses on the coastal zone and coastal processes.

COASTAL ENVIRONMENT: The sum of all external conditions (e.g. tides, waves, sediments) affecting built infrastructure near the coast.

COASTAL PROCESSES: Collective term covering the action of natural forces on the shoreline and nearshore seabed.

COASTLINE: Commonly, the line that forms the boundary between the land and the water, esp. the water of a sea or ocean.

CONTINENTAL SHELF: 1) The zone bordering a continent extending from the line of permanent immersion to the depth, usually about 330 ft to 660 ft (100 m to 200 m), where there is a marked or rather steep descent toward the great depths of the ocean. 2) The area under active littoral processes during the Holocene epoch. 3) The region of the oceanic bottom that extends outward from the shoreline with an average slope of less than 1:100 (vertical:horizontal), to a line where the gradient begins to exceed 1:40 (the continental slope).

CORIOLIS FORCE: Force due to the Earth's rotation, capable of generating and influencing oceanic and atmospheric currents. It causes currents to be deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.

CREST (OF WAVE): 1) The highest part of a wave. 2) That part of the wave above still-water level.

CRITICAL FLOW: The flow condition where the specific energy of flow is at a minimum and the Froude number for the flow is one; term from open-channel flow hydraulics. Related terms are sub-critical flow and super-critical flow.

CROSS-SHORE: Perpendicular to the shoreline.

CURRENT: 1) The flowing of water. 2) That portion of a stream of water which is moving with a velocity much greater than the average or in which the progress of the water is principally concentrated. 3) Ocean currents can be classified in a number of different ways. Some important types include the following: A) Periodic - due to the effect of the tides; such currents may be rotating rather than having a simple back and forth motion. The currents accompanying tides are known as tidal currents; B) Temporary - due to seasonal winds; C) Permanent or ocean - constitute a part of the general ocean circulation. The term drift current is often applied to a slow broad movement of the oceanic water; D) Nearshore - caused principally by waves breaking along a shore.

DATUM: Any permanent line, plane, or surface used as a reference to which elevations are referred.

DEPTH-LIMITED: Wave height is limited by the local depth of water.

DESIGN STORM: A hypothetical extreme storm whose wave's coastal protection structures will often be designed to withstand. The severity of the storm (i.e. return period) is chosen in view of the acceptable level of risk of damage or failure. A design storm consists of a design wave condition, a design water level, and a duration. Frequently in coastal flood analysis the design storm refers primarily to the water level elevation.

DIFFRACTION: The phenomenon by which energy is transmitted laterally along a wave crest as it moves into different depths, currents, or into the lee of a barrier such as a breakwater. The result is typically a change in wave direction and height.

DISSIPATION: Reduction in wave energy and height.

DIURNAL: Having a period or cycle of approximately one day.

DIURNAL TIDE: A tide with one high water and one low water in a tidal day.

DREDGING: Excavation or displacement of the bottom or shoreline of a water body. Dredging can be accomplished with mechanical or hydraulic machines. Most is done to maintain channel depths or berths for navigational purposes; other dredging is for shellfish harvesting, for cleanup of polluted sediments, and for placement of sand on beaches.

DUNES: Ridges or mounds of loose, wind-blown material, usually sand.

DURATION: The length of time a phenomenon occurs at a specific location. Storm surge duration is the length of time that the coastal flood levels are elevated because of the storm. This is related to how fast a storm is moving and how large the storm is. In wave modeling, duration is the length of time the wind blows in nearly the same direction over the fetch.

EL NIÑO: Is characterized by a large scale weakening of the trade winds and warming of the surface layers in the eastern and central equatorial Pacific Ocean. El Niño events occur irregularly at intervals of 2 to 7 years, although the average is about once every 3 to 4 years. They typically last 12 to 18 months, and are accompanied by swings in the Southern Oscillation, an interannual see-saw in tropical sea level pressure between the eastern and western hemispheres. During El Niño, unusually high atmospheric sea level pressures develop in the western tropical Pacific and Indian Ocean regions, and unusually low sea level pressures develop in the southeastern tropical Pacific. Southern Oscillation tendencies for unusually low pressures west of the date line and high pressures east of the date line have also been linked to periods of anomalously cold equatorial Pacific sea surface temperatures sometimes referred to as La Niña.

EL NIÑO SOUTHERN OSCILLATION (ENSO): The atmospheric component of El Niño. See definition of El Niño.

EPOCH: 1) Tidal epoch is a time related to astronomical cycles of the earth-moon-sun system and is about 19 years. 2) Geological epoch is a subdivision of the geologic timescale that is longer than an age and shorter than an era.

EROSION: The wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, and littoral currents.

ESTUARY: 1) The region near a river mouth in which the fresh water of the river mixes with the salt water of the sea and which received both fluvial and littoral sediment influx. 2) The part of a river that is affected by tides.

EUSTATIC SEA LEVEL CHANGE: Change in sea level due to change in the volume of the world's ocean basins and the total amount of ocean water. Vertical Land Movement (VLM) is not included. See Global Sea Level Rise.

EXPOSURE: The degree to which a transportation asset (road, bridge, etc.) experiences a hazard.

EXTRATROPICAL: A term used in advisories and tropical summaries to indicate that a cyclone has lost its "tropical" characteristics. The term implies both poleward displacement of the cyclone and the conversion of the cyclone's primary energy source from the release of latent heat of condensation to baroclinic (the temperature contrast between warm and cold air masses) processes. Cyclones can become extratropical and still retain winds of hurricane or tropical storm force.

EXTREME EVENT: Severe, rarely occurring event that usually causes damage, destruction or severe economic losses. Such events may include unseasonable weather, heavy precipitation, a storm surge, flooding, drought, windstorms (including hurricanes, tornadoes, and associated storm surges), extreme heat, extreme cold, earthquakes and tsunamis.

FEMA 540 RULE: Guidance FEMA uses to determine if a sand dune is large enough to survive a 100-year storm. If the cross-sectional area of the dune above the storm surge still water level is greater than 540 square feet, the dune is assumed to be large enough to survive.

FETCH: The distance or area in which wind blows across the water forming waves. Sometimes used synonymously with fetch length and generating area.

FETCH-LIMITED: Situation in which wave energy (or wave height) is limited by the size of the wave generation area (fetch).

FINITE-DIFFERENCE: A general type of numerical method for approximating the solutions to boundary value problems with differential equations using finite-difference equations, algebraic equations across small distances, to approximate derivatives.

FINITE ELEMENT: a general type of numerical method for finding approximate solutions to boundary value problems of differential equations which discretizes the area, or domain, of interest into small, variable-sized, usually triangular, mesh elements.

FLOOD: A general and temporary condition of partial or complete inundation of normally dry land areas from 1) the overflow of inland or tidal waters or 2) the unusual and rapid accumulation or runoff of surface waters from any source.

FREEBOARD: 1) The vertical distance between the water level and the top of a coastal levee or dike. 2) The distance from the still water level waterline to the low chord of the bottom of a suspended deck such as a bridge deck or offshore platform. 3) The distance from the crest of the design wave to the low chord of the bottom of a suspended deck such as a bridge deck or offshore platform.

GEOMORPHOLOGY: 1) That branch of physical geography which deals with the form of the Earth, the general configuration of its surface, the distribution of the land, water, etc. 2) The investigation of the history of geologic changes through the interpretation of topographic forms.

GLOBAL SEA LEVEL RISE: The sea level rise averaged across the world's oceans. This is the average change in sea level due to a change in the volume of the world's ocean basins and the total amount of ocean water. Vertical land movement (VLM) is not included. See Eustatic Sea Level Change.

GRID POINT: Location specified in the domain of a numerical model solution.

GROIN: Narrow, shore-normal, structure built to trap and retain littoral material as a shore stabilization technique. More than one groin, a groin field, is commonly used to stabilize a beach. Most groins are of timber or rock and extend from a seawall, or the backshore, well onto the foreshore and sometimes even further offshore. Sometimes (non-technical language) these are commonly called jetties, but in coastal engineering the term "jetty" is used for structures at inlets or river mouths.

GULF: 1) A relatively large portion of the ocean or sea extending far into land; the largest of various forms of inlets of the sea. 2) The Gulf of Mexico.

HEADLAND: A promontory extending out into a body of water.

HEADLAND BREAKWATER: A rock breakwater constructed to function as a headland by retaining an adjacent sandy pocket beach.

HIGH TIDE: The maximum elevation reached by each rising tide.

HIGH WATER: Maximum height reached by a rising tide. The height may be solely due to the periodic tidal forces or it may have superimposed upon it the effects of prevailing meteorological conditions. Non-technically, also called the high tide.

HIGH WATER MARK: A wet-dry line or debris line reference mark on a structure or natural object indicating the maximum high water level in a flood. Often these are noted inside flooded buildings which have removed wave action.

HIGHER HIGH WATER: The higher of the two high waters of any tidal day. The single high water occurring daily during periods when the tide is diurnal is considered to be a higher high water.

HINDCAST: Application of a numerical model to simulate a past event. Often used in model validation to see how well the output matches known events.

HOLOCENE: An epoch of the quaternary period, from the end of the Pleistocene epoch, about 12,000 to 20,000 years ago, to the present time. This is the geologic time epoch of the most recent rise in eustatic sea level in response to climate change and it continues to today.

HURRICANE: An intense tropical cyclone in which winds tend to spiral inward toward a core of low pressure, with maximum sustained (1-minute average) surface wind velocities that equal or exceed 75 mph or 65 knots (120 km/h) . Term is used in the Atlantic, Gulf of Mexico, and eastern Pacific.

HYDRODYNAMIC: Having to do with the science of moving water.

HYDROGRAPH: 1) The graph of the variation of still water level with time. 2) The graph of discharge with time.

INLET: 1) A short, narrow waterway connecting a bay, lagoon, or similar body of water with a large parent body of water. 2) An arm of the sea (or other body of water) that is long compared to its width and may extend a considerable distance inland.

JETTY: On open seacoasts, a structure extending into a body of water which is designed to prevent shoaling of a channel by littoral materials and to direct and confine (i.e. “jet”) the stream or tidal flow. Jetties are built at the mouths of rivers or tidal inlets to help deepen and stabilize a channel. Common (non-technical) usage of the term “jetty” can refer to groins.

KING TIDE: Non-technical term for an extremely high tide level due to regular astronomical (interactions of the moon/earth/sun system) fluctuations. Photos of these high tide levels have been used to help visualize and understand the impacts of sea level rise along the Pacific coast.

LIFE CYCLE COST ANALYSIS: An engineering economic analysis that allows officials to quantify the differential costs of alternative investment options for a given project.

LITTORAL: Of or pertaining to a shore, especially of the sea, usually the currents and sand movement driven by wave action.

LITTORAL DRIFT: The movement of beach material in the littoral zone by waves and currents. Includes movement parallel (longshore drift) and sometimes also perpendicular (cross-shore transport) to the shore. Also known as longshore sand transport.

LONGSHORE: Parallel to and near the shoreline; alongshore.

LONGSHORE SAND TRANSPORT: Movement of (beach) sediments approximately parallel to the coastline. Littoral drift.

LOW TIDE: The minimum elevation reached by each falling tide.

MARSH: 1) A tract of soft, wet land, usually vegetated by reeds, grasses and occasionally small shrubs. 2) Soft, wet area periodically or continuously flooded to a shallow depth, usually characterized by a particular subclass of grasses, cattails and other low plants.

MEAN HIGH WATER (MHW): The average height of the high waters over a 19-year period. All high water heights are included in the average where the type of tide is either semidiurnal or mixed. For diurnal tides, only the single high water (which is also the higher high water) occurring daily during periods is averaged to determine mean high water. Therefore, mean high water is also the same as mean higher high water in the diurnal case.

MEAN HIGHER HIGH WATER (MHHW): The average height of the higher high waters over a 19 year period.

MEAN SEA LEVEL (MSL): The average height of the surface of the sea for all stages of the tide over a 19-year period, usually determined from hourly height readings. Not necessarily equal to mean tide level.

METEOTSUNAMI: Long-wave motions principally caused by meteorologically-induced disturbances, including those associated with pressure jumps, frontal passages, and squalls.

MONTE CARLO: A class of computational algorithms that use repeated random sampling to obtain risk estimates.

MORPHOLOGY: The form and structure, and the changes of form and structure of the earth’s surface.

NONLINEAR: Occurring as a result of a mathematical operation that is not linear.

NOR'EASTER: Common storm type in the North Atlantic Ocean which produces northeast winds along the US Atlantic seaboard.

NUMERICAL MODELING: Refers to analysis of natural processes including storm surge, tidal circulation, and wave generation using computational methods with computers.

OFFSHORE: The direction seaward from the shore.

ONSHORE: The direction landward from the sea.

OVERTOPPING: Passing of water over the top of a structure (e.g. seawall, roadway) usually as a result of wave runup or storm surge. Riverine flow can contribute to overtopping.

OVERWASH: 1) The part of the uprush that runs over the crest of a berm or structure or barrier island and does not flow directly back to the ocean or lake. 2) The effect of waves overtopping a barrier island or coastal defense, often carrying sediment landward, which is then lost to the beach system.

PACIFIC DECADAL OSCILLATION: A long-lived El Niño-like pattern of Pacific climate variability.

PASS: In hydrographic usage, a navigable channel through a bar, reef, or shoal, or between closely adjacent islands. On the Gulf of Mexico coast, inlets are often known as passes.

PEAK PERIOD: Wave period corresponding to the frequency at the peak of the wave energy density spectrum. More of the energy in the sea state is at this wave period than at other periods.

PIER: A structure, usually of open construction, extending out into the water from the shore, to serve as a landing place, recreational facility, etc., rather than to afford coastal protection.

PILE: A long, heavy timber or section of concrete or metal that is driven or jetted into the earth or seabed to serve as a support or protection.

PINEAPPLE EXPRESS: A weather system characterized by a jet stream dip into the vicinity of Hawaii (thus the "pineapple") which carries a moisture-laden storm system to Washington, Oregon, or California. Unlike tropical events, these winter storms do not behave as cyclonic systems; instead they are characterized by high winds that drive waves onto coastal areas.

QUATERNARY PERIOD: The most recent, current, period in the geologic time scale.

RECESSION: Landward movement of the shoreline. A net landward movement of the shoreline over a specified time.

REFRACTION: The bending of wave crests as they move into shallower water resulting in a change in direction and height.

RELATIVE SEA LEVEL CHANGE: Sea level change at a coastal location relative to the land. This includes both the eustatic sea level rise component and the vertical land movement (VLM) component. This is the sea level change measured by long-term tide gages.

RETURN PERIOD: A concept used to define the average length of time between occurrences in which the value of the random variable, typically flood level, is equaled or exceeded.

REVETMENT: A layer or layers of stone, concrete, etc., to protect an embankment, or shore structure, against erosion by wave action or currents.

RISK: Chance or probability of failure due to all possible environmental inputs and all possible mechanisms. The concept of flood risk typically captures both the probability of the flood event and the consequences of the flood event.

RUBBLE-MOUND STRUCTURE: A mound of random-shaped and random-placed stones protected with a cover layer of selected stones.

RUNUP: The upper level reached by a wave on a beach or coastal structure, relative to the still water level.

SAFFIR-SIMPSON HURRICANE WIND SCALE: A 1 to 5 rating based on a hurricane's sustained wind speed.

SAND: Sediment particles, often largely composed of quartz, with a diameter of between 0.0024 inches and 0.079 inches (0.062 mm and 2 mm), generally classified as fine, medium, coarse or very coarse. Beach sand may sometimes be composed of organic sediments such as calcareous reef debris or shell fragments.

SAND BYPASSING: Hydraulic or mechanical movement of sand from the accreting updrift side to the eroding downdrift side of an inlet or harbor entrance. The hydraulic movement may include natural movement as well as movement caused by man.

SCOUR: Removal of underwater material by waves and currents, especially at the base or toe of a structure.

SEA LEVEL RISE (SLR): A rising long-term trend in mean sea level.

SEAWALL: A structure, often concrete or stone, built along a portion of a coast to prevent erosion and other damage by wave action. Often it retains earth against its shoreward face. A seawall is typically more massive and capable of resisting greater wave forces than a bulkhead.

SEDIMENT: 1) Loose, fragments of rocks, minerals or organic material which are transported from their source for varying distances and deposited by air, wind, ice, and water. Other sediments are precipitated from the overlying water or form chemically, in place. Sediment includes all the unconsolidated materials on the sea floor. 2) The fine grained material deposited by water or wind.

SEICHING: Wave oscillation of an enclosed or semi enclosed water body that continues, pendulum fashion, after the cessation of the originating force, which may have been seismic, atmospheric, or vessel-generated.

SEMIDIURNAL: Having a period or cycle of approximately one-half of a tidal day (12.4 hours). The predominating type of tide throughout the world is semidiurnal, with two high waters and two low waters each tidal day. The tidal current is said to be semidiurnal when there are two flood and two ebb periods each day.

SENSITIVITY: The degree to which an asset (road, bridge, etc.) is damaged or service is interrupted by the hazards

SHALLOW WATER: Commonly, water of such a depth that surface waves are noticeably affected by bottom topography.

SHOAL: 1) (noun) A detached area of any material except rock or coral. The depths over it are a danger to surface navigation. Similar continental or insular shelf features of greater depths are usually termed banks. 2) (verb) To become shallow gradually. 3) To cause to become shallow. 4) To proceed from a greater to a lesser depth of water.

SHORE: The narrow strip of land in immediate contact with the sea, including the zone between high and low water lines. A shore of unconsolidated material is usually called a beach. Also used in a general sense to mean the coastal area (e.g., to live at the shore).

SHORELINE: The intersection of a specified plane of water with the shore or beach (e.g., the high water shoreline would be the intersection of the plane of mean high water with the shore or beach). The line delineating the shoreline on National Ocean Service nautical charts and surveys approximates the mean high water line.

SIGNIFICANT WAVE HEIGHT: The primary measure of energy in a sea state that is calculated either as the average height of the one-third highest waves or via energy density spectral analysis methods.

STILL WATER LEVEL (SWL): The elevation of the water surface if all wave and wind action were to cease.

STORM SURGE: A rise in average (typically over several minutes) water level above the normal astronomical tide level due to the action of a storm. Storm surge results from wind stress, atmospheric pressure reduction, and wave setup.

STORM SURGE HYDROGRAPH: Graph of the variation in the rise and fall of the still water level with time due to a storm.

SUBMARINE: The surface of the earth under the ocean.

SUBSIDENCE: Sinking of a part of the earth's surface.

SURF ZONE: The zone of wave action extending from the water line (which varies with tide, surge, set-up, etc.) out to the most seaward point of the zone (breaker zone) at which waves approaching the coastline commence breaking, typically in water depths of between 16 to 33 feet (5 to 10 meters).

TIDAL EPOCH: A 19-year cycle in the astronomical (sun and moon) producing tide forces that is averaged to obtain tidal datums.

TIDAL INLET: 1) An inlet maintained by tidal flow. 2) Loosely, any inlet in which the tide ebbs and flows.

TIDAL WAVE: 1) The wave motion of the tides. 2) In popular usage, any unusually high and destructive water level along a shore. It usually refers to storm surge or tsunamis.

TIDE: The periodic rising and falling of the water that result from gravitational attraction of the moon and sun and other astronomical bodies acting upon the rotating earth. Although the accompanying horizontal movement of the water resulting from the same cause is also sometimes called the tide, it is preferable to designate the latter as tidal current, reserving the name tide for the vertical movement.

TIDE RANGE: The difference between high tide elevation and low tide elevation.

TOPOGRAPHY: The elevation and configuration of the earth's surface including its relief and the positions of roads, buildings, etc.

TRADE WINDS: The prevailing pattern of easterly winds in the tropics.

TRANSFORMATION: Change in wave height, length, direction, etc.

TROPICAL STORM: A tropical cyclone with maximum winds less than 75 miles per hour (119 km/h) and greater than 39 miles per hour (63 km/h). Less strength when compared with hurricane or typhoon.

TSUNAMI: A long-period wave caused by an underwater disturbance such as a volcanic eruption or earthquake. Commonly (non-technical usage) called "tidal wave."

VALIDATION: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.

VULNERABILITY: 1) The extent to which a transportation asset is susceptible to sustaining damage from hazards during extreme events considering climate change. 2) The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed; its sensitivity; and its adaptive capacity.

WAVE: A ridge, deformation, or undulation of the surface of the water which is caused by a disturbance of that surface and is propagating across that surface.

WAVE HEIGHT: The vertical distance between a wave crest and the preceding trough.

WAVE PERIOD: The time for a wave crest to traverse a distance equal to one wavelength. The time for two successive wave crests to pass a fixed point.

WAVE RUNUP: Is the uprush of a wave’s water up a slope or structure.

WAVE SETUP: Superelevation or increase in the mean (time-averaged) water levels due to the presence of waves.

WAVE-WAVE INTERACTIONS: Interactions between sea waves of different frequencies resulting in energy transfers between frequencies in seas which are accounted for in most wave models.

WEIR: A low dam or wall across a stream or flowing water.

WEIR-FLOW DAMAGE MECHANISM: Damage, including pavement undermining, of the downstream side of roadways due to coastal storm surge waters flowing across roadway embankment like it is a weir.

WETLANDS: Lands whose saturation with water is the dominant factor determining the nature of soil development and the types of plant and animal communities that live in the soil and on its surface (e.g. coastal marsh wetlands).

WIND SETUP: The vertical rise in the still water level due to wind stress.

WIND STRESS: The way in which wind transfers energy to the sea surface.

List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
ADCIRC	ADvanced CIRCulation model
ASCE	American Society of Civil Engineers
ART	Adapting to Rising Tides
ENSO	El Niño Southern Oscillation
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FIRM	Flood Insurance Rate Map
GC2	Gulf Coast 2 Study
GIS	Geographical Information System
HDS	Hydraulic Design Series
HEC	Hydraulic Engineering Circular
HWM	High Water Mark
IPCC	Intergovernmental Panel on Climate Change
MAP-21	The Moving Ahead for Progress in the 21st Century Act
MEOW	Maximum Envelope Of Water
MHHW	Mean Higher High Water. A tidal datum
MHW	Mean High Water. A tidal datum
MOM	Maximum of Maximums
MPO	Metropolitan Planning Organization
NAVD	North American Vertical Datum
NCA	National Climate Assessment
NHC	National Hurricane Center
NHI	National Highway Institute
NRC	National Research Council
NOAA	National Oceanic and Atmospheric Administration.
NOS	National Ocean Service
PDO	Pacific Decadal Oscillation
SLOSH	Sea, Lake, and Overland Surges from Hurricanes model
SLR	Sea Level Rise
SSIM	Storm Surge Inundation Map
STWAVE	STeady State spectral WAVE model

SWAN	Simulating WAves Nearshore model
SWL	Still Water Level
USACE	US Army Corps of Engineers
VLM	Vertical Land Movement
WAM	Global ocean WAve Model

Chapter 1 – Introduction

1.1 Background

The US transportation system is vulnerable to coastal extreme event storms today and this vulnerability will increase with climate change. Hurricane Sandy caused over $10 billion in damage to coastal roads, rails, tunnels, and other transportation facilities in New York and New Jersey (Blake *et al.* 2013, NOAA 2013). Hurricanes Ivan (2004), Katrina (2005), Ike (2008), and other storms have also caused billions in damage to coastal roads and bridges throughout the Gulf Coast. Portions of California State Route 1, the Pacific Coast Highway, have been relocated away from the ocean in response to bluff erosion threatening the highway. Costs of lost business when critical transportation services are interrupted after coastal storms have also been significant.

This vulnerability will increase as sea levels rise. Many projections of future sea levels suggest accelerated rise rates resulting from global climate change. Higher sea levels will combine with future extreme events to increase the vulnerability of coastal highways, bridges, and other transportation infrastructure. Thus, damage from coastal hazards such as hurricanes, high waves, tsunamis, and extreme tides will increase in cost, frequency, and magnitude. It is estimated that over 60,000 roadway miles in the US are exposed to coastal storm surge (FHWA 2008). The degree to which that exposure, and resulting vulnerability, will increase as a result of climate change is currently unknown.

The transportation authorization act, MAP-21 - the Moving Ahead for Progress in the 21st Century, lists “protection against extreme events” as an eligible project purpose for federal funding of construction, replacement, rehabilitation, or preservation of bridges (P.L. 112-141: Section 119 (d) (2) (B)). The FHWA guidance memo entitled “Eligibility of Activities to Adapt to Climate Change and Extreme Weather Events under the Federal-Aid and Federal Lands Highway Program” (FHWA 2012a), provides more specific information on the use of federal highway program funds in the planning, design and construction of highways to adapt to extreme events considering climate change. This memo stressed that “consideration of extreme events, their impacts on highways and transportation systems, and development of adaptation strategies should be grounded in the best available scientific approaches.” Adaptation activities need to be based on the current understanding of weather patterns affecting the location of a project or region, as well as projected changes in climate.

Thus, there is a need for technical guidance in assessing the exposure and vulnerability of highway infrastructure in the coastal environment that will be impacted by extreme events including considerations of the effects of climate change. This publication is intended to be technical guidance grounded in the “best available scientific approaches” to vulnerability and risk assessment and climate change.

1.2 Purpose

The purpose of this manual is to provide technical guidance and methods for assessing the vulnerability of coastal transportation facilities to extreme events and climate change. The focus is on quantifying exposure to sea level rise, storm surge, and wave action. It is anticipated that there will be multiple uses for this information, including risk and vulnerability assessments, planning activities, and design procedure guidance.

Extreme weather events can profoundly impact coastal transportation infrastructure. In a more general sense, the term "extreme weather" includes severe or unseasonable weather, heavy precipitation, a storm surge, flooding, drought, windstorms (including hurricanes, tornadoes, and associated storm surges), extreme heat, and extreme cold. Extreme weather events can be described as rarely occurring, weather-induced events that usually cause damage, destruction, or severe economic loss (FHWA 2012a). This manual focuses only on extreme events along the coast such as storm surge and waves found in hurricanes, nor'easters, fronts, and El Niño-related coastal storms on the west coast. Tsunamis are also discussed as extreme events.

Examples of damage to coastal infrastructure resulting from storm surge and waves that are addressed by the methods in this manual include:

- damage to coastal bridge superstructures in Hurricanes Ivan and Katrina due to waves on storm surge,
- damage to highway embankments and pavements due to waves and flowing water in storm surges from numerous coastal storms including Hurricanes Sandy, Katrina, Ivan, Floyd, and Ike,
- damage to roadways on coastal bluffs due to waves and wave runup in the El Niño-related coastal storms of the Pacific in 1992 and in the Great Lakes throughout the past several decades, and
- damage resulting from flooding of highways and tunnels in Hurricane Sandy.

Vulnerability is the extent to which a transportation asset is susceptible to sustaining damage from hazards during extreme events considering climate change. Vulnerability is commonly understood to be a function of three components as outlined and defined in Figure 1.1:

1. the degree of **exposure** to extreme events and climate change,
2. the **sensitivity** to extreme events and climate change, and
3. the **adaptive capacity** of the asset.

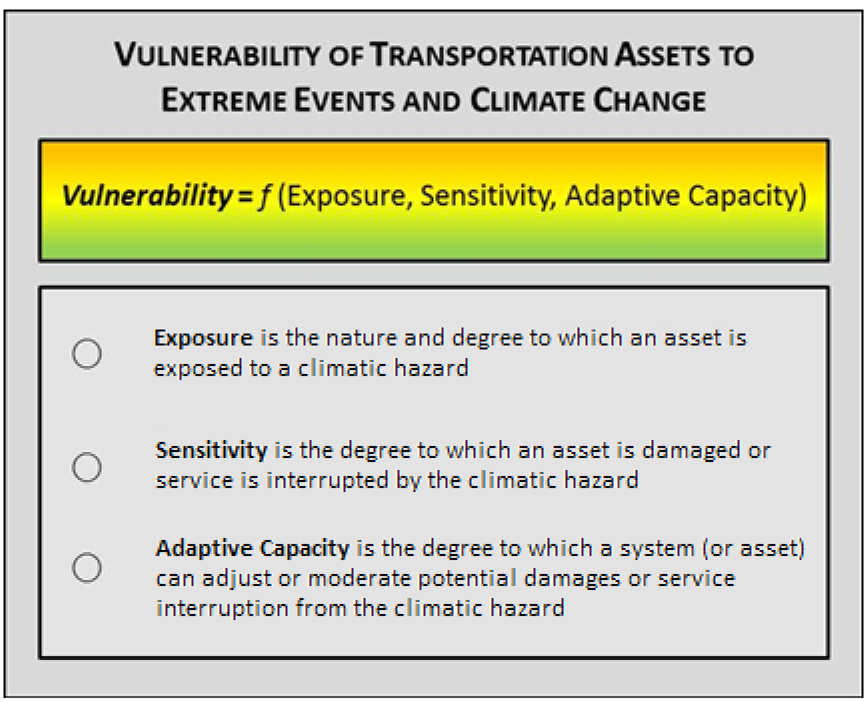

Figure 1.1. Vulnerability of transportation assets to extreme events and climate change.

This manual focuses primarily on appropriate methods for quantifying the **exposure**, that is, the first component above, of coastal infrastructure to extreme events and climate change. Some of the methods for quantifying sensitivity and logical adaptation approaches for coastal highways are discussed briefly in Chapter 3. The results can be used to support decision-making by determining potential impacts on transportation infrastructure. Advanced, replicable and transferrable methodologies for estimating the propagation of surge and waves into coastal areas are presented. This manual summarizes the current state of the practice for incorporating climate change and sea level projections into coastal storm surge modeling relevant to the analysis and design of transportation projects including:

- obtaining sea (or lake) level change estimates,
- selecting storm scenarios,
- using coastal surge and wave models, and
- interpreting results.

1.3 Target Audience

The target audience for this manual includes transportation engineers, coastal engineers, hydraulic engineers, civil engineers, roadway designers, field inspectors, construction supervisors, planners, scientists, and other technical personnel involved with transportation systems in the coastal environment. The manual is written to be understood by a wide cross-section of users with varying backgrounds and expertise.

This manual should help persons with little experience and training in coastal modeling and engineering understand some of the scientific methods and engineering approaches that are unique to the coast. The coastal environment is complex. Many of the processes and principles of coastal science and engineering are not often formally studied by personnel in a typical FHWA or State DOT engineering or planning unit. Also, some aspects of storm surge and wave modeling in the coastal environment are presently undergoing significant research and development resulting in changes to accepted practices. This document provides the transportation community with an overview and awareness of the fundamental principles of coastal surge and wave modeling appropriate for vulnerability assessments. Such awareness will allow practitioners to seek appropriate technical expertise for specific projects when needed. For experienced coastal engineers, scientists and modelers, this manual should serve as a reference document in providing specific highway-oriented assistance and consultation for vulnerability assessments.

1.4 Organization

This document is organized into five major chapters. Preceding Chapter 1 are a glossary and a list of acronyms. Both have a specific focus on coastal science and engineering terminology used in this document. Chapter 1, this chapter, discusses the background, purpose, target audience, organization, units, and related guidance.

Chapter 2 discusses the key regional coastal processes affecting the vulnerability of transportation assets, water levels and waves, numerical models of those processes, and the likely impacts of climate change on those processes. Specific emphasis is placed on projections of future sea levels.

Chapter 3 establishes how this guidance can be used within the frameworks of engineering risk and vulnerability assessments of transportation infrastructure. The tools and methods for quantifying risk, including return period, along the coast are discussed. This chapter also briefly discusses methodologies for estimating the sensitivity of - and damage to - coastal transportation infrastructure. Potential adaptation or countermeasure strategies that can provide adaptive capacity for a specific coastal asset are also briefly discussed. Many of the adaptations required for climate change and sea level rise are the same adaptations required for improving infrastructure resilience to extreme events with today's sea levels.

Chapter 4 describes recommended methods for performing risk and vulnerability assessments of coastal transportation infrastructure. Specific emphasis is on methods for quantifying the "exposure" of assets to storm surge and waves in extreme events with consideration of climate change. Three levels of effort are presented which are described initially in a broad context and then in regional discussions about the availability and location of products, data, tools, and methodologies that should be considered. Examples of specific information include where to find and how to use FEMA flood maps, the selection of an appropriate hydrodynamic model(s) to simulate the regional coastal processes of interest, and existing methodologies for estimating damage and failure due to water levels, waves, currents, and erosion.

Chapter 5 presents specific case studies to demonstrate how climate change and extreme coastal events have been incorporated into assessments of exposure and vulnerability. A consistent result is that there are very high levels of exposure to extreme events today and those levels will increase with sea level rise and climate change.

1.5 Units of this Document

This document primarily uses customary (English) units consistent with FHWA policy. However, in limited situations, both customary (English) units and SI units are used or only SI units are used because these are the predominant measure used nationwide and globally for these topics. In these situations, the rationale for the use of units is provided. The appendix provides information on units and unit conversions.

1.6 Related Guidance

This new manual is a standalone supplement, a "Volume 2," to the existing, primary FHWA Hydraulic Engineering Circular (HEC) document: "Highways in the Coastal Environment," HEC-25 (FHWA 2008). That primary technical manual provides more general, overall guidance for the analysis, planning, design, and operation of highways in the coastal environment. Some of the physical coastal science concepts and modeling tools that have been developed by the coastal engineering community that are applicable to highways are presented. These include engineering tools for waves, water levels, and sand movement. Applications to several of the highway and bridge planning and design issues that are unique to the coast are summarized including:

- coastal revetment design,
- planning and alternatives for highways that are threatened by coastal erosion,
- roads that overwash in storms, and
- coastal bridge issues including wave loads on bridge decks.

HEC-25 Volume 2 supplements the primary HEC-25 manual by recommending specific approaches for modeling and mapping storm surge and waves caused by extreme events under various climate change scenarios. Specific possible (i.e. projected) climate change scenarios, primarily in terms of sea level rise scenarios, are also presented. The surge and wave models discussed are existing models from the coastal engineering and coastal science literature which have been developed primarily for other purposes (e.g. insurance rate maps and coastal engineering design). They are presented here with specific emphasis on their use in vulnerability assessments and subsequent planning for extreme events and climate change as they relate to coastal transportation systems. HEC-25 does not provide detailed technical guidance on methodologies and approaches for using these modeling tools for vulnerability assessment, planning, and design. However, HEC-25 Volume 2 does provide this guidance and identifies state-of-the-practice methodologies for modeling storm characteristics and outlines conceptual approaches, or best practices, for their use.

FHWA (2012b) presents guidance on an overall “framework” for planning studies to assess the vulnerability of transportation facilities to climate change and extreme weather events. This manual presents guidance for assessing vulnerability within that overall framework (see Section 3.2.2 Vulnerability Assessment Framework). In the wake of the damage to bridges in hurricanes Ivan and Katrina in 2004 and 2005, FHWA developed recommended draft guidance for flood frequency and freeboard for the analysis and design of coastal bridges that includes quantitative, site-specific, consideration of risk levels for storm surge and wave heights (FHWA 2005). AASHTO (2008) discusses several levels of appropriate analysis for coastal bridges exposed to waves and storm surge in general terms including recommending a review by a qualified coastal engineer.

Creating a more resilient transportation system is a priority for FHWA and is consistent with recent U.S. Department of Transportation (DOT) policy on climate change adaptation (FHWA 2012a). Adaptation involves adjusting the way the transportation community plans, designs, constructs, operates, and maintains transportation infrastructure to protect against impacts caused by changes in climate and extreme weather events. The President’s Climate Action Plan directs federal agencies to ensure that climate risk-management considerations are fully integrated into infrastructure planning (Executive Office of the President 2013).

A Presidential Executive Order issued November 1, 2013, directs federal agencies to identify opportunities to encourage more climate-resistant investments in infrastructure and to develop and provide authoritative, easily accessible, usable, and timely data, information, and decision-support tools on climate preparedness and resilience (Executive Order No. 13653 2013). This manual provides scientific and engineering guidance which addresses these resilience-related goals and directives for coastal transportation facilities.

Chapter 2 – Relevant Coastal Processes and Climate Change Impacts

This chapter identifies the most relevant coastal processes affecting the vulnerability of transportation assets, discusses the likely impacts of climate change on those processes, and discusses some of the details of numerical models of those processes. The primary focus is on coastal water levels; including long-term average sea level, tides and storm surge; and waves. Some of the discussion is organized by region of the country since the relative importance of the different processes varies by region. Global sea level rise, including future projections, is emphasized in Section 2.3.1, Sea Levels, since it is expected to be important along much of the US coast and will be a critical aspect of climate change's impact on US society. These topics are referred to in Chapter 3, are used in Chapter 4 to develop suggested assessment methodologies, and are found in the case studies presented in Chapter 5.

2.1 Description of Relevant Coastal Processes

Many different natural processes and forces impact roads and bridges near the coast. This chapter focuses on those that are not typically experienced by inland roads, but present unique challenges to transportation professionals concerned with coastal roads. The primary natural processes of interest are:

- coastal water levels and
- waves.

Other processes, which are not focused on here, but can be important are high velocity flows, sand transport causing shoreline and barrier island response, upland runoff, coastal inundation through municipal storm sewers, degradation and failure of roadbeds due to elevated groundwater tables, drowning of coastal salt marsh, salt water intrusion and corrosion, and impacts to infiltration best management practices.

2.2 Damaging Processes of Extreme Coastal Events

This section briefly discusses the key coastal phenomena, or processes, in terms of damage to coastal highways – high water levels and the waves riding atop those water levels. There are significant regional variations in the relative importance of the different components (tides, storm surge, wave setup, etc.) that control coastal water levels in storms. Focus is given to water levels and waves because of their importance in controlling damage to coastal transportation infrastructure in extreme events, but three other processes - flow velocities in storm surge, sand transport, and related geomorphological changes - are also discussed. Below is a general introduction to these phenomena. Following these introductions, Sections 2.2.1 through 2.2.4 discuss some of the unique regional characteristics of these processes.

Astronomical **tides** are the slow rise and fall of the ocean waters throughout the day in response to the gravitational pull of the moon and the sun (see HEC-25 Section 3.1). The total water level during extreme events can be very sensitive to the phase of the tide, e.g. high tide or low tide. Tidal fluctuations are well understood and the reader is referred to the NOAA "tides and currents" website (http://tidesandcurrents.noaa.gov/) for much more regional information. The relative importance of tide phase varies with location and region as discussed below.

Storm surge is the rise of water level above the astronomical tide as a result of all meteorological forcing (see HEC-25 Section 3.2, Storm Surge). This forcing is dominated by wind but also includes barometric pressure and local rainfall runoff. Numerical modeling of storm surge for assessing exposure and vulnerability is discussed in detail in Section 2.4, Numerical Models of Coastal Processes.

At many coastal locations, a phenomenon called **wave setup** is also a component of storm surge. Wave setup occurs primarily in the surf zone and landward of the surf zone such as on a flooding barrier island or behind a reef. Wave setup is an increase in mean (time-averaged) water level at a location due to the presence of the waves. It is often thought of as due to the mass or momentum flux of the water by wave action and is greatest when waves are breaking (Dean and Walton 2010). The magnitude of the contribution of wave setup to storm surge can be up to several feet at some locations during major coastal storms.

Waves are one of the primary forces affecting our coasts. Waves have the ability to generate tremendous forces and cause considerable damage when they are riding on top of storm surge and are thus able to strike roads and bridges that are not typically designed for such forces. Waves also serve as a critical damaging process in terms of acute erosion and shoreline change during storm events.

Waves are described in Chapter 4 of the primary reference manual, HEC-25, including definitions, theories, and properties such as their transformation and breaking, models, generation, etc. Regional descriptions of wave characteristics, in terms of wave height and period, can be found in USACE (2002). HEC-25 Section 4.5, Tsunamis, includes a brief discussion of tsunami waves.

Waves striking built coastal infrastructure are often **depth-limited**, i.e. their height at a specific location is controlled by the water depth at and around that location. The depth-limited wave concept is part of numerous FEMA regulations, methods and guidance (e.g. FEMA 2003; FEMA 2011); US Army Corps of Engineers guidance in many situations (USACE 2002); and guidance in the ASCE-7 building code (ASCE 2010). Numerical wave generation and propagation models use a similar concept when estimating wave breaking in shallow water. This rather simple concept plays a significant role in the final results of many analyses, vulnerability assessments, risk-based coastal flood elevations, insurance rate maps, and engineering designs. This concept, depth-limited wave heights, is used in Chapter 4 of this manual.

There are significant regional variations in the relative importance of the different components (tides, storm surge, wave setup, etc.) that control coastal water levels in storms. Thus the US coast is divided into four general regions for this discussion.

2.2.1 Gulf of Mexico and South Atlantic Coast

This section summarizes the unique regional characteristics of the important coastal processes for the Gulf of Mexico and South Atlantic coasts of the US. The next three sections do the same for the other regions of the US coast; the mid-Atlantic and New England, the Great Lakes, and the Pacific.

Tropical storms and hurricanes are key extreme events along the Gulf of Mexico and South Atlantic coasts of the US. Storm surge allows waves to strike infrastructure at very high elevations. Waves on surge in the Gulf Coast hurricanes of 2004-2005 caused billions of dollars in damage to bridges including moving bridge deck spans that weighed over 340,000 pounds each.

Storm surge level varies significantly around our coasts. Coastlines with a shallow continental shelf can experience very high storm surges. Coastal Mississippi is one such location. The two highest recorded storm surges in US history - -Hurricane Camille (1969) at 21 ft and Hurricane Katrina (2005) at 27 ft - have occurred along the same portion of the Mississippi coast around Bay St. Louis. Given that the normal (astronomical) tide range along most of the Gulf coast is less than 2 ft, the relative phasing, or timing, of the tide and storm surge is not that important. However, the phasing can be of some importance on the Gulf coast during smaller more frequent storms. In some parts of the South Atlantic coast the tide range can be over six feet and the relative phasing of the tide and the storm surge can be important.

Storm surge can also vary significantly within the same estuary. For example, within Mobile Bay, Alabama, the peak storm surge magnitude in Hurricane Katrina increased from around 6 ft at the south end of the bay to around 12 ft at the north end. This was due to wind stress from the strong southerly winds during the storm. Similar variations in the wind stress component of storm surge are common throughout the US in all bays and lakes and are very pronounced in the shallow bays typical of the Gulf and South Atlantic coasts.

Storm surge in hurricanes at any specific location is very sensitive to the track of the center of the storm. When a hurricane makes landfall, the onshore winds are much higher to the right of the landfall location because of the counter-clockwise, cyclonic wind rotations. The waves and storm surge are thus also higher on that side. This sensitivity can be particularly noticeable in the shallow bays typical of the Gulf and Atlantic coasts.

Extreme precipitation and watershed runoff to the coastal water body can significantly affect the magnitude and timing of storm surge related flooding at some bay locations. In other words, runoff can alter the shape of the coastal storm surge hydrograph, or time-history of water levels, at a specific location. The degree to which rainfall contributions are important in coastal flooding depends upon the watershed and storm characteristics (e.g. size, speed, duration).

2.2.2 Mid-Atlantic and New England Coast

The storm surge in Hurricane Sandy caused much damage along the New Jersey and New York coast including the flooding of the Brooklyn-Battery Tunnel and eight New York City Subway tunnels (Hurricane Sandy Rebuilding Task Force 2013). Storm surge and waves due to both tropical and extratropical (e.g. nor'easter) storms; tides; episodic storm-induced shoreline change; and watershed runoff to coastal waters are key processes along the mid-Atlantic and New England coast of the US.

The effect of tides on flood levels is significant in this region. Typical (astronomical) tide ranges at different locations along the mid-Atlantic and New England coast vary from 2 to 9 ft. The storm surge in Sandy ranged up to 9 ft. Thus, the total water level at the peak of the storm was sensitive to how closely the peak storm surge coincided in time with the astronomical high tide. The monthly phase of the tide can also be important since high tide elevations vary up to 2 ft throughout the month in this region. For example, if Hurricane Sandy had occurred two weeks earlier or two weeks later on a full-moon tide phase, the total peak surge water levels would have been over a foot higher in elevation throughout the region.

Storm surge **duration**, or the time that the storm surge is elevated, can also be very important in this region. One of the most destructive storms in history, the nor'easter called the "Ash Wednesday Storm" of 1962, caused much of its damage along the mid-Atlantic coast due to its relatively long duration. The storm surge and wave action lasted for 2½ days over five semi-diurnal high tides, or "five high tides." The extended duration prolonged beach storm erosional processes and caused extensive property damage. Along the northern New Jersey shore, some of the inundation (and the post-storm damage photography) from Hurricane Sandy (2012) was similar to that from the Ash Wednesday Storm 50 years earlier.

Storm track can also be important along this coast. For example, Hurricane Sandy took a fairly rare sharp left turn that brought it into the New Jersey coast perpendicular to the shoreline and this contributed to the high storm surge in the New York City area (see Figure 2.1).

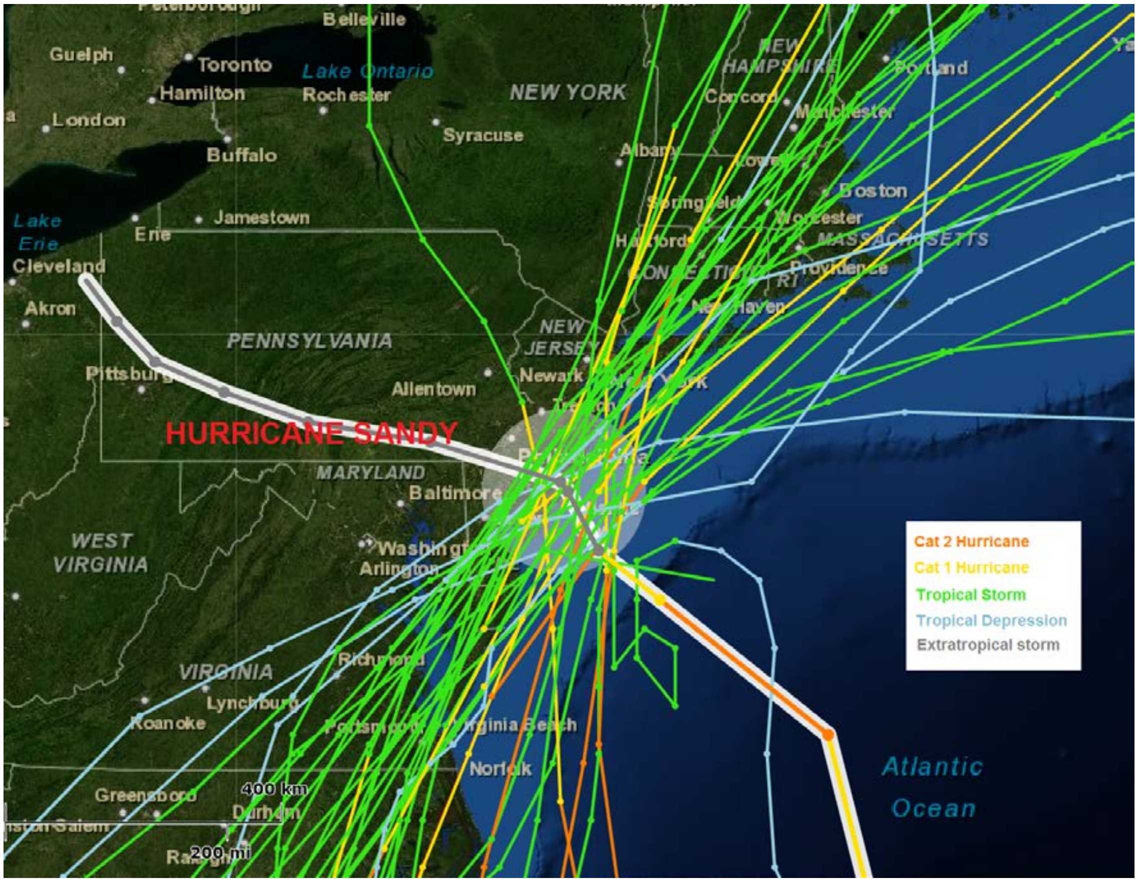

Figure 2.1. Path of Hurricane Sandy compared to other storm tracks that have passed within 50 miles of Atlantic City, NJ.

2.2.3 Great Lakes Coast

Waves generated by frontal systems; bluff erosion; storm surge; and seiching of the lakes are key coastal processes in the Great Lakes. (See Figure 2.2.) The impacts of these processes are influenced by long-term fluctuations in lake levels. Meteotsunamis (meteorologically-induced long-wave motions) can also have an effect.

Water levels in the Great Lakes fluctuate in response to precipitation in their drainage basins and other factors including temperature and ice cover. There are seasonal fluctuations of between 1 and 2 ft. Figure 2.3 shows an example of recent fluctuations of Lakes Michigan and Huron (also shown is the 6-month forecast lake levels at the time this graphic was downloaded August 2013). The Great Lakes experienced some record low lake levels in 2012. Figure 2.4 shows a much longer historical record of average annual lake levels. The dashed, horizontal line is the average for the 93 year period of record. The past decade has been a period with below average lake levels. Gronewold *et al.* (2013) is an interactive, on-line “Great Lakes Water Level Dashboard” with historic data on lake levels as well as the long-term forecasts based on climate change models.

Figure 2.2. A map of the Great Lakes.

The bluffs around the shores of the Great Lakes recede due to natural geologic processes as well as interruptions in longshore sand transport. Many of the coastal highway problems in the Great Lakes are related to bluff erosion problems. High lake levels cause increased bluff erosion as waves strike higher elevations. Interestingly though, there are erosion issues related to the historically low water levels, too. The lower levels expose the base of seawalls to different levels of air, ice and waves.

The size of the Great Lakes allows for considerable wave generation during wind storms. Also, storm surge can be significant, particularly in bays near the ends of the lakes, due to wind stress. One related phenomenon is the "seiching" of the lakes. Seiching is a long-period (several hours duration in the lakes) oscillation of the water levels after passage of a weather front. Lake Erie and Lake Ontario are particularly susceptible to these extreme storm surge levels and subsequent seiching motions. A storm in 1985 caused so much wind stress across Lake Erie that the water level at Toledo dropped 4 ft while the water level at Buffalo rose 4 ft. The water level in the middle of the lake, near Cleveland, remained nearly constant. Also, investigations of seiching in Lakes Michigan and Huron reveal that the two systems are coupled and cannot be considered separately.

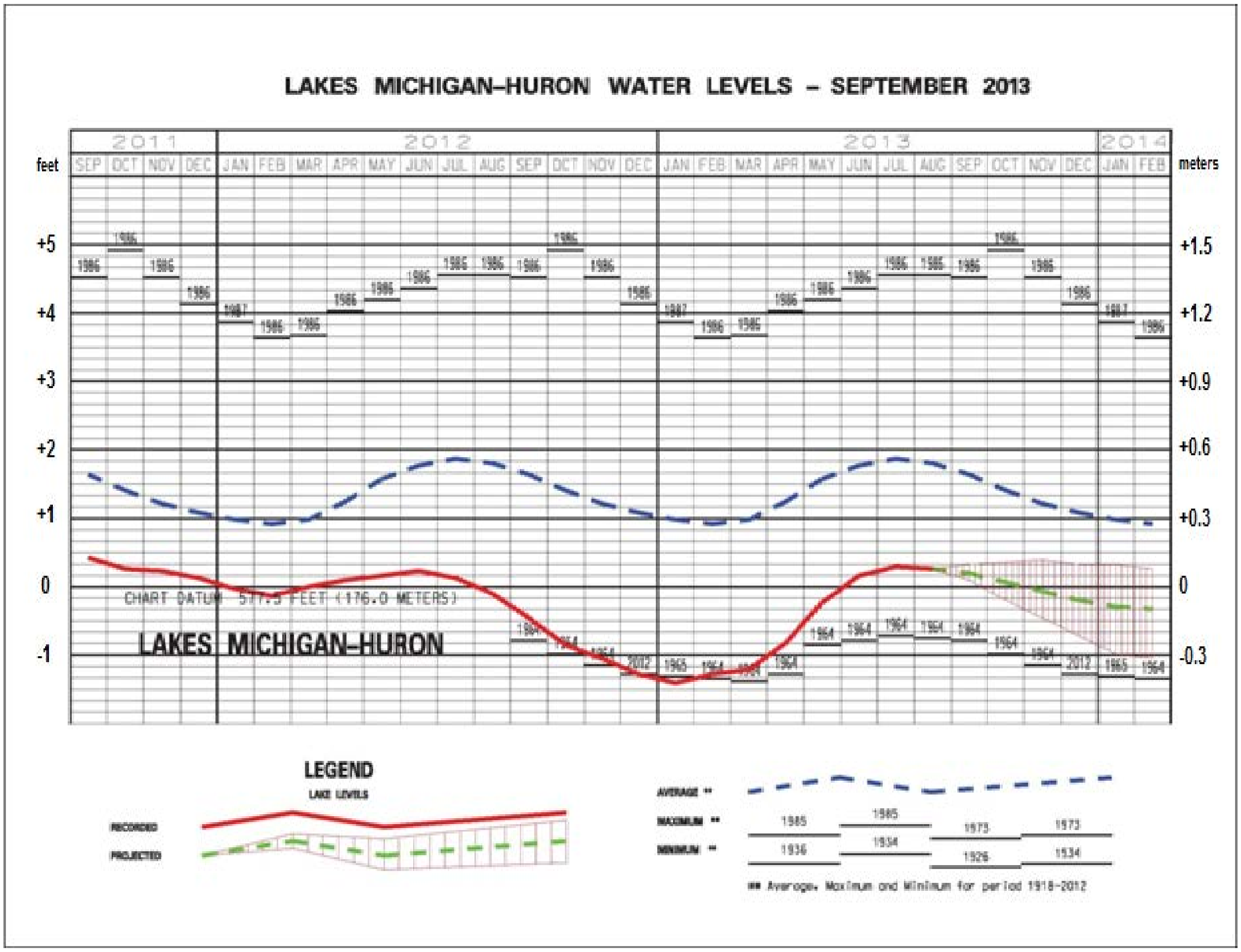

Figure 2.3. Example of seasonal lake level fluctuations (USACE-Detroit District, 2013).

One phenomenon that occurs in the Great Lakes, as well as in all water bodies, is the meteotsunami. These can explain freak wave occurrences that have occurred in the Great Lakes (Anderson *et al.* 2012) and along the Atlantic coast where they are called squall line surges (Dean and Dalrymple 2002). Barometric pressure fluctuations can combine with wind fields to cause wave oscillations that can propagate alongshore in response to the distant forcing. For tsunamis the distant forcing is a submarine landslide and for meteotsunamis the forcing is a meteorological disturbance on the water surface such as very quick increases in winds or a pressure disturbance-anomaly related to a weather front (Monserrat *et al.* 2006).

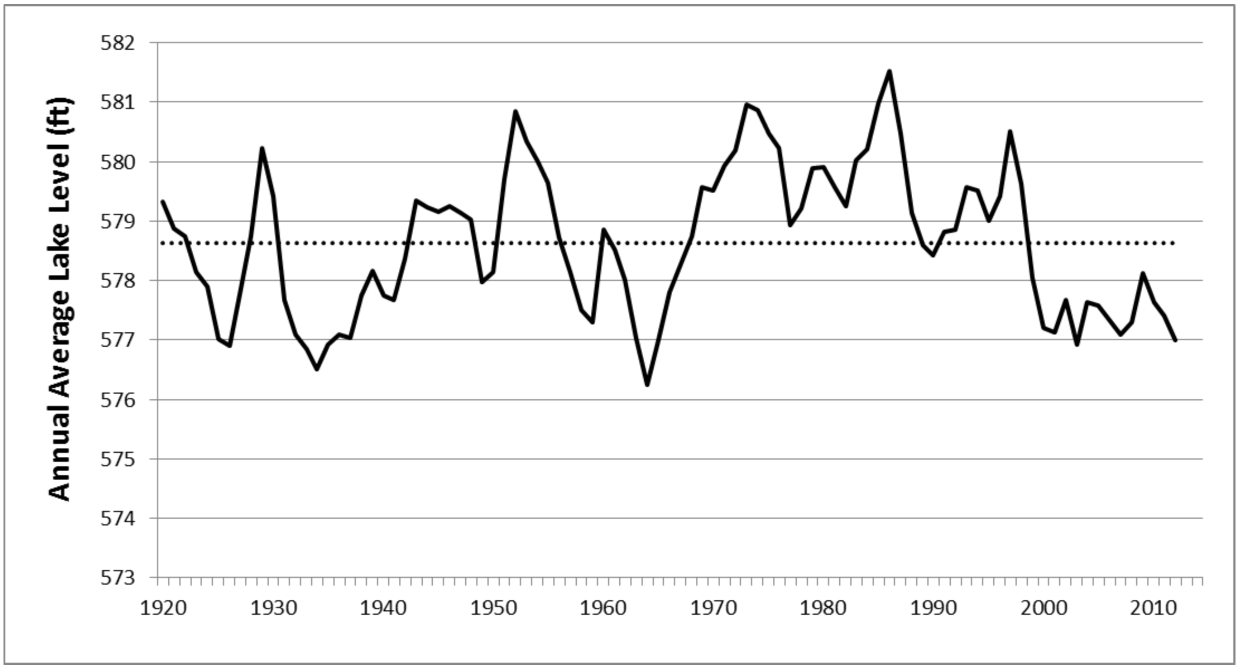

Figure 2.4. Annual lake levels fluctuations – Lakes Michigan and Huron (dashed line is the long-term average).

2.2.4 Pacific Coast

Waves, tides, water level responses to storms during El Niño episodes, and tsunamis are key coastal processes along the Pacific coast of the US. Extratropical storms dominate although extremely rare tropical storms have impacted southern California and Hawaii. The frequency and intensity of damaging coastal storms are influenced by El Niño episodes, the Pacific Decadal Oscillation (PDO), and El Niño Southern Oscillation (ENSO). El Niño is a weather pattern characterized by a large scale weakening of the trade winds and warming of the surface layers in the eastern and central equatorial Pacific Ocean. El Niño events occur irregularly at intervals of 2 to 7 years, although the average is about once every 3 to 4 years. They typically last 12 to 18 months, and are accompanied by swings in the Southern Oscillation (SO), an interannual see-saw in tropical sea level pressure between the eastern and western hemispheres. During El Niño, high sea levels and very high waves can strike the Pacific Coast of the US. Wave-driven processes of importance include wave runup and wave setup.

The key coastal processes controlling coastal flooding along the Pacific are so different from those along the rest of the country's coast that FEMA develops coastal flood maps differently (FEMA 2005). The laws of physics are the same everywhere, of course, but the relative magnitudes of the coastal flood level constituents vary significantly. Storm surge, particularly the wind stress and barometric pressure components of storm surge, are significantly less along the Pacific Coast than elsewhere in the US. An extremely large storm surge magnitude on the Pacific coast is 1 to 2 ft: a full order of magnitude smaller than in the Atlantic and Gulf of Mexico. One reason for this difference is the continental shelf. It is very narrow and steep on the Pacific coast. Water depths within miles of the Pacific coast compare with water depths hundreds of miles offshore of the Atlantic and Gulf coast. This decreases the relative effects of wind stress and increases those of wave setup and runup on the total water level along the coast.

Wave-driven processes, particularly wave runup, dominate the surf zone and coastal flooding during Pacific storms. Wave **runup** is the uprush of a wave's water up a slope or structure.

Quantitatively, runup is defined as the elevation difference between the limit of maximum wave uprush on a beach or structure and the still water level. The wave periods (the time between wave crests: see HEC-25 Section 4.1, Definitions, Theories, and Properties of Waves) of typical waves in the Pacific are much longer than those in the Gulf of Mexico or even the Atlantic due to the size of the ocean. Swell wave energy propagating from storms over thousands of miles is common. Wave runup is sensitive to wave period: the longer the wave period, the higher the runup.

Wave setup, the increase in mean (time-averaged) water level due to the presence of the waves (described above in Section 2.1), is an additional increase in the elevation of the water surface landward of breaking. Wave setup increases with wave height. Thus, due to the large waves that strike the Pacific coast frequently, the wave setup component of the total water level at the coast during storms can be significant.

US Pacific Coast tides range from about 6 ft in the south to 9 ft in the north and much higher in Alaska. However, since major Pacific storms typically have durations of 3 to 4 days, all tide phases usually occur during a storm (FEMA 2005). The phasing of storm water levels with monthly or annual maxima in the astronomical tides, or king tides, can be very significant.

The El Niño episode of 1982-83 included several record-breaking high wave events/storms which caused structural damage and severe erosion along the Pacific coast of the US (Seymour *et al.* 1984). Another major El Niño episode occurred in 1997-98 (USGS 1999). During El Niño episodes, for intervals of a year or two, changes in the trade winds cause a shift of Pacific Ocean waters to the east with an increase in local sea level along the US Pacific coast of up to 1.5 ft (FEMA 2005). Typically a series of major winter storms are spawned during the El Niño episode which generate large, long-period waves that strike the coast on this elevated sea level.

Runoff from coastal watersheds can be a significant component of coastal flooding on the Pacific Coast. In particular “Pineapple Express” storms can bring some of the largest multi-day rainfalls to watersheds which drain to the Pacific coast (Schick 2008; Dettinger *et al.* 2012). Pineapple Express storms represent a subset of “atmospheric river” storms that are relatively narrow regions of the atmosphere that transport water vapor,

Tsunamis cause more damage along the Pacific Coast of the US than along other US coasts. Tsunamis ("tidal waves” in popular usage) normally result from an underwater disturbance (usually an earthquake with submarine landslides) that triggers a series of waves that can travel many hundreds or thousands of miles. In the open ocean, the waves may move 450 miles per hour. Reaching shallower waters, the waves decrease speed, but gain amplitude. Tsunamis appear on the coast as a series of successive waves where the period from wave crest to wave crest can range between 2 and 90 minutes (but normally between 10 and 45 minutes). Typically the first of these waves is not the largest but is often preceded by a dramatic and rapid lowering of the local sea level.

The 1964 Alaskan Earthquake sent tsunami waves between 10 and 20 ft high along the coasts of Washington, Oregon, and California. Hawaii and Alaska can expect a damaging tsunami on the average of once every seven years, while the West Coast of the US experiences a damaging tsunami once every seventeen years (HEC-25). Runup and damage due to a tsunami are related to the phase of the tide at the time of tsunami impact. The American Society of Civil Engineers and FEMA are developing a building code for tsunamis which will be incorporated into building codes for the Pacific states in the next few years (Chock *et al.* 2011; Chock 2012).

2.3 Climate Change Impacts on Damaging Coastal Processes

This section discusses the impacts of climate change on the coastal processes that are most critical to coastal highways: sea level, storm surge, and waves. Particular emphasis is given to global sea level rise. Other physical coastal processes, such as beach erosion and coastal geomorphology, are briefly addressed. Other related processes such as temperature, rainfall, and ecological processes are not considered here.

A tremendous volume of research and publications related to aspects of global climate change has been written. Two major, multiple-author, summary works are the National Climate Assessment (NCA) and the Intergovernmental Panel on Climate Change (IPCC). The NCA is the federal government report prepared by the US Global Change Research Program that summarizes the broad body of knowledge developed in this area (Melillo *et al.* 2014). Sources of information for the NCA include the body of scientific research and a number of synthesis reports prepared by large, inter-agency groups specifically for input to the NCA.

The IPCC is an international effort originally established by the United Nations and the World Meteorological Association. The panel has developed updated "Assessment Reports" on the current state of scientific knowledge in climate change and its potential environmental and socio-economic impacts. The fourth Assessment Report was released in 2007 (IPCC 2007) and the fifth Assessment Report on The Physical Science Basis was released in 2013 (IPCC 2013).

Both of these major summary works, the NCA and the IPCC, discuss the importance of climate change on sea levels. For example, the NCA states that sea level rise has increased the risk of storm-surge damage and flooding for coastal communities:

> *"Infrastructure across the US is being adversely affected by phenomena associated with climate change including sea level rise, storm surge, heavy downpours and extreme heat."* (Melillo *et al*. 2014)

Many other summary presentations of research on the causes and effects of climate change along the coasts have been published in recent years (e.g. Fletcher 2013).

2.3.1 Sea Levels

This section discusses the effects of climate change on sea levels. The process of sea level rise (SLR) is the primary concern related to global climate change for coastal cities. Sea levels are currently rising along most US coasts and there is a concern that the rate of rise may accelerate. Sea level rise is of particular concern because of the possibility of extensive impacts on the coastal environment and population including impacts on the transportation infrastructure. Those impacts include both submergence of very low-lying areas and increased impacts of waves during extreme events.

This section specifically discusses:

- tide gage measurements of relative SLR (past century),
- satellite measurements of SLR (since 1993),
- longer-term, geologic evidence of relative SLR (past 10,000+ years),
- estimates of present day, global, eustatic SLR rate,
- projections of future SLR that should be used in coastal transportation vulnerability assessments, and
- an example calculation demonstrating how future sea levels can be estimated for a specific US coastal location.

In this section of this report some of the discussion is presented in the metric system because so much of the science related to sea level rise is presented in millimeters per year in the literature and the order of magnitude issues are more clearly presented in those units. English units are also presented.

2.3.1.1 Sea Level Rise Data

This section summarizes the available sea level rise (SLR) data. Sea levels have likely been rising not only in the past century, but for the past several millennia. There are different methods to measure and estimate past sea levels including the geologic record, tide gages, and satellites.

Plots of relative sea level data for several US locations based on historical tide gage data are available in many references including FHWA (2008). The average rate of relative sea level change, which accounts for changes in both land and ocean elevation, varies with location. A NOAA web site - http://tidesandcurrents.noaa.gov - provides ready access to those data.

Figure 2.5 summarizes the long-term sea level trends as measured by tide gages around the US (NOAA 2013). Along most of the US coast, the relative sea level is rising. The rates of rise vary by location due to regional variability of landmass subsidence or uplift (also called Vertical Land Movement or VLM) and other physical phenomenon including oceanic circulation patterns. In a few locations, particularly Alaska and some Pacific Northwest areas, the relative SLR is negative; in other words, relative sea level is falling. In these cases, the rate of global eustatic SLR is not keeping pace with the rate of upward VLM resulting in a negative relative SLR rate. Zervas (2009) presents detailed analysis of the sea level changes at all the US tide gages.

For the past century, the global **eustatic** SLR rate (the rate with landmass elevation effects removed) has been estimated to be 1.7 mm/yr (0.067 in/yr) based on tide gages (IPCC 2007). This corresponds to about a 0.6 ft rise in global eustatic sea level during the past century. Most of the US Atlantic and Gulf coasts experience much more **relative** sea level rise than the global eustatic rate because of VLM. See Figure 2.5, Zervas (2009), or the "Sea Level Trends" part of the NOAA "Tides and Currents" website (NOAA 2013) for rates of relative sea level change at specific gage locations around the US coast which inherently include VLM.

Sea levels can also be measured by satellite altimetry (Leuliette *et al.* 2004; JPL 2013). The sea surface has been mapped by satellites several times per month since 1992. Sea level is measured across large portions of the earth's oceans. The measurements are not limited to the locations of the long-term tide gages that are all on the coast and mostly in the northern hemisphere. One aspect of the sea level change data as measured by satellites is its spatial, or regional, variability across oceans. Figure 2.6 shows the regional mean sea level trends. The values shown range from SLR rates much higher than the global eustatic rate in portions of the western tropical Pacific to negative values (i.e. sea level has fallen) in portions of the eastern Pacific.

The global average, or eustatic, sea level rise rate as measured by satellites is higher than that measured by tide gage analyses. The satellite data are summarized in Figure 2.7. Based on satellite data, the average rate of global mean sea level rise has been 3.19 mm/yr (0.13 in/yr) since 1992 (CNES 2013).

Coastal geologists can estimate sea levels that predate tide gages using techniques including radiocarbon dating of coastal sediment cores (e.g. see Fletcher 2013). This "proxy" data can be combined with other geological evidence to estimate ancient sea levels extending back several hundred thousand years. The global eustatic sea level was probably 300 ft to 400 ft (90 m to 120 m) lower 20,000 years ago than it is today (see HEC-25 Section 5.1, Overview of Coastal Geomorphology). The past 12,000 to 20,000 years is the Holocene Epoch at the end of the

Quaternary Era. It is characterized by the rise of global sea level in response to the melting of the last of the Wisconsin ice-age glaciers (Davis and Fitzgerald 2004). The Holocene SLR can be divided into two distinct time periods. Prior to about 6,000 years ago, sea level rose at a much faster rate of 10 mm/yr (0.39 in/yr) or 1 m/century (3.28 ft/century). The rate of rise slowed significantly about 6,000 years ago. It has been suggested that the SLR rate was only 0.1 to 0.2 mm/yr (0.004 to 0.008 in/yr) when averaged over the last 3,000 years (Church et al. 2001).

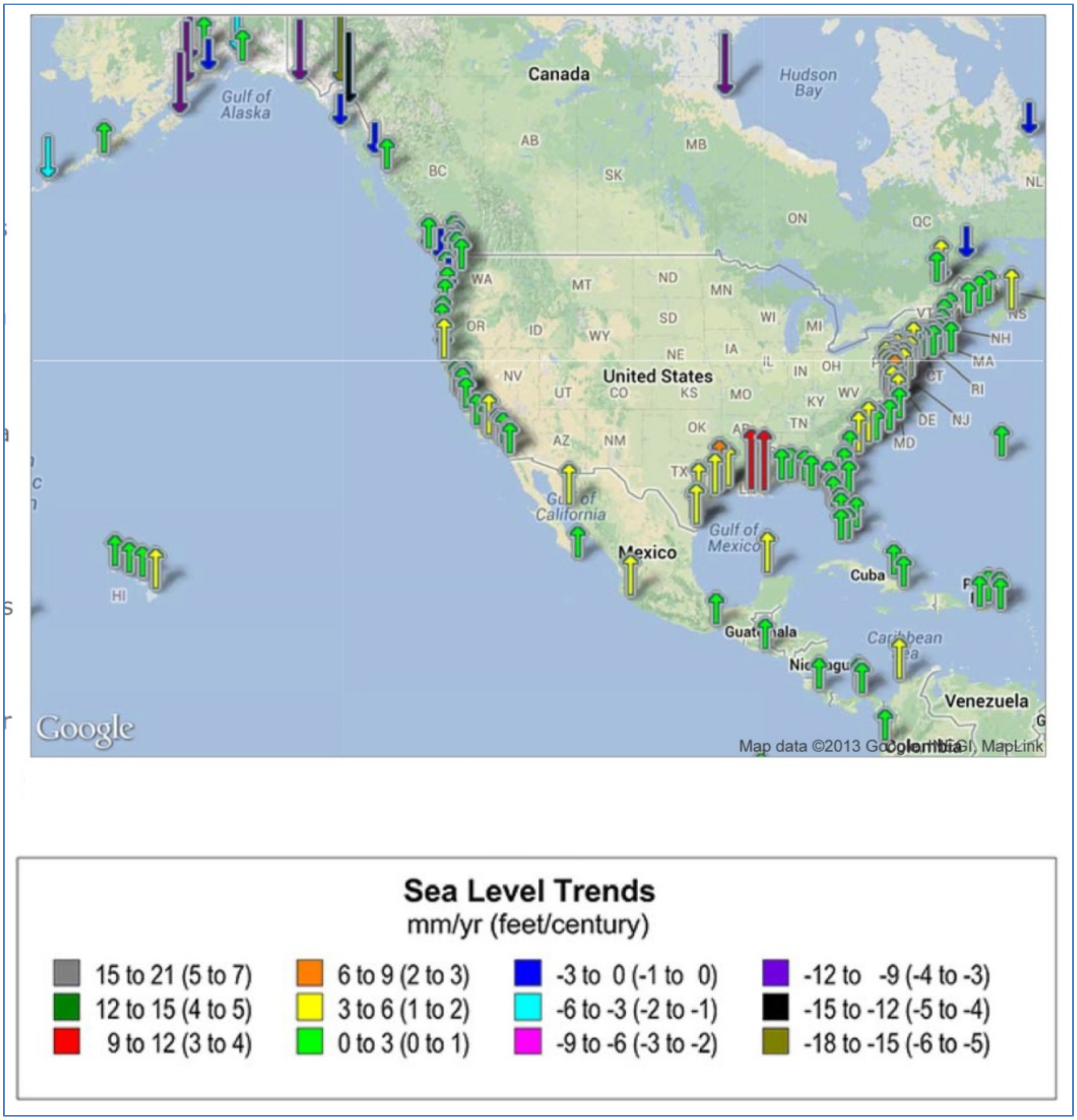

Figure 2.5. Regional variation in sea level changes measured by tide gages around the US (image captured from the NOAA CO-OPS, Tides and Currents web-site Sept. 6, 2013).

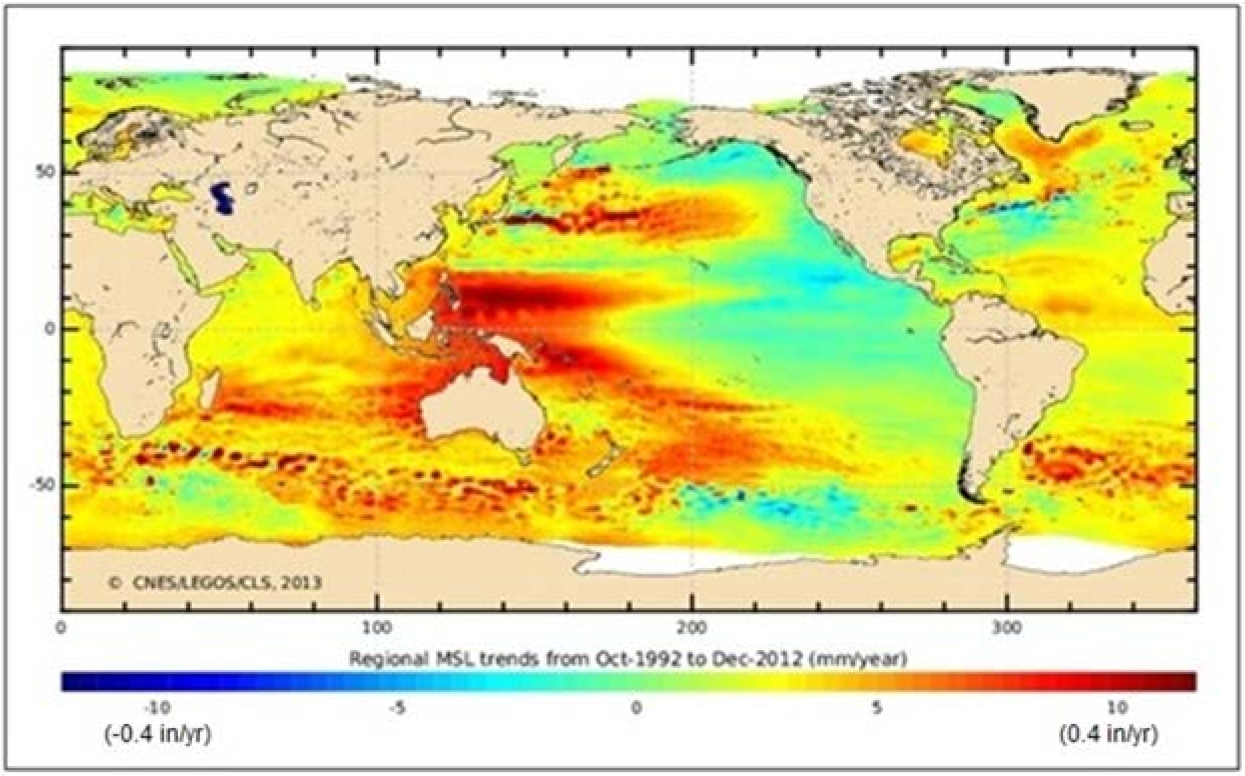

Figure 2.6. Map of sea level change as measured by satellites 1992-2012 (adapted from CNES 2013).

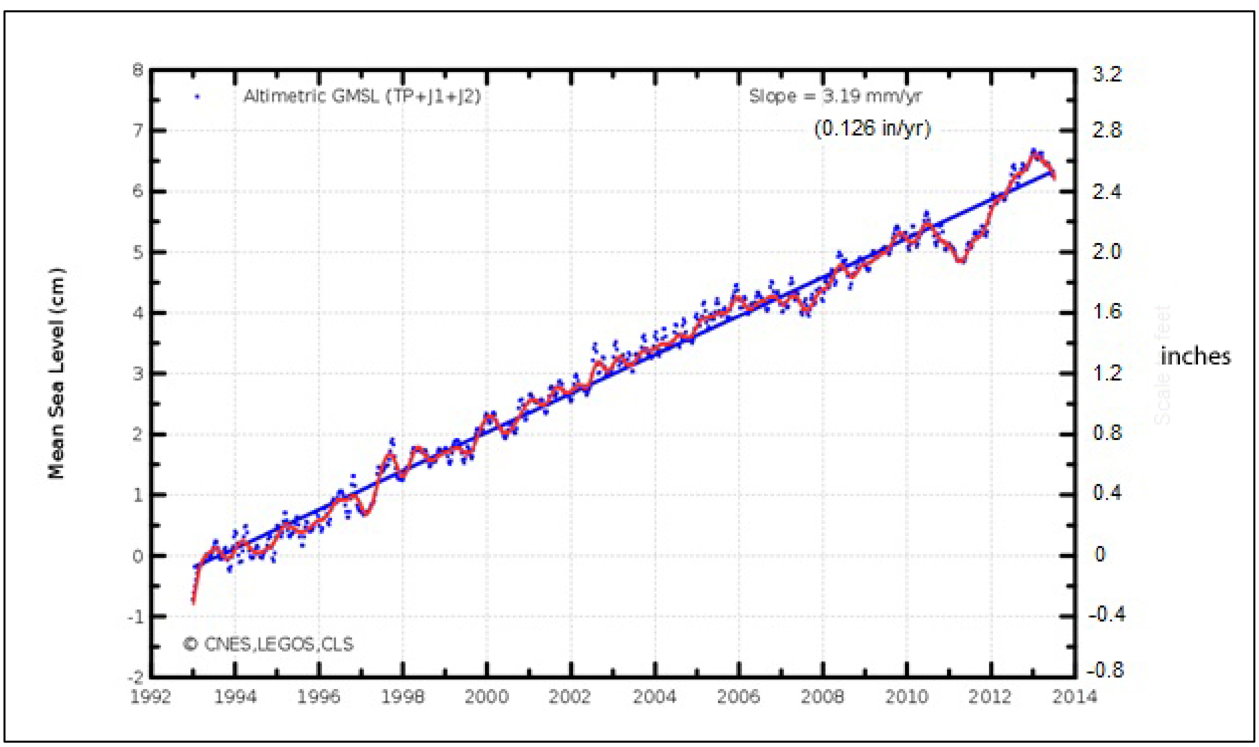

Figure 2.7. Global mean sea level rise 1992-2012 as measured by satellite altimetry (adapted from CNES 2013).

Many investigators have found evidence of regional variation in sea level rise in the past century. For example, Sallenger *et al.* (2012) suggest that there is a regional “hotspot” in sea level rise rate along the Mid-Atlantic States in part due to changes in oceanic currents, temperatures, and salinities.

There is an ongoing debate in the literature as to whether historic SLR data exhibit a recent increase in the rate of SLR, that is, whether the rate has accelerated in the recent past. A number of investigations have suggested that SLR has been accelerating in recent decades (Merrifield et al. 2009; Church and White 2006; Church and White 2011; Hamlington et al. 2011). A SLR acceleration conclusion can be reached by comparing the rate as measured by tide gages over the past century (1.7 mm/yr) with the rate measured by satellites over the past two decades (3.2 mm/yr). However, confidence in such a conclusion would be higher if accelerations were measurable within the same data set, either the tide gage data or the satellite data, or within both. The acceleration rate found by Church and White (2011) in tide gage data, 0.009 mm/yr^2 (0.00035 in/yr^2), is small. It will add less than 100 mm (3 inches) of sea level change in the next century. This is significantly below most of the sea level rise projections/scenarios discussed below and less than the contribution from the global, eustatic, “linear” rate (1.7 mm/yr) discussed above.

Other investigators have found that historic SLR rates measured by tide gage data have not been accelerating (Houston and Dean 2011, Douglas 1992). This is consistent with site-specific tide gage data plotted in FHWA (2008) and on NOAA’s web-sites (NOAA 2013). The implication is that while sea level is rising, the rate of rise is not increasing at the locations of US tide gages. While the Houston and Dean (2011) findings are not discussed in the NCA, they are by Parris *et al.* (2012), the synthesis report that focused on sea levels and was prepared by a large, inter-agency science group specifically for input to the NCA. Parris *et al.* (2012) conclude that, “the presence or absence of accelerations in sea level rise and the causal mechanisms remain an area of scientific debate.” The tide gages, of course, only measure the historical rates and do not forecast future rates.

2.3.1.2 Projections for Sea Level Rise

The key issue, however, is future sea levels. SLR rate accelerations are projected by global climate models that suggest climate change will contribute to increased melting of ice in glaciers/sheets and thermal expansions of the ocean – the main causes of global sea level rise (NRC 2012). This section outlines some of the projections of future sea levels that are available to assess the vulnerability of coastal transportation infrastructure. Projections discussed here may be used in Chapter 4 and Chapter 5 of this manual. Most of these projections include some acceleration from the SLR rate typical of the past century. A range of projections is available and it is likely that the science of these projections will continue to evolve.

The National Research Council developed a report on sea level changes with specific commissioning from the three western states of California, Oregon, and Washington (NRC 2012). Their projection is for global eustatic sea level to rise 2.7 ft by the year 2100. The projected rate of rise is summarized in Figure 2.8. A range of estimates is shown to account for the uncertainties in the best-available science. The range is from 1.7 ft to 4.6 ft by 2100. These values can be used in coastal vulnerability assessment nationwide, but need to be adjusted for local changes in relative sea level which include VLM based on tide gage data.

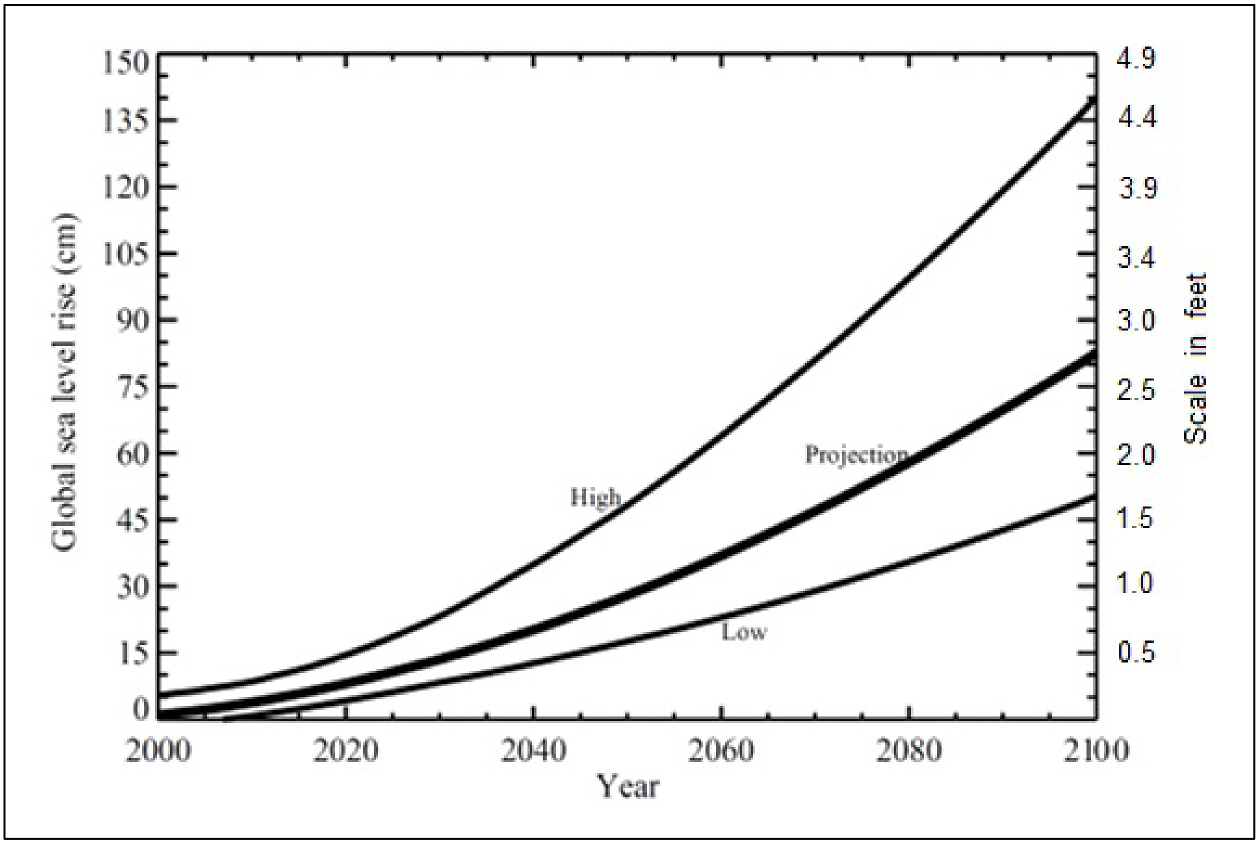

Figure 2.8. Global sea-level rise projections (adapted from NRC 2012).

Figure 2.9 shows the past and projected changes in global SLR from the NCA (Melillo *et al.* 2014). It shows much of the historic data; including some older "proxy" data, tide gage data, and satellite data as well as several projections for sea level rise over the next century. The future scenarios show two ranges for the year 2100. The wider range, from 0.66 ft to 6.6 ft above present levels, follows Parris *et al.* (2012) – the synthesis report that focused on sea levels prepared specifically for input to the NCA. The lowest value, 0.66 ft, is generally consistent with the historic global SLR rate for the past century. Also shown along the right-side of Figure 2.9 by the vertical orange bar is the range of SLR projections recommended by the NCA for the year 2100 (Melillo *et al.* 2014). This recommended projection range is from 1 ft to 4 ft above present levels (this is the global, eustatic portion of SLR and it is relative to the year 2000). The range in the projections reflects uncertainty about how glaciers, ice sheets, ocean temperatures, currents, and winds will react to climate change. Any of the projection values shown in this curve may be used for assessing vulnerability of transportation systems to climate change.

The selection of a projection is at the investigator's discretion and there is no clearly "correct" method for estimating future SLR. However, the best available science should always be used. The most recent projections from the NRC (2012) or the NCA (Melillo *et al.* 2014) are recommended for use in coastal vulnerability assessments although both higher and lower projections could be used. Several state DOT's have developed guidance on incorporating SLR for their use in planning (e.g. Caltrans 2011).

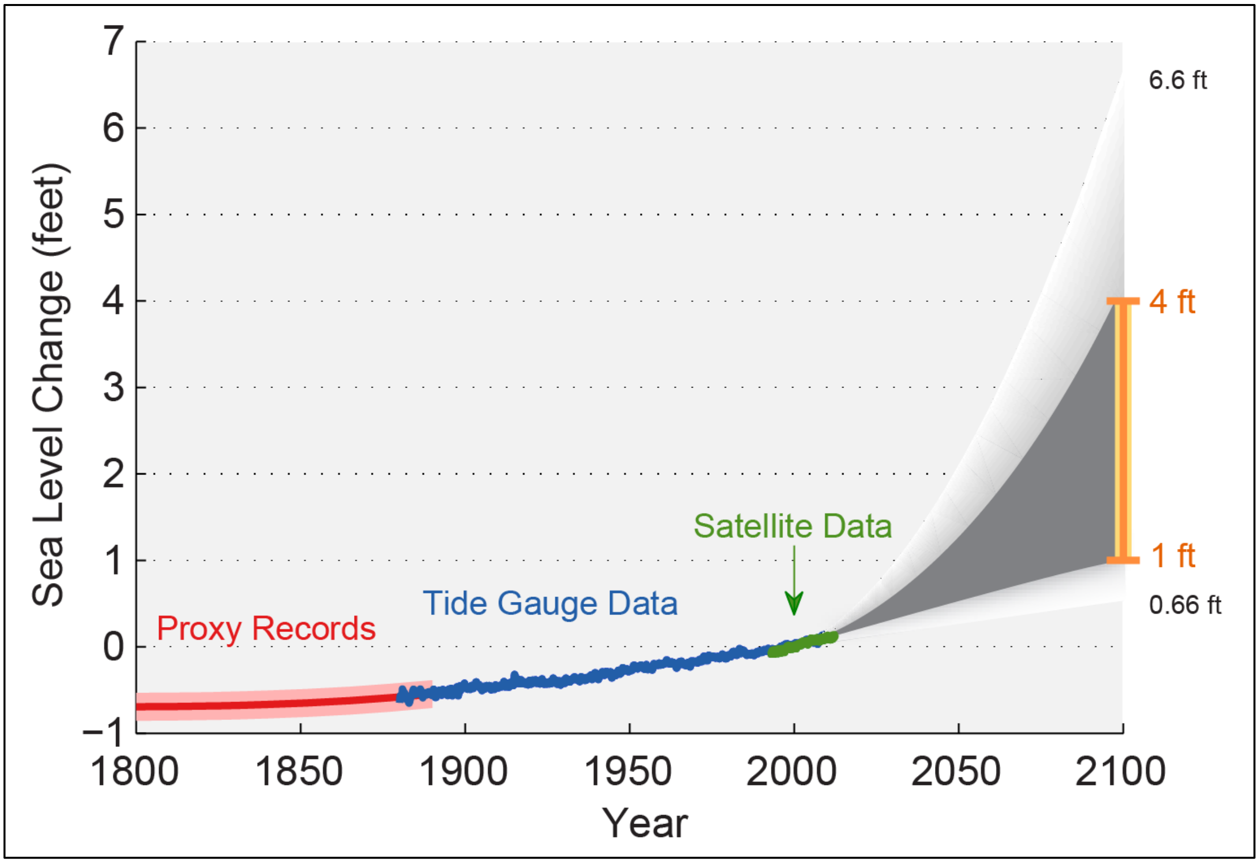

Figure 2.9. SLR data and projections from the National Climate Assessment (Melillo *et al.* 2014).

SLR projections may be based on a simple "model" equation of the rate of change without a strict basis in detailed geophysics. The simple model equation for the future eustatic component of sea level is:

$$E(t) = at + bt^2 \tag{2.1}$$

where:

$E(t)$	=	eustatic global sea level change
t	=	time
a	=	existing linear sea level rise rate
b	=	SLR acceleration rate term

Originally made popular by the NRC (1987) and still used in modified forms in federal guidance today (USACE 2013), the importance of this equation is that any future sea level change can be reproduced by adjusting the model parameters. Model parameters could be adjusted to be consistent with more recent and complex analyses.

This model equation allows for acceleration in SLR rate and can be used for different planning horizons. The existing linear sea level rise rate, a, is now generally accepted to be a = 0.0056 ft/yr (1.7 mm/yr). The SLR acceleration term, b, can be set to achieve a specific amount of rise based on the scientific guidance described previously considering the reference year of the projection, the projection horizon, and the projected rise.

For example, to adapt Equation 2.1 to the 4 ft eustatic sea level rise projection from the NCA (Figure 2.9), the reference year is 2000, the projection horizon is to the year 2100, and the projected rise over that time, *E(t)*, is 4 ft. From this, the overall time, *t*, is 100 years (2100 – 2000). Substituting the known values into Equation 2.1 yields:

$4\ ft = (0.0056\ ft/yr)(100\ yr) + b(100\ yr)^2$

Solving for the unknown, $b = 3.44 \times 10^{-4}$ ft/yr^2. The equation for other projections can be fit in the same manner.

Projections of future sea levels for use in assessing the vulnerability of coastal transportation infrastructure to extreme events and climate change can be developed with the following overall general conceptual approach:

$$\begin{bmatrix} \textit{Future} \\ \textit{Sea Level} \end{bmatrix} = \begin{bmatrix} \textit{Current} \\ \textit{Sea Level} \end{bmatrix} + \begin{bmatrix} \text{Pr}\textit{ojected} \\ \textit{Sea Level Change} \end{bmatrix} \tag{2.2}$$

where:

Future Sea Level = the estimated sea level in the future at a specific location

Current Sea Level = the sea level at that specific location now (or at the beginning of the planning horizon)

Projected Sea Level Change = an estimate or projection of the total change in sea level at that location over the planning horizon

The projected sea level change is the sum of two components: 1) the change in sea levels due to global eustatic SLR and 2) local effects on relative sea levels (including VLM). This is conceptually represented as:

$$\begin{bmatrix} \text{Pr}\textit{ojected} \\ \textit{Sea Level Change} \end{bmatrix} = \begin{bmatrix} \textit{Change due to} \\ \textit{Eustatic SLR} \end{bmatrix} + \begin{bmatrix} \textit{Local Effects on} \\ \text{Re}\textit{lative Sea Level} \end{bmatrix} \tag{2.3}$$

Substituting the symbol for eustatic SLR from Equation 2.1 and defining a symbol for the local effects on relative sea level gives:

$$\begin{bmatrix} \text{Pr}\textit{ojected} \\ \textit{Sea Level Change} \end{bmatrix} = E(t) + L(t) \tag{2.4}$$

where:

Change due to Eustatic SLR = E(t) = an estimate or projection of the eustatic SLR (global value with landmass elevation changes removed) based on the best available science (e.g. the NRC or NCA projections shown above)

Local Effects on Relative Sea Level $= L(t)$ = the estimated future **relative** SLR rate with the global, eustatic SLR component removed.

The change due to eustatic SLR, *E(t)*, typically assumes some future acceleration in the SLR rates as shown in Figures 2.8 and 2.9 above. That term can be estimated using Equation 2.1.

The local SLR rate, *L(t)*, is often calculated by subtracting 1.7 mm/yr (0.067 in/yr) from the local relative sea level change as measured by a tide gage. The use of existing tide gage data for estimating the local SLR rate implicitly assumes that the future VLM will be similar to the existing VLM. This is often the best available assumption in many locations and consultation with the USGS is appropriate in areas that may be experiencing changing VLM rates.

Once the projected sea level change is estimated this value must be added to the current sea level to determine the future sea level as described in Equation 2.2. Current and projected sea levels are usually referenced to a tidal datum (mean sea level). To compare with land-based transportation assets, these elevations must be converted to the relevant survey datum as outlined in HEC-25 Section 3.1.2, Tidal and Survey Datums.

The procedure for projecting future sea levels outlined in this section is similar to guidance from the USACE (USACE 2011, USACE 2014). An online calculator tool based on the Corps guidance - http://www.corpsclimate.us/ccaceslcurves.cfm - can be used to make sea level projections for any location and any future SLR assumptions. The US Army Corps of Engineers (USACE) is involved in many coastal engineering projects and their guidance is to incorporate the effects that projected future sea level change could have over a project life cycle including managing, planning, engineering, designing, constructing, and maintaining those projects.

2.3.1.3 Example Calculation of Projected Future Sea Level

The methodology for calculating future projected sea levels at a specific location can be applied at coastal locations throughout the US. This section presents an example calculation of projected future sea level for a location near Norfolk, Virginia. The planning horizon is 50 years. Since the year the analysis is conducted is 2014, the target year of interest is 2064. The NCA projection of 4 feet by 2100 (see Figure 2.9) is selected for this example.

The general procedure steps are:

1. Estimate eustatic global sea level change, *E(t)*, using Equation 2.1
2. Estimate local effects on relative sea level, *L(t)*, using tidal gage records
3. Solve for projected sea level change equal to *E(t)* + *L(t)* using Equation 2.4
4. Compute current sea level and tie it to an appropriate survey datum for comparison to land based transportation assets using HEC-25 Section 3.1.2, Tidal and Survey Datums
5. Compute future sea level by adding current sea level to projected sea level change using Equation 2.2, including any adjustments to incorporate partial tidal epochs

Step 1

The first component of Equation 2.3, the change due to eustatic SLR, E(t), can be estimated using Equation 2.1 as:

$$E(64\text{ yr}) = a\,(64\text{ yr}) + b\,(64\text{ yr})^2 = (0.0056\text{ ft/yr})(64\text{ yr}) + (0.000344\text{ ft/yr}^2)(64\text{ yr})^2$$

$$= 0.36\text{ ft} + 1.41\text{ ft}$$

$$= 1.77\text{ ft}$$

Where t = 64 yr is used since the NCA projections are based on the change from the year 2000; a = 0.0056 ft/yr corresponding with the accepted global, eustatic sea level rise rate (1.7 mm/yr) ongoing for the past century; and b = 0.000344 ft/yr^2 corresponding to the value that will provide the total eustatic component at of SLR of 4 feet by the year 2100 as shown above. The projected change resulting from eustatic SLR by 2064 is 1.77 ft.

Step 2

The second component of Equation 2.3, local effects on relative sea levels, is estimated using the tide gage record for the NOAA Sewell's Point (Norfolk), VA tide gage (Figure 2.10). The measured, ongoing relative sea level rise rate is 0.0146 ft/yr (4.44 mm/yr). Therefore, the local effects on relative sea levels, $L(t)$, can be estimated as:

L(64 yr) = [(0.0146 ft/yr) - (0.0056 ft/yr)] (64 yr)

= [0.009 ft/yr] (64 yr)

= 0.58 ft

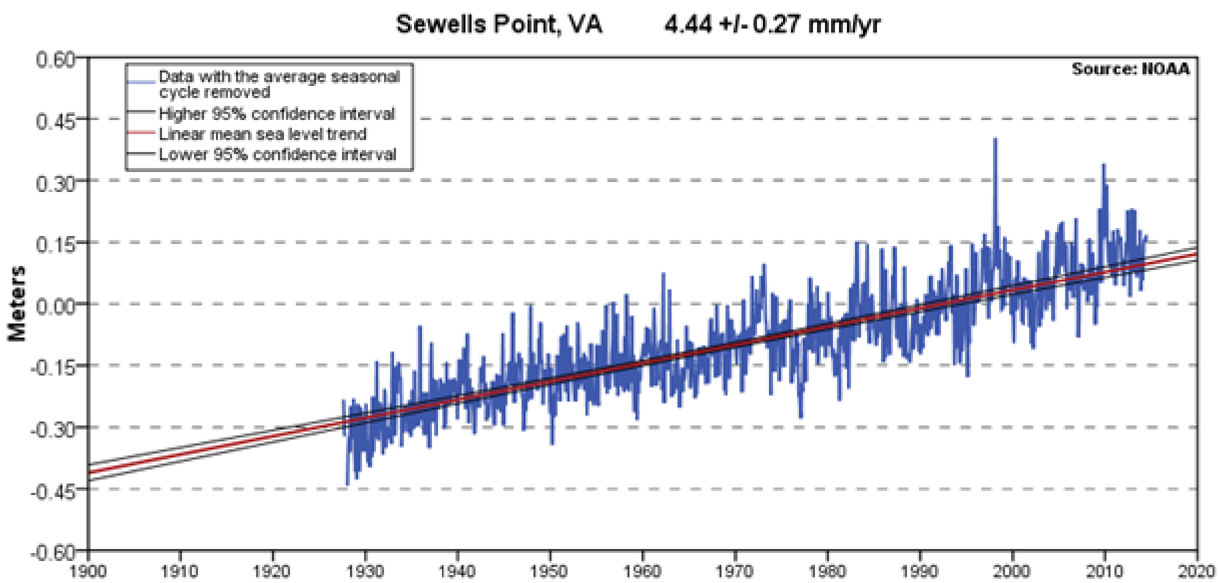

Figure 2.10. Sea level changes as measured by the Norfolk, Virginia tide gage (from NOAA).

Step 3

Entering these values into Equation 2.4 yields the projected sea level change:

[*Projected Sea Level Change*] = *E(t)* + *L(t)*

= 1.77 ft + 0.58 ft

= 2.35 ft

Therefore, the projected increase in sea level at Norfolk will be 2.35 ft by the year 2064 using the higher curve projected by the NCA (this is compared to the year 2000). Other projections can be developed both for different sea level rise rate scenarios (by changing the value of *b* to match the assumed eustatic change) and for different planning horizons (by changing the value of *t*).

Step 4

To compute the future sea level, the projected sea level change must be added to the current sea level in accordance with Equation 2.2. The current sea level elevation must also be tied to an appropriate survey datum, such as NAVD88, to allow comparison with the elevations of land-based transportation assets. These steps are accomplished by accounting for the variations in tidal datums through time and the relationships between survey and tidal datums that vary with location (see HEC-25 Section 3.1.2, Tidal and Survey Datums). NOAA's online tide station records provide the link between the NAVD88 survey datum and the mean sea level datum for the most recent tidal epoch: 1983 through 2001.

For this Sewell's Point example, the projected sea level change is tied to the common survey datum, NAVD88, by consulting NOAA's online tide station records. For the most recent tidal epoch, the record for the Sewell's Point gage shows that the NAVD88 datum was 0.26 ft (0.079 m) above the mean sea level datum. That is, mean sea level at Sewell's Point is at an elevation of -0.26 ft NAVD88.

Step 5

Mean sea level is often referenced to the midpoint of the tidal epoch which in this case is the year 1992. Therefore, the elevation of mean sea level in 1992 is known (-0.26 ft NAVD88) and the sea level rise from 2000 to 2064 was calculated earlier and is known (2.35 ft). The sea level rise from 1992 to 2000 is needed to complete the estimate. The measured trend of 0.0146 ft/yr (4.44 mm/yr) at the gage can be used to estimate the rise over the 8 year period from 1992 to 2000. That is, 8 times 0.0146 equals 0.12 ft of relative SLR. Therefore, taking the elevation of mean seal level in 1992 and adding the rise from 1992 to 2000 and from 2000 to 2064 yields:

Sea level in 2064 (NAVD) = -0.26 ft + 0.12 ft + 2.35 ft = 2.21 ft

Thus the mean sea level in 2064 in Norfolk, Virginia using the higher NCA projection is estimated to be about 2.2 ft NAVD88.

The procedure outlined in this example can be applied at any coastal location along the Gulf, Atlantic, or Pacific coasts where tide gage data are available. For locations between two tide gages, interpolation may be appropriate depending on the regional variability of relative sea level changes as measured by the nearest tide gages. The procedure can be adapted for other projections of eustatic sea level changes including projections developed in the future as the science evolves. The procedure takes into account local tide gage elevations and land subsidence rates combined with projected accelerations in global SLR. This procedure assumes that the local VLM in the future will match the VLM of the recent past as measured by the tide gage. The online sea level calculators, e.g., http://www.corpsclimate.us/ccaceslcurves.cfm, are more detailed versions of a similar procedure.

2.3.2 Lake Levels

This section briefly discusses the effects of climate change on lake levels. The mean water levels on the Great Lakes are not related to the sea levels of the oceans. Great Lake levels depend on the hydrologic balance including precipitation, runoff, evaporation and outflow. Climate change will influence much of this balance (Hayhoe *et al.* 2010).

The cumulative effects of climate change on lake levels in the Great Lakes are unclear as there are varying conclusions in different studies. Most studies conclude that lake levels will fall (Hayhoe *et al.* 2010, Angel and Kunkel 2010) but there are questions about the level of reduction (Lofgren *et al.* 2011). Mackey (2012) presents a range of possible scenarios with reductions of 0.66 ft (0.2 m) to about 3.3 ft (1 m) by the end of the century. Gronewold *et al.* (2013) is an interactive, on-line "Great Lakes Water Level Dashboard" which allows for graphical presentations/comparisons of the long-term lake level forecasts based on climate change models. The magnitude of the range in fluctuations is similar to long-term water-level changes in the lakes (e.g. 33-yr, 60-yr, 160-yr fluctuations), making it difficult to differentiate between climate change and climate variability (Baedke and Thompson 2000; Baedke *et al.* 2004).

The net effect of climate change on winds, and thus, storm surge, waves, seiching, and meteotsunamis, in the Great Lakes is also unclear.

2.3.3 Storm Surge

This section discusses the likely effects of climate change on storm surges along all US coasts. The impact of stronger future storms on surge is not clear. However, it is clear that as sea levels rise, coastal storm surge elevations and flood depths will rise at the locations of many existing coastal transportation facilities. This rise will allow for larger waves to strike them. Interestingly, this rise in surge depths will probably be somewhat "nonlinear" as described below.

Storm surge is a function of the strength, size, speed, and track of the storm. Sea surface temperatures are clearly related to these storm characteristics. Pressure gradient and winds at the sea surface create the surge. Thus, it is logical that climate change will affect oceanic storms through increases in sea surface temperatures. This is true of tropical and non-tropical storms, e.g. nor'easters. For example, the major storms of the Great Lakes are characterized by winds associated with arctic high-pressure systems. To the degree that those weather systems are affected by climate change, so too will the resulting storm surge, waves and seiching of lake water levels.

There has been a substantial increase in virtually every measure of hurricane activity in the Atlantic since the 1970s and these increases have been linked, in part, to higher sea surface temperatures (Melillo *et al.* 2014). There have long been concerns about linkages between climate change and the strength of individual coastal storms as well as the frequency of, and damage produced by, coastal storms.

However, in spite of these logical linkages, research on the effect of climate change on coastal storms provides varied conclusions. There are significant issues with the historical data record and other factors (Church *et al.* 2001; IPCC 2007; Knutson *et al.* 2010). Knutson *et al*. (2010) summarizes the research in the past decade into each of these aspects (strength, frequency, damage) related to tropical storms. Bender *et al.* (2010) have suggested, based on atmospheric models, that there may be an increase in the number of large hurricanes but a slight decrease in the overall frequency of all tropical storms in the north Atlantic.

It is clear that sea level rise will increase flood depths along the coast due to storm surge. However, this will likely not be a "one-to-one" or linear relationship. A one foot rise in sea level will not necessarily produce a one foot rise in storm surge elevation at most coastal locations. This is because of the complex physics of coastal storm surge inundation and wave propagation. As sea levels rise, storm surges will change because the areas flooded by the surge will change. Storm surge at any location for a specific storm is a complex function of the storm's interaction with the ground elevations around that location. Those interactions will likely change somewhat as different areas will be flooded at different depths. A significant portion of onshore storm surge is due to wave setup which is very sensitive to local depth and ground slope. There will also, likely, be geomorphological changes along the coast, such as wetland changes as described briefly in Section 2.3.5 below. These will also affect the relationship between sea level rise and increased storm surge elevations.

Several recent, numerical, hydrodynamic model studies of storm surge under different sea level rise scenarios have demonstrated this "nonlinear" response of storm surge (and also waves) to increased water levels (Smith *et al.* 2010; Choate *et al.* 2012; Hagen and Bacopoulos 2012; Atkinson *et al.* 2013). In some cases and locations, particularly in shallow water near the coast, the incremental change in storm surge can be greater than the corresponding sea level rise. In other words, the storm surge increase will be amplified compared with the sea level rise. In other cases and locations, the storm surge increase will be less than the sea level rise increment but still greater than a similar storm surge on present-day sea levels.

2.3.4 Waves

This section discusses the effects of climate change on waves. Waves on storm surge typically produce much of the damage to roads and bridges during coastal storms (Douglass et al. 2004; FHWA 2008). The effects of climate change on the waves that will be striking most coastal transportation infrastructure include the effects on local water depth such as sea level rise and storm surge. The effects due to changes in wind fields which generate the waves may be less important.

Deep-water, offshore wave heights in the oceans around the US may have been increasing during the past century (e.g. Allan and Komar 2000). Ruggiero (2013) argues that increasing storm wave height in the US Pacific Northwest has had a more significant role in the increased frequency of coastal flooding and erosion than the rise in sea level over the past 30 years and may continue to be more important than, or at least as important as, sea level rise in the coming decades. Some atmospheric modeling suggests that global climate change may reduce deep-water and offshore wave heights in some locations, particularly the northern hemisphere, while increasing it in other locations (Hemer et al. 2013).

The major storms of the west coast include the El Niño related storms and most coastal damage in California occurs during periods of coincidence of extreme sea levels, extreme wave levels, and freshwater floods from coastal mountains. There is evidence that the frequency and magnitude of these extreme coastal events have been increasing for the past several decades. Given the sensitivity to climate on each process, the hazards are projected to significantly increase in future decades (Komar et al. 2011). Based on atmospheric modeling, Cayan et al. (2008) have suggested that the rate of future increases will follow the pattern of increase in sea levels, i.e. if sea level rise follows the higher projected scenarios, extreme events affecting the west coast and their duration will also increase significantly.

Waves striking built infrastructure along the coast are often depth-limited, as discussed above in Section 2.2, Damaging Processes of Extreme Coastal Events, so their height, and therefore power to cause damage, is controlled by the depth at that location. Thus, the effects of climate change on local depth, including sea level rise plus storm surge, during a future storm may be the most important effect of climate change on waves. In other words, as sea levels rise, damaging storm waves will be larger at many locations (where waves are depth-limited) and extend farther inland producing more damage to infrastructure not built for those conditions. This will occur regardless of the effects of climate change on offshore, ocean wave heights.

There are other locations and situations, e.g. deep bays during hurricanes, where the wave heights are not depth-limited; rather they are fetch-limited (the distance that the wind blows across the water controls the wave heights). In those situations, the local wind speed is a limiting factor on wave height. Climate change influences on wind speeds could be important in those situations. Wave height is influenced by wind speeds in fetch-limited situations as is described in the primary reference manual (see section 4.4, Wave Generation, HEC-25).

Ice can prohibit wave generation and as climate change increases the “ice-free” durations in northern latitudes, including the Arctic Ocean and the Great Lakes, waves will cause more damage to the coast. Native American communities on the north slope of Alaska have suffered losses of historic and cultural sites due to wave-driven erosion processes in recent decades (Jones et al. 2008). Ice can also remove sediments from the beach as ice flows include the sediment and move it offshore into deeper water when they move (Hampton et al. 1999). Additionally, ice flows are known to remove armor stones from rock revetments through a process called “ice picking” as shown in Figure 2.11. Ice picking occurs when a layer of thick ice collects on large armor stones, leaving attached cantilevered portions of ice on partial thawing, which in turn topple the stones down the revetment slope (Smith and Carter 2011).

2.3.5 Other Coastal Processes

Climate change will affect other critical coastal processes including the coastal geomorphology of shoreline recession, bluff erosion, barrier island migration, and wetland development. Sea level is a critical component of coastal geology. The type of coast and beach at each location is partially controlled by the “geologic framework” that created it. This framework includes the local geologic formations and the interplay between vertical land movements, sediments, sea level changes and waves which have shaped our coasts over the past millennia (FHWA 2008).

Figure 2.11. Example of “ice picking” (photo courtesy of Ruth Carter).

As sea levels rise, wave-driven erosional forces will act farther up on coastal bluffs and cause increased erosion (Hampton *et al.* 1999). Furthermore, as climate change modifies the timing, duration, and volumes of precipitation within a watershed, and as temperature modifies the state of precipitation (snow/rain/runoff), the quantities of water and sediment delivered to the coast in the form of fluvial discharge will undoubtedly affect some of these coastal processes.

The long-term fate of some of the presently low-lying barrier islands as sea levels rise has been questioned. Is it reasonable to assume that a specific barrier island will still be in place in 2100 if sea levels have risen by 0.5 ft? by 6 ft? Barrier islands have a number of natural migration mechanisms that have allowed them to move and survive the sea level rise of the past several millennia (Davis 1994). However, some former barrier islands off the Louisiana coast have now become underwater sand shoals.

One complicating factor is the human response or adaptation. For example, within the past several centuries, human modifications have had significant impacts on our coasts. Human efforts, including dredging of navigation channels and trapping of sand by coastal structures, have removed over one billion cubic yards of beach sands from US beaches and caused many of the most severe beach erosion and shoreline recession problems in the past century (Douglass *et al.* 2003). However, many of those issues related to erosion caused by blocking of the natural littoral drift have been addressed with the use of improved artificial sand bypassing during the past few decades. Artificial sand bypassing is the use of mechanical dredging equipment to place sand dredged from navigation channels or trapped by coastal structures on the downdrift beaches. Also, beach nourishment, the direct placement of large amounts of good quality sand on the beach to widen the beach and one of the primary engineering responses to beach erosion and shoreline recession today, has ceased and reversed recessional shoreline change trends along many of our highly developed US coastal communities (Douglass 2002, Houston and Dean 2013).

Coastal wetlands will respond to future sea levels in different ways. The stability of a coastal wetland depends on sea and land levels, the biological production of the salt marsh, and the deposition of sediments that maintain the marsh surface in a dynamic equilibrium with the local mean sea level (Morris *et al.* 2002). Many present-day coastal wetlands have adjusted to the historic rate of sea level rise already. Protected coastal wetlands have the ability to vertically grow and adjust to some increments of rise. However, large areas of coastal wetlands in some locations, particularly coastal Louisiana, are being converted from marsh to shallow open water habitat due to land subsidence (essentially an increased rate of local sea level rise), reduced sediment influx due to river engineering, and dredged canals. This process can be important in some of the modeling discussed in Chapter 4. For example, Smith *et al.* (2010) have adjusted Manning's "n" values (the empirical coefficient quantifying surface roughness in most storm surge models) to account for changes, including conversion from marsh to open water, in coastal wetlands due to higher sea levels.

2.4 Numerical Models of Critical Coastal Processes

This section provides an overview of numerical modeling of storm surge, waves, and coastal morphology. The focus is on the type of numerical models that can be used in quantitative assessment of the vulnerability of coastal transportation assets to extreme events and climate change. Model validation is also briefly discussed.

Models discussed in this section are listed in Table 2.1 along with a brief comment as to the type of possible application/use in assessing vulnerability of coastal infrastructure. Engineers and scientists with specialized training in these coastal models should be included in teams applying them to assess transportation infrastructure. The specific use of some of these models for this purpose is discussed in Chapter 4. Examples of vulnerability assessments using some of these models are presented in Chapter 5.

Table 2.1. Numerical coastal models cited in this section.

Model/Program	Comments
ADCIRC	Hydrodynamic model (often used to model storm surge)
SLOSH	Storm surge model
ET-SURGE	Storm surge forecasting model
DELFT-3D	Hydrodynamics, waves, and morphology model
MIKE-21	Hydrodynamics, waves, and morphology model
FVCOM	Hydrodynamic model
WAM	Wave model
STWAVE	Wave model
CMS	Hydrodynamics, waves, and morphology model
SWAN	Wave model
CH3D	Hydrodynamic model
EDUNE	Dune erosion model
SBEACH	Cross-shore morphology model
XBEACH	Hydrodynamics, waves, and morphology model
CSHORE	Cross-shore wave and morphology model
CHAMPS	Cross-shore wave and morphology model

2.4.1 Storm Surge Models

There are a number of different numerical storm surge models. One of the more commonly used models is the ADvanced CIRCulation model (ADCIRC). ADCIRC was originally developed for the Corps of Engineers as a hydrodynamic circulation model for coastal waters (Luettich et al. 1992; Westerink et al. 1994). It now has an active research and application community in academia, agencies, and consulting. The ADCIRC program is actually a collection of numerical models that can be used to simulate tidal flows, water levels, and constituent transport (e.g. salt, larvae, contaminants, etc.) in two or three dimensions throughout the water column. However, it is most commonly used in a two-dimensional (depth-integrated) fashion. These programs utilize the finite element method in space allowing the use of highly flexible, unstructured grids. Although ADCIRC does not explicitly model wind waves, it can incorporate their effects on storm surge. Gradients in wave momentum can be specified as additional model inputs which must be obtained from a separate wave model. Appropriate coupling between ADCIRC and a numerical wave model has been found to yield accurate storm surge elevations which include wave setup effects (Dietrich et al. 2011). Central to its use in modeling storm surge, the ADCIRC model includes Holland-type (Holland 1980) parameterization of tropical storms based on general storm characteristics like central pressure, maximum wind speed, radius to maximum winds, etc. These models, including some significant enhancements inherent to ADCIRC, make it a useful tool for simulating storm water levels in tropical storms. The ADCIRC model is suggested for the higher levels of effort vulnerability assessments discussed in Chapter 4.

There are numerous other hydrodynamic models that can be used to estimate storm surge water levels. While their details vary, they all typically solve some similar set of governing conservation equations for mass and momentum, accept similar types of boundary conditions and forcing, and do not explicitly model the waves. One well-known example is the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model developed by the National Weather Service (Jelesnianski et al. 1992; Glahn et al. 2009). The SLOSH model solves a set of equations to develop two dimensional (horizontal) distributions of storm water levels forced by spatially variable wind fields. SLOSH is computationally efficient and is used to develop national forecasts of storm water level. The SLOSH model has been used for years to develop coastal Storm Surge Inundation Maps (SSIMs) primarily for input to emergency evacuation decisions. There are some inherent limitations in SLOSH which have led some investigators toward other models like ADCIRC for detailed mapping of coastal flooding. The SLOSH model accounts for a local balance between the sea surface slope induced by the wind stress and the restorative forces of gravity and Coriolis and bottom drag but it does not include some of the governing physics explicitly such as momentum acceleration effects and wave setup effects. These can be important components of storm surge mapping in some situations.

Other storm surge models include the extratropical storm surge model ET-SURGE (or ETSS) developed by NOAA as an operational forecast tool providing surge guidance for extratropical storms like nor'easters. The ET-SURGE model is a variation of SLOSH forced by real-time output of winds and pressures from NOAAs National Centers for Environmental Prediction's Global Forecast System (Kim et al. 1996; Glahn et al. 2009). Other hydrodynamic models which can be used for storm surge modeling include the Curvilinear Hydrodynamics Three Dimensional (CH3D) model (Sheng, 1990; Johnson et al. 1991), the DELFT3D model (Vatvani et al. 2012), the MIKE-21 Model (Savioli et al. 2003) and the Finite Volume Coastal Ocean Model (FVCOM; Chen et al. 2006). These models offer fully three-dimensional results of extended coastal ocean processes. Others, like the Corps of Engineers' Coastal Modeling System (CMS) strictly provide two dimensional (depth-integrated) solutions (Buttolph et al. 2006).

Some models, including ADCIRC, DELFT3D, and MIKE 21, are capable of modeling waves and dynamically incorporating their contributions to storm surge through momentum transfer and wave setup. Such models are said to be dynamically coupled as the circulation and wave model results are passed back and forth in order to model the effects of waves on storm surge and currents, as well as the effects of storm surge and currents on wave generation, transformation and breaking.

When the expected contribution of wave setup to the total storm surge is expected to be small, as in the Gulf of Mexico, it is also possible to "loosely" couple separate storm surge and wave models. This is achieved by performing the wave modeling at selected times during the storm duration using the corresponding predicted water levels from the storm surge model. In this manner, wave generation, transformation and breaking are affected by the change in local depth throughout the storm simulation. Alternatively, it may also be appropriate to consider a single simulation of waves using the "maximum envelope of water" (MEOW), the highest surge elevations at each location, predicted by the surge model. While the contribution of wave setup to storm surge is typically small in the Gulf of Mexico, its magnitude may become significant along the Atlantic coast.

Most of the available storm surge models compute the velocity of flow in the incoming and outgoing surge. Thus, the velocity of flow, usually depth averaged, is a part of the output. These flow values can be important in some damage mechanisms including hydrodynamic forces on structures. However, the resolution and detail in the velocity estimates from these models depends on the resolution and detail in the numerical grid/mesh of the model. Individual building edges and road embankments may or may not be appropriately accounted for in the model depending on the grid resolution. Conservative approximations for estimating the velocity of flow are outlined in Section 4.1.2, Level of Effort 1: Gulf Coast and South Atlantic Coasts, but, in general, those approximations should only be used when numerical model estimates are not available.

2.4.2 Wave Models

This section briefly discusses the available numerical models for simulating wave characteristics that can be applied for an evaluation of vulnerability to extreme coastal events. Wave models may be steady state, providing wave characteristics over a spatial domain that corresponds to one realization in time, or time-dependent. The appropriate selection of a model will depend on the scale of the process being simulated, as well as the nature of the problem being evaluated.

The prediction of storm surge and waves at the local scale (i.e. barrier island) often relies on a definition of wave characteristics at the basin scale (i.e. ocean). The Global Ocean Wave Prediction Model (WAM) is commonly used to provide wave boundary conditions for nearshore wave models (Group, 1988). The model predicts the growth of wind waves from sea surface roughness and wind characteristics, and simulates nonlinear wave-wave interactions as well as the dissipation of short waves. WAM provides wave conditions at each model grid point at chosen times. While WAM is effective at simulating basin-scale wave propagation it should not be used to simulate the propagation and transformation of waves close to shore.

Simulating nearshore wave propagation requires consideration of wave transformations that occur in intermediate to shallow water depths (when the local depth is less than one-half of the wavelength). Such processes include wave refraction and shoaling, current-induced refraction and shoaling, wave diffraction, and wave breaking. Appropriate treatment of these wave transformations becomes increasingly important during storm surge events as coastal topography is inundated. The Steady-State Spectral Wave (STWAVE) model provides steady-state solutions of wave transformation-propagation over variable bathymetry in two dimensions. The STWAVE model is also a wind-wave generation model and accepts depth-averaged currents from a circulation model to simulate current-induced wave shoaling and refraction (Smith *et al.* 2001). STWAVE is capable of simulating most nearshore wave transformations of interest on a rectangular, Cartesian grid. However, the treatment of wave diffraction is simplified and wave reflections are not considered.

The USACE CMS model has a stand-alone wave model, CMS-Wave, having capabilities similar to those of STWAVE with some enhancements (Lin *et al.* 2008). CMS-Wave is a two-dimensional wave transformation model. Similar to STWAVE, the CMS-Wave model is capable of wind-wave generation and propagation over variable bathymetry, and includes nearshore wave transformations including shoaling, refraction, diffraction, reflection, and breaking.

The Simulating Waves Nearshore (SWAN) model has been adapted for coupling with many different types of general circulation models. The SWAN model is capable of simulating two-dimensional (horizontal) wave propagation in time and space in Cartesian or spherical coordinate systems. The SWAN model simulates random, short-crested wind-wave generation and propagation in coastal and inland waters (Booij *et al.* 1999; Ris *et al.* 1999). The wave model is capable of simulating nearshore wave transformations as well as transmission and reflection. The SWAN model has been successfully coupled with ADCIRC (Dietrich *et al.* 2011) and CH3D (Sheng *et al.* 2006) as part of tightly coupled hindcast and forecast simulations of storm surge and waves.

2.4.3 Coastal Morphology Models

Morphology models in coastal vulnerability assessments for extreme events and climate change should be applied with considerable care and with the realization that the inherent uncertainties will be significantly greater than those of the hydrodynamic (surge and waves) models. The fundamental, governing physics imbedded in numerical models of coastal sediment transport are not nearly as well understood as those of the hydrodynamics. Coastal sediment transport has been an active area of fundamental research for decades and the problems relate primarily to our inability to model the complex, multi-phase, turbulent flow fields under a variety of time-scales.

The simulation of storm surge and wave characteristics with complex numerical models often provides enough detailed information to estimate local sediment transport. Accounting for differential sediment transport rates over an incremental area provides an opportunity to predict morphologic change. Such models range in complexity and accept wave and water level results from separate hydrodynamic models. In some cases these models utilize sophisticated coupling with wave and circulation models.

FEMA procedures use what can be considered a simple, parametric, empirical form of a cross-shore morphology model to address issues related to whether a sand dune will survive a coastal storm (Hallermeier and Rhodes, 1988). This is combined with a form of a depth-limited wave model to estimate the combination of surge levels and wave crest elevations to map coastal flood plains for establishing building elevation minimums (see HEC-25 Section 5.4).

Two examples of simple cross-shore morphology (i.e. dune erosion) models are EDUNE (Kriebel and Dean, 1985; Kriebel, 1986) and SBEACH (Larson and Kraus, 1989, Larson *et al.* 1990). These models require a definition of the initial beach profile, or bathymetric profile, as well as storm wave and water level characteristics. The models seek to describe a modified beach profile that is in equilibrium with the storm conditions. While the models typically capture the dune erosion and overwashing events well, the simple cross-shore morphology models are not as capable of accurately predicting the redistribution of sediments to deeper portions of the profile. In most cases this would not present a limitation when considering impacts to built infrastructure along the coast.

There are a few numerical models of coupled waves, flow, and morphology being used in the coastal engineering research community. The XBEACH (Roelvink *et al.* 2009) and CMS (Buttolph *et al.* 2006) models are both two-dimensional models capable of simulating the coupling between waves, currents, sediment transport and morphology in a time-dependent fashion. Sediment transport modeling, by its very nature, is typically not as well understood as hydrodynamic modeling. While XBEACH is specifically a wave propagation model with morphologic updating capabilities, the CMS suite of models also accounts for morphologic change due to currents and water levels. Even more complex, the modeling suite DELFT3D can estimate morphologic change (Roelvink *et al* 1998). Although the EDUNE and SBEACH models are relatively easy to apply, they do not provide a time history of morphologic response during storm events, nor do they seek to describe morphologic change in a direction parallel to the coast. The XBEACH, CMS, DELFT3D, and MIKE 21 models, by comparison, provide estimates of the temporal and spatial morphologic change including dune erosion, overwashing, and breaching. Less complex, coupled, one-dimensional (transect) models are CSHORE (Johnson *et al.* 2012) and CHAMPS (FEMA 2007).

2.4.4 Model Validation

Numerical models should be validated and/or calibrated before performing simulations that capture the effects of climate change. Model **validation** is typically performed by simulating an historic event that impacted the study area. This is commonly referred to as a model **hindcast**. In model validation, the model predictions are directly compared to historic water level and wave measurements in the study area. In model calibration, certain model parameters are changed, or tuned, until model predictions match observations for the same historic event. Direct comparisons of model predictions and observations are limited to only those locations where historic measurements have been made. These typically include tide gages (http://tidesandcurrents.noaa.gov/), wave buoys (http://www.ndbc.noaa.gov/), or recorded high water marks after storms (http://www.fema.gov/). An example of a validation of storm surge model results is briefly presented in the case study found in Section 5.1.5 of this manual. The validation simulations are typically included in an exposure assessment as they serve as a baseline to which the effects of climate change are compared.

The validation and calibration of shoreline change models are only possible when the requisite data, like shoreline position and elevations, are available both before and after the hindcast storm event. Such data are rare, so these comparisons are not made routinely. Pre- and post-storm shoreline position and elevation data are available in limited locations for some recent storms in the form of coastal LiDAR data. These data can be obtained from the NOAA Coastal Services Center Digital Coast web portal (http://www.csc.noaa.gov/digitalcoast/).

Chapter 3 – Risk, Vulnerability and Adaptation

This chapter establishes how this manual can be used to develop **vulnerability** assessments for coastal transportation infrastructure within the traditional framework of engineering risk. The concept of flood "**risk**" typically captures both (a) the probability of a flood event, and, (b) the consequences to human health, the environment and economic activity associated with that flood event. Tools appropriate for the quantitative evaluation of both probability and consequences for coastal transportation assets are presented in this chapter.

Section 3.1 discusses the traditional engineering methods of estimating the probability of occurrence of extreme events (or failure for designs based on those events) and how those concepts are typically developed for coastal flood water levels. Emphasis is on the design **return period** or annual risk of occurrence concept and how that typically is applied to develop estimates of the frequency of occurrence of coastal flood water elevations. The concepts and approaches outlined in this section are referred to in Chapter 4, Analysis Methods for Assessing Extreme Events and Climate Change.

Section 3.2 describes how climate change vulnerability assessments for coastal transportation facilities have been done and how this guidance document relates to the existing FHWA-DOT **assessment framework** for climate change vulnerability (FHWA 2012b).

Section 3.3 discusses coastal damage mechanisms and the **sensitivity** of transportation assets to coastal storms and climate change. This includes common types of damage to roadways, bridges, rails, and tunnels. These damage mechanisms will be the major consequences of sea level rise and climate change.

Section 3.4 briefly discusses the available **adaptations** and countermeasure strategies for improving the adaptive capacity of coastal transportation systems to extreme events and climate change. Many of the adaptations for climate change and sea level rise are the same adaptations required today to improve infrastructure resilience to extreme events with today's sea levels.

3.1 Engineering Risk at the Coast

This section discusses how traditional engineering risk concepts are typically developed for coastal storm water levels. This includes a brief introduction to the common engineering concept of design storm based on return period, e.g. the "100-year storm" or the "1%-Annual-Chance-Flood" (Section 3.1.1). A common misunderstanding of risk levels implied by the return period terminology is discussed.

The well-established general approaches for estimating the coastal storm-frequency relationship are presented in Section 3.1.2. There are some regional differences in the approaches that are described for the Atlantic and Gulf Coast separately from those for the Pacific and Great Lakes Coasts. Two of the readily available coastal risk map products, Flood Insurance Rate Maps (FIRMs) and SSIMs, are discussed in Section 3.1.3. The FIRM is very useful in quantitative risk assessment of extreme events. Other approaches, including a brief discussion of the problems with using the Saffir-Simpson Hurricane Category scale for quantifying coastal flooding risk, and, the life cycle approach as a long-term goal, are briefly mentioned in Section 3.1.4.

3.1.1 Return Period and Probability of Occurrence

Extreme natural events, such as river floods or coastal floods, vary in ways that appear to be random and can often be considered to be random for the purposes of engineering analysis and design. Techniques of probability and statistics are used to analyze these random flood events in water resources engineering. Historic records are used to understand the frequency of occurrence of a range of flood event magnitudes.

Probability of exceedance is often referred to in terms of the average "**return period**," T, of a given flood magnitude. For example, a flood with a return period of 100 years has a 1 percent (1/100) probability of being equaled or exceeded in any year. Note that the return period is the average number of years between floods equal to or greater than this magnitude. Return period, *T*, is related to probability of exceedance, P_e, by the equation,

$$P_e = 1/T \tag{3.1}$$

It should be emphasized that the return period or recurrence interval *T* is a long-term average. It is an average over a very large number of floods over a very long time span. To fully determine this average, one would need to observe and analyze a very long record of floods – perhaps thousands of years of floods. These fundamental concepts of return period are explained in many engineering textbooks (e.g. Roberson *et al.* 1998) and other FHWA manuals including HDS 2 (FHWA 2002).

The use of the term "1%-annual-exceedance-probability-flood" is often preferred to the equivalent "100-year flood" because of confusion about the latter term in the general public including decision-makers. The flood with a return period of 100 years (P=0.01) has a 0.01 or 1 percent chance of occurring or being exceeded this year or any year (see USGS 2010). Likewise, a 50-year flood has a 2 percent chance of occurrence in any year. A layperson may assume a 100-year flood is not going to occur for another hundred years or that there is only a 1 percent chance it will occur in the next 100 years and thus the terminology may not be adequately communicating the risk.

From the perspective of an asset's service life (or design life), the longer the service life, the greater the risk of such an extreme event level occurring during the service life. The probability that a design flood level will be equaled or exceeded at least once during the service life of the project (the probability of occurrence) is,

$$P = 1 - \left(1 - \frac{1}{T}\right)^n \tag{3.2}$$

where:

P	=	probability that the design flood level will be equaled or exceeded in *n* years
n	=	design or service life, years
T	=	the return period of the design storm, years

This equation is a reduced form of the binomial distribution common in quantitative risk analysis (see Equation 4.81 of Hydraulic Design Series No. 2, 2nd ed. (FHWA 2002))

For example, if the design storm for a transportation asset is a 50-year storm, T = 50 and the design or service life is 30 years, then the probability of occurrence in the next 30 years is P(occurrence in 30 years) = 1 - $(1-0.02)^{30}$= 0.45 = 45 percent. There is a 45 percent chance that the 50-year flood or greater will occur at least once in the next 30 years.

Figure 3.1 shows a family of lines corresponding to different risk levels expressed as P = probability of occurrence, as a function of T = design return period, and n = years of service. The same relationship is shown in Table 3.1. For example, as shown in either Figure 3.1 or Table 3.1, the probability of occurrence of a 100-year storm increases from 1 percent for a service life of 1 year (by definition), to about 10 percent for a service life of 10 years, 18 percent for a service life of 20 years, 39 percent for a service life of 50 years, and about 63 percent for a service life of 100 years. In other words, there is a 63 percent chance that the 100-year flood will be equaled or exceeded at least once in the next 100 years.

Figure 3.1. Probability of occurrence as a function of return period, T, and years of service, n.

Table 3.1. Probability of extreme event occurrence for various periods of time.

Length of Service (Years)	Frequency – Recurrence Interval					
	10-year	25-year	50-year	100-year	500-year	700-year
1	0.10	0.04	0.02	0.01	0.002	0.001
10	0.65	0.34	0.33	0.10	0.02	0.01
20	0.88	0.56	0.33	0.18	0.04	0.03
25	0.93	0.64	0.40	0.22	0.05	0.04
30	0.96	0.71	0.45	0.26	0.06	0.04
50	0.99+	0.87	0.64	0.39	0.10	0.07

Another way to use Figure 3.1 or Table 3.1 is to consider what design storm level is required to attain a given risk level. For example, it might be desired for critical facilities to reduce the probability of failure to a smaller level, say a 5 percent risk of occurrence in the next 25 years. Table 3.1 and Figure 3.1 show that the design storm level would have to be T=500 years to attain that low level of probability. For extremely critical facilities, even less frequent design storms can be adopted. For example, 2,000-year events are used for some spillway designs or some structural designs for earthquake forces and some designs related to nuclear power plants consider design return periods of up to 100,000 years. Design storm return periods used for the evaluation of most types of transportation infrastructure range from 10-year to 500-year depending on the type of infrastructure.

A transportation asset may not experience any damage with a flood level that exceeds its design level. The relationship between flood level and damage depends on numerous other factors including the type of asset (bridge, tunnel, or roadway), the characteristics of the asset (on piles, at grade, on an embankment, etc.), the site-specific topography, and the wave heights at that site. Damage mechanisms common in coastal transportation systems are discussed briefly later in Section 3.3.

3.1.2 Coastal Storm Flood Frequencies

Storm flood elevation is often the parameter of primary interest in coastal hazards assessment because it, along with waves (which are controlled in part by flood level), is often responsible for damage. There is an established, general approach for estimating the frequency, or return period, of coastal storm levels. It was initially developed in the 1970's with the advent of modern computing and has evolved with better computers and improved methodologies. The numerical modeling requires substantial investments in both computing power and trained personnel skilled in coastal modeling. The approach is fairly complex and varies in different parts of the country because of the differences in key coastal processes as described in Chapter 2.

3.1.2.1 Atlantic and Gulf Coastal Surge Frequencies

The general approach for estimating the surge-frequency relationship along the Atlantic and Gulf coasts was originally developed in the 1970-1980's by NOAA, the Corp of Engineers, and FEMA. The general approach is to numerically simulate the full complexity of the physical processes controlling coastal flooding and to derive statistics from the results (the local response) of that analysis (FEMA 2007). Multiple runs of numerical, hydrodynamic storm surge models with some frequency analysis controlling the input modeled storm parameters are used. The surge-frequency relationship is then determined at all locations based on the surge results of the multiple model runs. The numerical model provides the link between the known statistics of the generating forces and the desired statistics of coastal flood levels. The primary reason for the development of such an approach is that the historic coastal storm surge elevation at any location is very dependent on geography and on the path, or track, taken by any individual storm. Thus, if any given historical storm had taken a slightly different track the surge at many locations would have been different. Computer modeling allows for consideration of the impact of similar storms with different tracks and different strength parameters (wind speed, barometric pressure, forward speed, size etc.). Sometimes historic, actual storms are input to the model. "Synthetic" or hypothetical storms which have not actually occurred but could have, based on the frequency analysis of the storm parameters of the historic storms, can also be included so that more realistic coastal flood risk estimate at all locations can be developed. This general approach assumes that future storms will be similar to past storms and thus does not account for possible changes in storm characteristics and frequency due to climate change.

The most common approach to the selection of the input parameters for synthetic hurricanes is the Joint Probability Method (JPM) originally used by NOAA (Ho and Myers, 1975). Historic storm parameters (e.g. wind speed, storm size, landfall location, etc.) are gathered and used to develop a set of statistically representative input storms. The JPM assumes that the probabilities for each parameter are independent and fit some probability distribution. Recently, the JPM has been extended for "Optimal Sampling" to reduce the required number of modeled storm events without impacting the resulting statistics (Niedoroda *et al.* 2010; Toro *et al.* 2010a;

Toro *et al.* 2010b). This JPM-OS technique is needed because the high-performance computational storm surge models have expanded to increase resolution as computing power has increased. An alternative technique to the JPM for developing the surge-frequency relationship at any location is an Empirical Simulation Technique (EST). The EST does not make assumptions about the distributions of the parameters but derives the surge-frequency relationship based on the modeled runs of actual and synthetic storms (Scheffner *et al.* 1996).

Any numerical storm surge model can be used in the general approach for developing coastal surge-frequency estimates (see Section 2.4.1 Storm Surge Models). However, several agencies including FEMA and USACE have begun to use the Advanced CIRCulation Model (ADCIRC) for much of their coastal storm surge modeling (e.g. Algeo and Mahoney, 2011) for developing surge frequencies. The ADCIRC model was used for the storm surge modeling in the Gulf Coast 2: Phase 2 transportation study discussed in Section 5.1 as a case study of how to include the effects of climate change on storm surge.

3.1.2.2 Pacific and Great Lakes Coastal Surge Frequencies

The methods typically used for the Pacific Coast and Great Lakes coasts to estimate the surge-frequency relationship differ from those described above for the Atlantic and Gulf Coast. In these regions, historic storms are simulated, i.e. hindcast, with numerical surge and wave models to develop a long, say 50 year, database of water levels at all locations. These results are then evaluated to estimate the surge-frequency relationship. FEMA (2005) outlines that agency's guidelines for the Pacific coast. A "total water level" approach is suggested which directly includes wave runup as well as the storm surge. This may also be referred to as the "storm response method" in some literature. Where hindcast storm water levels and waves for a period of at least 30 years can be developed, the extreme values such as the 1 percent-Annual-Flood are estimated with Generalized Extreme Value Distribution Method.

Similarly, for the Great Lakes, a total water level approach is recommended for estimating 1 percent-annual-flood levels based on numerical hindcasts of 50 years of historical storms (Melby *et al.* 2012; FEMA 2012; Nadal-Caraballo *et al.* 2012). The historical approach typical of the Pacific and Great Lakes coasts avoids the JPM for developing input storms but the numerical modeling effort is still very complex, often with ADCIRC or a similar storm surge model, and requires significant computing resources and experienced coastal modelers.

3.1.3 Available Estimates of Storm Surge – SSIMs and FIRMs

Two commonly available coastal mapping products are SSIMs and FIRMs. Coastal storm surge inundation maps (SSIMs) are developed by NOAA primarily for input to emergency evacuation decisions. As such, they are created to be conservative so that local decision-makers can have them in front of them for evaluation as hurricanes approach. SSIMs show areas which can possibly flood due to different Saffir-Simpson categories of hurricanes. They are essentially maps of modeled (typically with SLOSH) potential inundation areas from the worst possible storms (track and strength) of each Saffir-Simpson storm category. They provide an upper-bound, or worst-case, flood level for each category storm. They are generated by running the storm surge model for numerous possible tracks and strengths in each category storm and recording the highest flood levels from all the storms. Thus, they are not flood maps from any specific storm but the worst-case at each location. There is no risk or probability level associated with SSIMs but the "Category 5" SSIMs can provide an overall upper-bound, or worst-case, flood zone for all hurricanes.

Coastal flood insurance rate maps (FIRMs) are generated by FEMA to be generally consistent with FIRMs in riverine systems. They are essentially maps of the 100-year coastal flood plain developed with the general approach to surge-frequency estimation described above (FEMA

2007). The primary purpose of the FIRMs is to establish flood insurance rates in coastal flood plains based on a rational, consistent basis. Coastal FIRMs also show the FEMA “Base Flood” depth at specific locations. The base flood includes additional elevation above the still water level (SWL) to account for the wave crest elevations which can exist in that local depth of water. One difference between FIRMs and SSIMs is that the FIRMs are consistent with typical risk-based analysis and can be used for rational engineering design. The differences between these two commonly available coastal surge map products, the FIRMs and the SSIMs, are explained in USACE (2011b).

3.1.4 Other Approaches to Coastal Risk

One alternative to the numerical storm surge modeling approaches for developing the coastal surge-frequency relationship is to use frequency statistics developed directly from measured, historical water level data. Water level data is recorded at a series of tide gages around the country. However, these data sets should not be used for vulnerability assessments or designs for extreme events unless it can be confirmed that they reflect the extreme water levels that have occurred. Extreme water levels are often not recorded because the gages become inoperative during extreme events due to physical damage, lost power, or not being designed for such elevations. Also, because of the complexities of the interaction of storms with coastal geography (bathymetry and topography) surge varies significantly within relatively short distances. Another reason to not use analyses of these data sets directly is that such an approach could be storm-specific, i.e., emphasize planning/designing for the last big storm. Coastal peak flood elevation data can be supplemented with careful high-water mark surveys after storms. However those data are often subject to interpretation error and have only been collected with significant spatial coverage after major coastal storms in the past several decades. In general, not enough storm surge observations are available to make estimates of storm surge-frequency.

The Saffir-Simpson Hurricane Scale cannot be used for assessing the vulnerability (or for design) of most coastal transportation infrastructure. This is because wind is not the primary environmental design issue and the Saffir-Simpson scale is a wind speed scale. The winds create the surge and waves, which do the damage, but there is usually only marginal correlation between a hurricane’s wind strength and either surge or waves at any specific location along the coast. For example, the same hurricane will have very different surge and wave effects along the coast to the left of landfall, where peak winds are offshore and reducing surge and waves, than to the right of landfall, where peak winds are onshore and increasing surge and waves. Thus, statements like, “this should be designed to survive a Category 3 hurricane,” as a basis for planning and design decisions are problematic and should be avoided (unless direct wind loads are the critical damaging phenomenon, e.g. for traffic signs or building roof design).

Life cycle cost analysis approaches for quantifying risk and incorporating it into engineering design are gradually replacing frequency-based analyses in many areas of civil engineering and planning. At this time, such is probably beyond the level of analysis required for assessing vulnerability of transportation facilities to extreme events and climate change. However, for individual, critical facilities it may be the proper, ultimate goal. The Coastal Engineering Manual (USACE 2002) describes methodologies for risk-based analysis in coastal engineering, and the reader is directed to Thompson *et al.* (1996) and Almodovar *et al.* (2008) for specific case study application of the life cycle approach to coastal infrastructure (not directly related to highways). The life cycle approach addresses a number of possible realizations of project evolution during its design life. This approach can simulate different cumulative damage scenarios; can incorporate management decisions (i.e. repair, replace, etc.) and accounts for changing climatic conditions over time. The life cycle approach requires some understanding of the probabilities of key variables and is often a data-driven exercise. Ultimately, probabilities and risk describing the project elements are derived through an analysis of project performance of numerous (i.e. thousands) estimates of the project life cycle. This is most commonly done with Monte Carlo-like simulations or other statistical techniques. Transportation infrastructure/assets typically have long life cycles. Also the characteristics of the areas surrounding coastal transportation facilities are subject to change either through natural or human impacts. And, within the life cycle of some assets, the statistics and/or characteristics of key variables may change due to the impacts of climate change. Economics can be integrated into the life cycle approach and considered simultaneously with technical performance in order to more appropriately describe risk and vulnerability.

3.2 Coastal Vulnerability Assessments

This section briefly summarizes the literature on methods for assessing the exposure of transportation infrastructure to the impacts of climate change and describes how this guidance document is related to the existing FHWA-DOT assessment framework for climate change vulnerability.

3.2.1 Vulnerability Assessments for Coastal Highways

Hyman et al. (2008) summarized the limited research into the effect of climate change on highways available at that time. ICF (2009) summarized the literature on climate change vulnerability assessment, risk assessment, and adaptation approaches including some efforts outside of the U.S.

A basic approach used by most investigators (e.g. Titus 2002) is a mapping overlay technique with projected future sea levels and roadways for beginning to characterize the extent of road inundation as a surrogate to vulnerability. The technique has been called the “bathtub” approach (FHWA 2012b). Gesch et al. (2009) provides a partial list of the investigations which have used the basic technique and NOAA (2012) describes many of the details related to the mechanics of how to apply a basic inundation mapping technique.

Earlier studies used only sea level but some later studies combine that with storm surge estimates. This approach is usually accomplished by the addition of the two components in recognition of their importance in assessing impacts of sea-level rise on infrastructure (Gill et al. 2009). In other words, it is not just the sea level rise which will be important but the storm surge after sea level has risen. Douglass et al. (2005) used a form of the technique to assess the existing vulnerability of the US coastal highway system to storm surge alone (with no consideration of sea level rise) by overlaying the FEMA 100-year flood plains on road maps to estimate that there are 60,000 road miles occasionally exposed to coastal surge and waves.

Kafalenos et al. (2008) used the basic inundation mapping technique in part one of the “Impacts of Climate Change on Transportation Systems and Infrastructure: The Gulf Coast.” That study is a multi-year, multi-phase study (see FHWA 2014). Phase 1 of the study, “Gulf Coast 1,” quantified the highway miles in areas with ground elevations below levels selected to account for storm surge and sea level rise in the study area from Galveston, Texas to Mobile, Alabama.

The second phase of that study, the “Gulf Coast 2” or “GC2” study used a more complex method for mapping exposure that is highlighted as a case study in this manual (see Section 5.1). Numerical models with different assumed input future sea levels are used to map exposure to storm surge and waves. Some of those results have been included in the National Climate Assessment (Melillo et al. 2014). One of the conclusions is that there is a very high level of exposure of our coastal transportation infrastructure to coastal storms today and that level will increase with increasing sea levels.

Coastal exposure and vulnerability mapping efforts not specifically focused on transportation infrastructure have been done by others using a similar approach. Smith et al. (2010) evaluated storm surge and waves across the marshes of southern Louisiana with assumed scenarios of sea level rise. They found that increases in maximum surge elevations were not linear with the sea level rise assumptions. In particular, for moderate hurricanes the surge levels could increase significantly more than the sea level rise. Li et al. (2013) assessed the impacts of climate change on the naval facilities in the Norfolk area. Atkinson et al. (2013) modeled sea-level rise effects on storm surge and nearshore waves on the Texas coast. They conclude that because of the complexities, "there is no one-size-fits-all response to relative sea level rise descriptive of all locations" and that "site-specific computer modeling should be used to evaluate the risk facing coastal communities."

The FHWA sponsored "pilot" planning level studies on vulnerability and risk assessments of infrastructure to the projected impacts of climate change and extreme weather events in 2011-2012 (FHWA 2014). Most of those studies used some form of an inundation mapping approach for sea level rise, storm surge, or some combination (ART 2012a; NJTPA 2011; Oahu Metropolitan Planning Organization 2011; and Washington DOT 2011). Most of those studies found a high level of vulnerability to coastal storms today that will increase with increasing sea levels. One of those pilot planning level studies is highlighted as a case study in Section 5.2 of this manual.

3.2.2 Vulnerability Assessment Framework

This section describes how this guidance document is related to the existing FHWA-DOT assessment **framework** for climate change vulnerability. Vulnerability assessment, the process of identifying and quantifying the vulnerabilities of a system, is a part of risk management in many different aspects of society (business, national security, infrastructure, etc.). The FHWA's Climate Change & Extreme Weather Vulnerability Assessment Framework is a guide and collection of resources for use in analyzing the impacts of climate change and extreme weather on transportation infrastructure (FHWA 2012b). "The framework," summarized in Figure 3.2, outlines three components for such studies:

- defining study **objectives** and scope,
- **assessing vulnerability**, and
- integrating the results into **decision making**.

The first component, defining objectives and scope, includes articulating the objectives, selecting/characterizing the relevant transportation assets, and identifying climate variables for study. This includes consideration of the intended outcomes, the target audience, the geographical and temporal limits of the study, and the level of detail needed.

This supplemental manual, HEC-25 Volume 2, addresses a portion of the second component in the FHWA framework, "assessing vulnerability." The climate inputs of most concern in this guidance document are sea level rise with waves and surge from extreme events. Developing information on sensitivity to climate includes both:

- quantifying the "exposure" to extreme events and climate change and
- evaluating the damage/sensitivity mechanisms.

This manual focuses primarily on appropriate methods for quantifying the exposure of coastal infrastructure to extreme events and climate change. However, some of the methods for quantifying damage/sensitivity mechanisms as well as logical adaptation approaches for coastal transportation assets are discussed briefly in the next two sections.

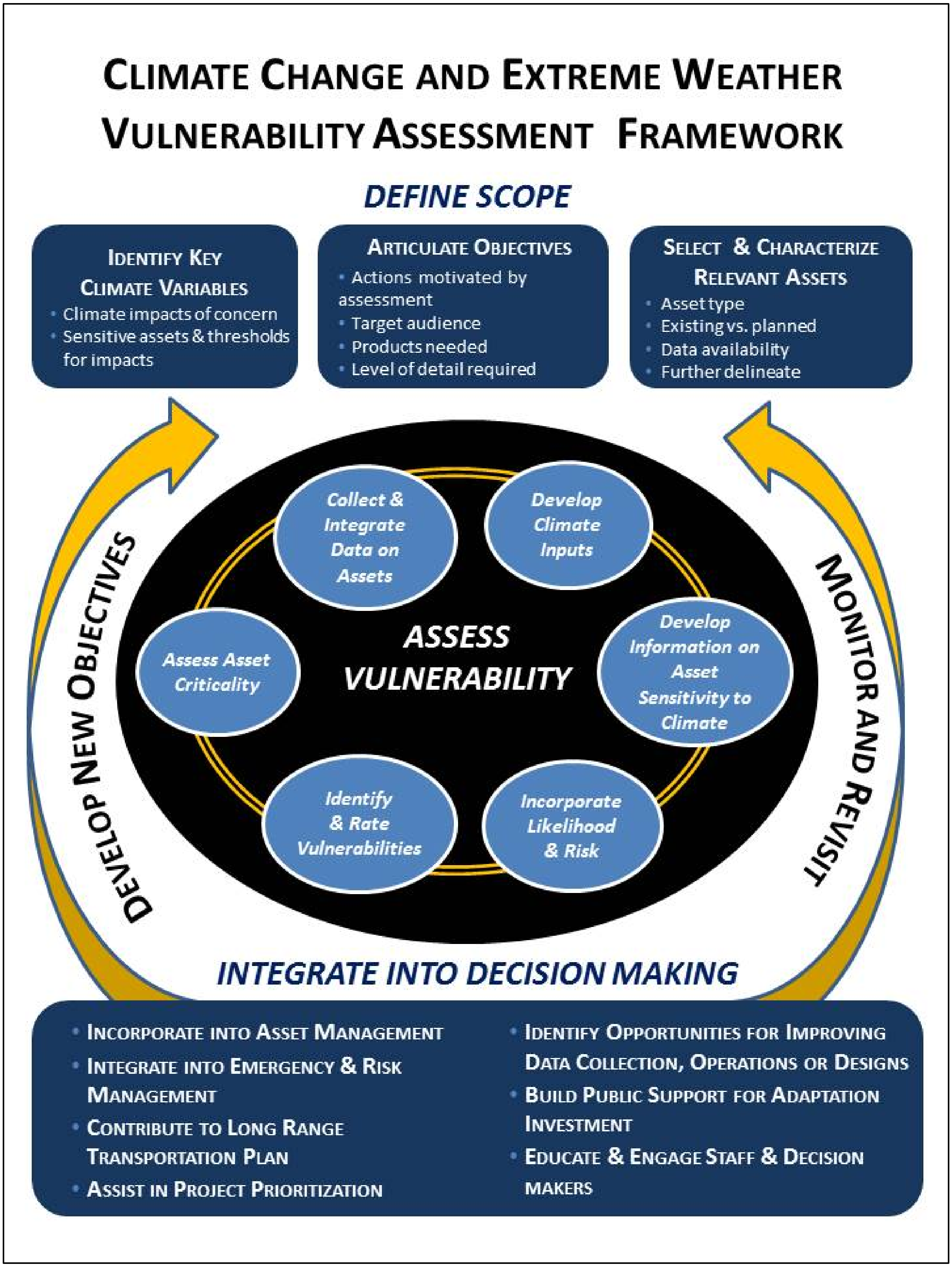

Figure 3.2. Climate change and extreme weather vulnerability assessment framework (from FHWA 2012b).

The third component of the FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework is integrating the results of vulnerability assessment into decision making. This can take the form of integration into asset management plans, hazard mitigation plans, transportation planning project selection criteria, or other transportation agency programs and processes. Also, a transportation agency might be interested in using the results to inform the development of specific adaptation strategies for assets identified as highly vulnerable to coastal storms and climate change.

3.3 Climate Change and Extreme Events: Damage Mechanisms

This section discusses coastal damage mechanisms and the sensitivity of transportation assets to coastal storms and climate change. This includes damage to roadways, bridges, rails, and tunnels with the following mechanisms:

- roadway damage by wave attack,
- roadway and railway damage by coastal "weir-flow,"
- roadway damage by bluff erosion and shoreline recession,
- bridge deck damage by waves on surge,
- structure damage by wave runup,
- tunnel and road damage by overtopping, and
- damage by tsunamis.

The vulnerability of coastal transportation assets to these damage mechanisms will increase with climate change because the damage mechanisms are sensitive to sea levels and storm surge. There is some limited guidance on the details of the sensitivity levels for most of these coastal damage mechanisms in the coastal engineering community but there is a need for more research in this area to improve our ability to assess the vulnerability of our existing coastal transportation system.

3.3.1 Roadway Damage by Wave Attack

Many coastal roads are on constructed embankments or natural bluffs that can be eroded by wave action during extreme events. These embankments are often damaged to the extent that the roadway pavement is undermined and damaged. Embankments used as approaches to coastal bridges are particularly susceptible to this **wave attack** damage mechanism in extreme coastal events as illustrated in Figure 3.3. In this case, the peak storm surge allowed waves to attack the embankment which was not designed for those conditions. Note the bridge over a coastal water body in the background and the undermined pavement in the foreground.

This susceptibility of the approaches occurs in areas where they are at higher elevations than most of the roadway due to bridge clearance issues. Apparently, the higher elevation subjects these portions of the embankment to direct action of larger wave heights while nearby lower-elevation embankments are submerged beneath much of the wave action (Douglass *et al.* 2004). The damage can be complete or partial depending on the duration of the storm surge and the design of the embankment. The damage is common on the side of the embankment exposed to large waves during the coastal storm.

The sensitivity of roadways to wave attack depends on the storm characteristics at the specific location (surge level and duration, wave heights, etc.) as well as the embankment condition/design (grass, exposed sand, slope protection, etc.). The single most important storm parameter is likely wave height at the embankment. For very small waves embankments designed for rainfall events will survive coastal storm events for the duration of a storm surge. In other words, the embankment will be inundated but not damaged if there are only very small waves and very small flow velocities. However, if wave heights are of any significant height, say H > 0.5 ft, most soil embankments will erode. Proper design of coastal revetments for wave attack is summarized in Chapter 6, Coastal Revetments for Wave Attack, HEC-25. The fundamental tool is Hudson's Equation for sizing the revetment armor stone as a function of wave height, slope, etc. Hudson's Equation is based on a low level of damage (5 percent of the armor stones moving during design conditions). The US Army's Coastal Engineering Manual (USACE 2002) presents methods to evaluate higher percentage levels of revetment damage as well as other methods for designing coastal revetments.

Figure 3.3. Partial embankment damage caused by wave attack.

3.3.2 Roadway and Railway Damage by Coastal "Weir-Flow"

Storm surge waters flowing across the road and down an embankment can cause damage as illustrated in Figure 3.4. In this photo of US 98 (Destin, FL) taken in 2005 the ocean (Gulf of Mexico) is to the right and storm surge elevation is just slightly greater than the roadway elevation. This is the coastal **"weir-flow"** damage mechanism described in more detail in HEC-25 Chapter 8, Highway Overwashing. Much of this damage to road pavements is observed on the landward side of the road and not the seaward side of the road. Waves on the flowing surge waters can increase the scour potential on the landward side of the road significantly. Two related damage mechanisms occur as storm surge recedes: weir-flow damage on the seaward side of the roadway as surge waters flow back out to sea late in the storm, and scour of the embankment caused by flow parallel to the road as water moves to "breaches" or lower spots in the road as the storm surge recedes.

Figure 3.4. Example of the weir-flow damage mechanism as it occurs.

The sensitivity of roadways to damage from the weir-flow damage mechanism depends on both the hydraulics and the embankment conditions (slopes, elevations, cover). However, there is very little guidance on the rate of damage of roadway embankments to the coastal weir-flow damage mechanism. Both laboratory tests and field observations indicate that embankment shoulders of unvegetated loose sand (common in many coastal areas) erode with even minimal overtopping flow (Section 8.2, HEC-25). Vegetated shoulders and embankments made of compacted sub-soils will erode slower and thus may experience less than total pavement damage if the storm conditions, particularly surge duration, are mild enough.

Railway embankments experience the same damage mechanisms as roadway embankments: direct wave attack and the weir-flow mechanism. Figure 3.5 shows damage to a railway embankment which occurred during Hurricane Katrina. The incoming or rising-limb storm surge flowed across the tracks from left to right in this photograph. The damage was primarily due to the weir-flow mechanism as the storm surge elevations exceeded the rail elevations.

Figure 3.5. Railway embankment damage caused primarily by the weir-flow damage mechanism.

3.3.3 Roadway Damage by Bluff Erosion and Shoreline Recession

Roadways along many coasts are threatened and damaged by coastal **bluff erosion** and **shoreline recession**. Usually, the damage occurs during an extreme event but the vulnerability had previously been increased by the shoreline recession. Figure 3.6 shows an example of a highway (North Carolina route 12, ocean to the left in the photo) that was damaged in the latter stages of Hurricane Ida (2009). The roadway is located along a receding shoreline which has progressively increased the vulnerability of this highway. This type of damage will continue to occur as sea levels rise. These phenomena are geological processes that impact coastal highways and are often accounted for in design through engineering or siting. The damage and sensitivity of rate of bluff and shoreline erosion at different locations is a function of the site-specific geology. Chapter 7, Roads in Areas of Receding Shorelines, HEC-25 discusses general considerations in this design situation. Some states have developed detailed maps of the coastal hazards of bluff erosion which can be used as a basis for evaluating the increased vulnerability to extreme events and climate change (see e.g. Revell *et al*. 2011).

3.3.4 Bridge Deck Damage by Waves on Surge

Bridges over coastal waters can be severely damaged and destroyed by **wave-induced loads** if storm surge allows the wave to strike the bridge deck (Figure 3.7). This damage mechanism, loads induced by repeated individual waves striking the bridge superstructure, is discussed in HEC-25 Section 9.3, Coastal Bridge Wave Forces.

Figure 3.6. Pavement damage due to waves and surge in an extreme event (NC DOT photo).

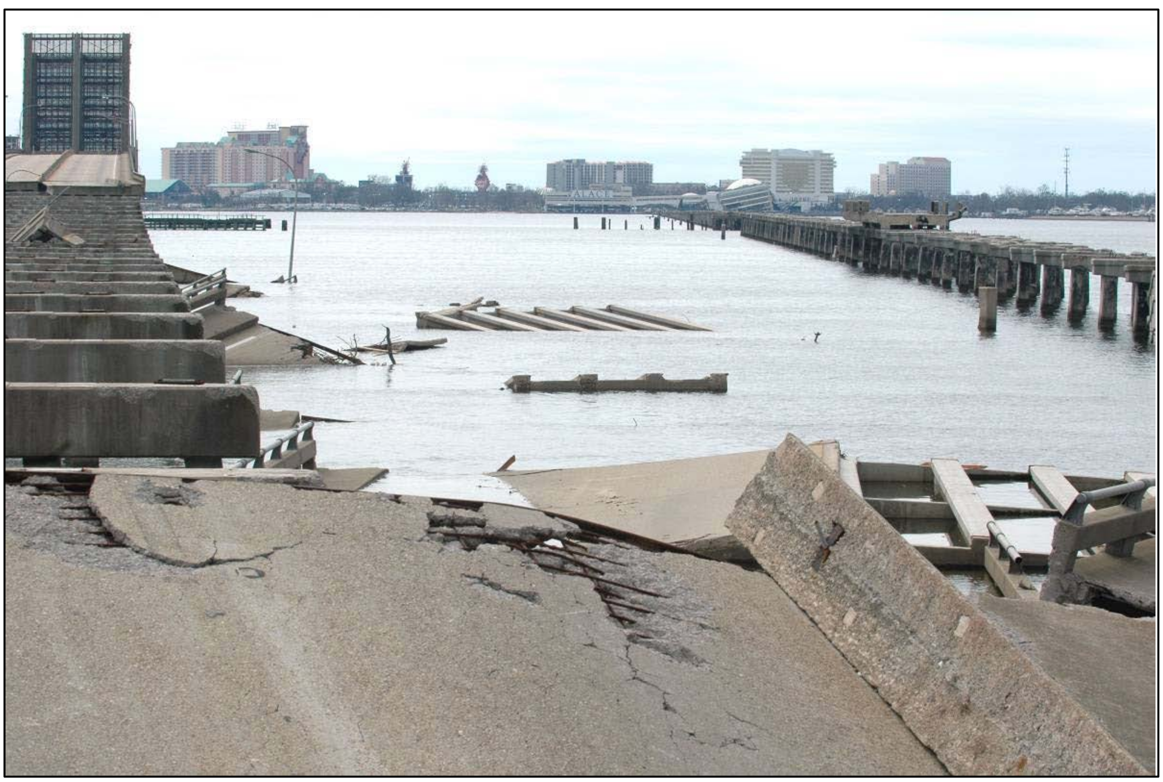

Figure 3.7. Two bridges destroyed by wave loads in Hurricane Katrina.

Figure 3.7 shows two bridges destroyed by wave loads in Hurricane Katrina. The bridge on the left (US 90) was a wider replacement for the bridge on the right (which was used for fishing only for years prior to Katrina). The newer bridge was built at about the same elevation as the older bridge even though the older bridge had been severely damaged in Hurricane Camille in 1969. Bridge deck sections removed from the sub-structure by waves are visible in the shallow water in the center of the photograph. The newer bridge was not elevated higher than the older bridge even though the older bridge had been damaged by storm surge and waves in Hurricane Camille in 1969. Possible implications of this sequence of events are that 1) design standards must be adapted as we learn more about exposure and vulnerability along the coast, 2) a correlation between critical surge/wave height and vulnerability may exist (note the undamaged spans at higher elevations on the left bridge), and 3) sea level rise will complicate that correlation.

Sensitivity to this damage mechanism depends primarily on the wave heights which can strike the structure during the peak of the storm and the relative elevation of the storm surge as compared to the bridge elevation. Most bridge decks can survive wave-induced loads if just the crests of the largest wave heights are striking the bridge deck. Most damage occurs when the storm surge (still water level) elevation is at or slightly above that of the low chord of the bridge deck. At this condition, the full waves can strike the rigid structures and the loads can be extremely high with each individual wave. Laboratory experiments have found the wave loads to be as much as 3 times the dead weight of bridge decks when the storm surge (still water level) is very near or just above the bridge deck elevation (Douglass *et al*. 2007).

The sensitivity of bridge decks to extreme events and climate change can be evaluated by estimating the effect of storm surge, wave heights and sea level rise on the wave loads. Sensitivity of specific bridges to wave-induced loads can be evaluated using available methods for estimating those loads (e.g. HEC-25 Appendix E, A Method for Estimating Wave Forces on Bridge Decks or AASHTO 2008) and comparing those loads with the structural resistance (weight and connections) to those loads. Sea level rise related to climate change will increase the vulnerability of many existing coastal bridges and more research is needed into the methods for estimating and reducing wave-induced loads for vulnerability assessment and adaptation planning. Wave loads on bridge decks are extremely sensitive to the storm surge elevation and thus extremely sensitive to sea level rise.

3.3.5 Structure Damage by Wave Runup

Wave runup causes high velocity flows in individual waves to flow above the storm surge still water elevation where it can cause structural damage and scour. Wave runup is the uprush of a wave's water up a slope or structure. HEC-25 Section 6.4, Practical Issues for Coastal Revetment Design, provides some guidance on estimating the extent of wave runup on structures. More such guidance, including guidance on estimating wave runup on beaches can be found in USACE (2002) and FEMA (2005). ASCE (2010), FEMA (2011), and USACE (2002) provide guidance for estimating loads on structures in the coastal flood plain. These loads include breaking and broken wave-induced loads, hydrostatic and buoyancy loads, and flow-induced hydrodynamic loads. Much of the load guidance is a function of local depth and/or local, depth-limited, wave height.

The sensitivity of damage caused by wave runup mechanisms to extreme events and climate change can be evaluated by estimating the effects of storm surge, wave effect of storm surge, wave heights and sea level rise on the loads and the extent of runup. In particular, the damage caused by wave runup will increase as sea levels rise and storm surge increases.

3.3.6 Tunnel and Road Damage by Overtopping

Hurricane Sandy flooded some highway and transit tunnels when the storm surge elevation exceeded the elevation of the tunnel entrances, or portals. The basic damage mechanism of overtopping is inundation resulting from flow over the portal walls and down entrances. Tools to estimate the hydraulics of such flows are available in hydraulic engineering textbooks. There are several specific damage mechanisms related to such flooding including damage to electrical systems, ventilation systems, and blockage of the tunnel itself. The sensitivity of a specific tunnel to this damage is related to the storm characteristics and the tunnel portal design. Of critical importance are the elevations of the storm surge and the portal walls. A form of a detention pond analysis can be used to evaluate the internal level of flooding in a tunnel for specific storms. Often a small amount of flood water will not damage tunnels as they are designed for some stormwater drippage off vehicles and cleaning.

A related issue for some tunnels and many coastal highways is flooding due to wave overtopping. **Wave overtopping** is water splashing over a seawall when runup exceeds the elevation of the top of the wall. Wave overtopping onto coastal roads is fairly common during storms in many parts of the country. Two aspects of overtopping of interest to the design engineer are the time-averaged volumetric rate of overtopping and the intensity or force of a single wave overtopping event. Guidance on estimating wave overtopping rates can be found in Pullen *et al.* (2007). Overtopping rate is a function of freeboard (the elevation difference between the storm surge still water level and the wall crest) and wave height. It is extremely sensitive to storm surge level in extreme events and thus, will be extremely sensitive to sea level rise.

3.3.7 Damage by Tsunamis

Tsunamis damage transportation assets through extreme hydrodynamic loads, scour, and debris impact loads. The hydrodynamic forces include hydrostatic forces, buoyant forces, drag forces, surge or impact forces (Nistor *et al.* 2010). Bridges and roadways on embankments both suffer damage in tsunamis. The 2011 Japan tsunami destroyed bridges through a variety of damage mechanisms including hydrodynamic loads removing bridge decks (much like the hurricanes in the southeastern US). Some lower elevation bridge decks survived while higher elevation decks did not (Chock *et al.* 2013). Many bridge approach embankments were damaged by scour due to water flowing over the embankment (Yashinsky 2011), which appears to be very similar to the weir-flow damage mechanism common in storm surge described above.

3.4 Adaptation Strategies for Coastal Highway Infrastructure

This section discusses possible adaptation strategies for coastal transportation infrastructure to extreme events and sea level rise. Adaptation is preparing for the impacts of extreme events and climate change on the nation’s transportation infrastructure and systems. Specifically, it refers to planning, designing, constructing, operating, or maintaining transportation infrastructure while incorporating consideration of extreme events and climate change. This may include providing protective countermeasures intended to prevent, delay or reduce the severity of problems related to extreme events and climate change.

The best coastal highway infrastructure adaptation strategies for coping with extreme events and future climate change are most likely forms of coastal engineering and planning already utilized today. Because society has long lived along the coast, coastal engineering is an ancient field. However, the challenges facing today’s engineers and planners may be among the greatest ever because of the on-going migration of society to coastal areas while sea levels are projected to rise to elevations unprecedented in modern times (see Section 2.3.1 – Sea Levels).

Adaptation strategies to respond to coastal infrastructure problems related to extreme events and sea level rise may be categorized as follows:

- Manage and maintain
- Increase redundancy
- Protect
- Accommodate
- Relocate

Combinations of these strategies may also be employed. The next five sub-sections discuss these types of strategies and provide examples of each.

3.4.1 Manage and Maintain

One category of adaptation strategies is to **maintain** existing infrastructure for optimal performance and **manage** the response to extreme events through advanced preparation. Examples include:

- Increase and target maintenance activities (e.g. culvert cleaning)
- Relocate movable assets prior to forecast storm events (e.g. moving maintenance vehicles and equipment to less vulnerable areas)
- Enhance and practice emergency procedures
- Stockpile and strategically place fuel, temporary bridges, and road construction materials for quick deployment

Many coastal DOT's already use these, and other, forms of specialized management and maintenance to prepare for - and in response to - coastal storms. These procedures have been developed internally to maintain and restore service in response to coastal storms and flooding.

3.4.2 Increase Redundancy

Another category of adaptation strategies is to **increase the redundancy** of the system. This means ensuring that transportation services provided by infrastructure can be supplied by other means/alternatives. Examples include:

- Identify and enhance, as appropriate, alternative roads, routes, or modes to serve transportation needs during times of compromised service (e.g. enhanced ferry service)
- Consider constructing or enhancing closely spaced roads perpendicular to the coastline versus one roadway parallel to coastline

Coastal transportation organizations typically address the redundancy issues such as ferries in planning-level activities in the wake of or in preparation for storm events.

3.4.3 Protect

A common category of adaptation strategies is to **protect** the existing system. The goal is to reduce or eliminate damage by providing protective physical barriers to climate stressors and extreme events. This may include "hard" structures such as seawalls or revetments and "soft" strategies such as beach nourishment and vegetation plantings. Protective strategies keep water away from infrastructure or provide resistance to the damaging forces of water and waves. Examples include:

- New or enlarged seawalls, bulkheads, revetments, etc. (hard structures to provide barriers or resistance to damaging forces)
- Beach nourishment (soft strategy to move water away from infrastructure)
- Dune restoration and vegetation (soft strategies to provide barriers and resistance to damaging forces)
- Living shorelines along sheltered coasts (combination of hard and soft structures/strategies to increase resistance to damaging forces)

"Hard" engineering structures have been used to protect many coastal transportation assets. These include **seawalls, bulkheads, revetments**, breakwaters, groins, and jetties. These structures protect many miles of coastal roadways and railways today. HEC-25 Section 7.6, Coastal Structures, briefly describes the functional design purpose of different types of coastal structures and HEC-25 Chapter 6, Coastal Revetments for Wave Attack, presents guidance on the structural design of coastal revetments. USACE (2002) presents more guidance on the design of seawalls and revetments. The most common successful type of coastal revetment for wave attack is a rubble-mound structure consisting of an engineered slope or pile of rocks (or other armor units). Because the rocks can move, there is an inherent flexibility in these structures as compared with completely rigid structures. As sea level rises, it can be expected that these solutions will be considered in more situations to protect assets that are not now threatened. Also, existing seawall and revetment structures will have to be modified to withstand higher wave conditions as sea level rises. This may include increasing their height and include placement of new layers of rock to strengthen existing seawalls as well as construction of new seawalls (Ewing 2010).

"Soft" engineering includes beach nourishment and dune restoration. The general goal is to use engineering that more closely mimics the natural system of beaches and dunes. **Beach nourishment** is the direct placement of large amounts of sand on the beach to widen the beach (see HEC-25 Section 7.6.1, Beach Nourishment). Beach nourishment is a commonly used adaptation to sea level rise and has been successful used to stabilize recessional shorelines in many places in the country (NRC 1995, Douglass 2002). Beach nourishment with sand dune restoration also reduces damage to landward built infrastructure. For example, beach communities in New Jersey with nourishment and constructed sand dunes suffered significantly less damage in Hurricane Sandy than other nearby communities (Houston and Dean 2013). Beach nourishment and dune restoration is being used extensively along the New Jersey and New York shore in response to Hurricane Sandy to support the long-term sustainability of the coastal ecosystem and communities as well as to reduce the economic costs and risks associated with future storm events (US Congress 2013).

Modern coastal engineering shoreline stabilization solutions often combine beach nourishment with coastal structures. These solutions are "hybrid" solutions using components of the "soft" and "hard" approach. The primary purpose of the structure is to retain the sand. Some of these "hybrid" solutions emulate natural geomorphology features such as pocket beaches between headlands where the sand nourishment is placed between constructed headland breakwaters (see HEC-25 Section 7.6.2, Combining Beach Nourishment with Structures).

The term "soft engineering" can also include "green" infrastructure engineering such as wetland creation and living shorelines. Living shorelines are combinations of structure, vegetation, and sand (in some cases) to stabilize the shoreline and provide nearshore habitat to allow native species of flora and fauna to flourish. They are alternatives to traditional bulkhead or revetment structures along sheltered bay and river shorelines. More research is needed on the engineering of these green coastal infrastructure approaches to better survive extreme events and climate change.

3.4.4 Accommodate

Another category of adaptation strategies is to **accommodate**. The infrastructure is modified or redesigned to better coexist in a climate-stressed environment. Examples include:

- Increasing bridge deck elevations and strengthen bridge structures,
- Lowering roadway profiles to allow overwash without pavement damage during extreme events
- Raising tunnel portal walls to reduce likelihood of flooding

Careful assessment of the vulnerability of the infrastructure to extreme events and climate change is required to develop cost-effective accommodation strategies. An understanding of magnitudes, probabilities, and uncertainties of projected climate stressors such as sea level rise and extreme events is particularly important when considering this strategy for the long-term extension of the design life of infrastructure assets. Accommodation strategies may also be used for short or medium term design horizons.

Increased elevation is an adaptation option for coastal bridges subject to wave attack during extreme events. Several of the major bridges destroyed by hurricanes in the southeastern US were replaced with new bridges elevated much higher to avoid those wave loads in extreme events. These included:

- I-10 bridge over Escambia Bay near Pensacola, FL
- I-10 bridge over Lake Pontchartrain near Slidell, LA
- US-90 bridge over Bay Saint Louis, MS
- US-90 bridge over Biloxi Bay, MS

Another option is to increase the connection strength to the bridge substructure. This approach, however, will transfer those loads to the substructure and foundation, so care must be taken to evaluate wave-induced load failure mechanisms such as pile bending or shear failure, failure of the pile to bent cap connections, and possible soil failure around the foundation (Robertson et al. *2011*; Douglass *et al.* 2006).

Increased elevation is an adaption option for seawalls that protect roadways and tunnel entrances. Increasing the elevation of the roadway is an option for those roads that flood because of wave runup and overtopping and are already protected by seawalls or revetments. Temporary doors or storm surge barriers have been used at some tunnel portals for many years and the further development of these has been suggested as an adaptation for coastal tunnels that can flood in extreme events. More research into effective tunnel options is needed.

3.4.5 Relocate

The final category of adaptation strategies is relocation. The goal is to lessen or eliminate exposure to climate stressors by **relocating** infrastructure away from the coastline. This could be in conjunction with disinvestment, repurposing, abandoning or removing existing exposed infrastructure. Examples include:

- Relocating infrastructure further inland away from the coastline
- Repurposing or reclassifying paved road to all-terrain vehicle road

- Reconditioning a damaged vehicular bridge to serve as a pedestrian bridge or fishing pier

Relocation or abandonment has long been a common response to shoreline recession and bluff erosion. Recession and erosion are natural processes which become a problem primarily when built infrastructure is threatened. For example, storm-related bluff erosion led to a relocation of a portion of the coast-parallel California 1, the Pacific Coast Highway, in April 2013. HEC-25 Section 7.5, Relocation Considerations, includes discussion of a few other roads that have been relocated throughout the country in the past several decades. The discussion includes one section of a coast-parallel road in Texas that was abandoned after storm damage in 1989. At that location, relocation of the roadway landward away from the Gulf of Mexico was constrained by the ecological value of the coastal wetlands in a National Wildlife Refuge. Similar issues, the ecological value of natural wetland and barrier island habitat, have led to consideration of relocating up to 12 miles of NC 12 from that barrier island onto a bridge in the bay (FHWA 2010). Portions of roadways have already been relocated in response to storm damage as shown in Figure 3.8 and Figure 3.9. At some locations, relocation is constrained by private property.

Figure 3.8. Relocation example in North Carolina (NC 12).

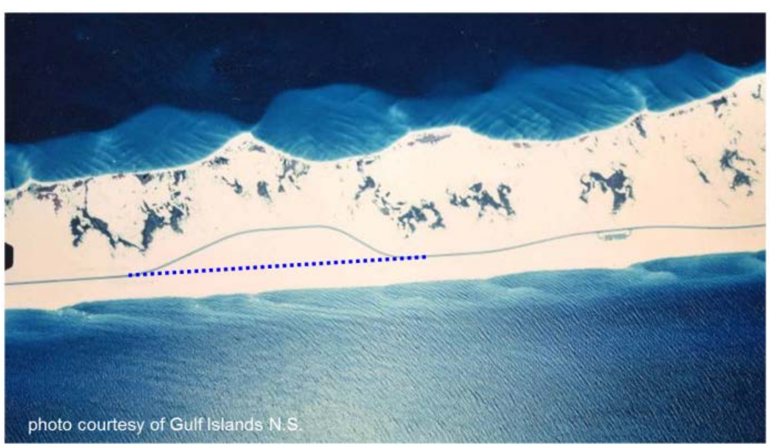

Figure 3.9. Relocation example in Florida (FL 399).

USACE (2014) presents that agency's guidance concerning adaptation strategies for incorporating sea level change in the planning of the Corps' coastal works. It addresses a number of concerns that transportation organizations face with coastal infrastructure including discussions about appropriate time horizons and ranges of scenarios for planning.

All of the adaptation options discussed above (manage and maintain, increase redundancy, protect, accommodate, and relocate), including **combinations** thereof, should be considered for transportation assets vulnerable to extreme events and climate change. For example, some combination of relocation, accommodation (lowering of roadway), and protection (dune construction and a buried revetment on the embankment) have been proposed and constructed for some coast parallel roads that have been damaged by frequent overwashing such as shown in Figures 3.8 and 3.9 (FHWA 2008). This approach is a reasonable adaptation to climate change in these situations. These types of decisions have been made throughout history along the coast in both real-world applications and theoretical analyses. It is likely that they will have to be made more often by the transportation engineering community as sea levels rise in the next several decades.

Chapter 4 – Analysis Methods for Assessing Extreme Events and Climate Change

This chapter presents guidance on specific methodologies for assessing exposure of coastal transportation infrastructure to extreme events and climate change. Varying levels of effort are broadly described in Section 4.1, General Framework, and specific guidance is provided in the subsequent regional sections of this chapter, Section 4.2 to Section 4.6. The availability and location of existing products, data, tools, and methodologies that could be considered at each level are discussed. Examples of specific information include where to find and how to use flood hazard maps, the selection of an appropriate hydrodynamic model(s) to simulate the regional coastal processes of interest, and some references to existing methodologies for estimating sensitivity to water levels, waves, currents, and erosion.

4.1 General Framework

Vulnerability assessments may range from broad planning overviews to highly detailed investigations employing state-of-the-art modeling tools. In addition to considering the type of assets that may be affected by extreme events and climate change, investigators have varying levels of budget and available expertise that may also define the scope of an investigation. Therefore, it is appropriate that this guidance present techniques for different “levels of effort” for the assessments. This section provides a broad overview of the proposed levels of effort for performing a vulnerability assessment of coastal transportation infrastructure to extreme coastal events and climate change. The amount of detail and degree of complexity grow with each subsequent level of effort, as does the quality of the assessment. The degree of uncertainty in the results, however, decreases with each subsequent level of effort. The suggested levels of effort are broadly:

- **Level of Effort 1: Use of Existing Data and Resources -** Use of existing inundation (FEMA) or tsunami hazard maps to determine the exposure of infrastructure under selected sea (lake) level change scenarios, and sensitivity to depth-limited wave or wave runup processes.
- **Level of Effort 2: Original Modeling of Storm Surge and Waves -** Modeling of surge and wave fields for specified storm and climate change scenarios, or modeling of tsunami inundation under climate change scenarios.
- **Level of Effort 3: Modeling in a Probabilistic Risk Framework -** Modeling of surge, sea levels, currents, and waves, or tsunamis, including the impacts of climate change, in a probabilistic risk framework.

4.1.1 Level of Effort 1: Use of Existing Data and Resources

The purpose of the “Level 1” approach is to provide some meaningful information about the level and coverage of exposure to damaging storm parameters without having to perform complex modeling or calculations. This lowest level of effort is simpler to perform and relies on the use of established maps and tools to determine the degree to which a particular asset or area is exposed to the effects of extreme events and climate change.

Since the Level 1 approach is relatively simple, a number of climate change scenarios, specifically sea level rise scenarios, can be considered. Accordingly, the goal of a Level 1 study might be to capture the sensitivity of a particular asset or area to the effects of sea level rise instead of predicting an accurate value of flooding depth or wave height, etc. In this manner the Level 1 approach can be used as a screening tool to identify those areas or infrastructure assets that are exposed to the effects of sea level rise. These specific areas can be evaluated in more detail through additional refinements of a Level 1 approach or by including them in assessments with higher levels of effort.

The degree of uncertainty in results obtained in a Level of Effort 1 assessment will be relatively high. The results will include all of the assumptions and uncertainties inherent in existing inundation or flood hazard maps (or other existing tools used). The most commonly available, existing data are typically the FEMA flood insurance rate maps (FIRMs) and the corresponding Flood Insurance Studies (FIS). Those studies focus on quantifying the rare flood events including the 100-year flood and 500-year flood levels. In some cases, other agency flood maps and studies may be available.

An example of a Level 1 study is highlighted in Section 5.2, Case Study: Adapting to Rising Tides - San Francisco Bay. That case study developed inundation maps for one county for planning purposes. Two sea level rise scenarios (16 inches and 55 inches) were evaluated. The primary process of interest was flood depths, but some limited evaluation of waves was included.

4.1.2 Level of Effort 2: Modeling of Storm Surge and Waves

The purpose of the “Level 2” approach is to provide detailed information about exposure under extreme events with climate change. In such a study, one or more climate change scenarios can be explicitly incorporated into model simulations so their effects on the critical coastal processes can be determined. Performing a Level 2 study requires the use of sophisticated hydrodynamic models that simulate storm surge and waves, or tsunamis. The development and application of these models, as well as interpretation of their results, should generally be performed by a trained coastal engineer with expertise in hydrodynamic modeling.

A requirement of the Level 2 study is to thoughtfully select and model extreme events of interest. These could be events of record for a region (e.g. a specific hurricane), a storm that had a notable impact on a specific piece of infrastructure (e.g. bridge failure), or perhaps even an event that has not yet occurred (e.g. hurricane with a shifted track, tsunami, etc.). In this manner, a goal of the Level 2 study could be to demonstrate the degree to which climate change will modify the exposure of an asset or area relative to a present-day (baseline) scenario. The results of a Level 2 study will generally not be probabilistic in nature. However, it may be possible to assign a return period to a scenario if an historic storm or event (i.e. one that has previously occurred) is selected for analysis. It may be helpful to consider a range of possible event and climate change scenarios that span from more frequent, lower-intensity events to infrequent, higher-intensity events. Practically, the Level 2 study may be limited to modeling less than, say two dozen, extreme event and climate scenarios.

While each Level 2 study will be unique, there is an underlying methodology that will be common to all studies. Every Level 2 study should include:

- selection of extreme event and climate change scenarios appropriate for the region;
- development of suitable hydrodynamic modeling tools;
- validation of the hydrodynamic model(s) using hindcast simulations and observations; simulation of the extreme event and climate change scenarios; mapping of the hazards (e.g., inundation, waves, wave runup); and
- assessments of exposure under each scenario.

While a Level 1 study uses inundation or flood hazard maps developed by others, new maps will be developed for each specific storm (or tsunami) and climate change scenario evaluated as part of a Level 2 study. Such mapping constitutes a significant amount of work and serves purposes beyond the exposure assessment, like communication and public outreach. Therefore, it is crucial that great care is taken in the preparation of these maps and that they are readily understood by lay persons.

The time and effort required to complete a Level 2 study is significantly greater than a Level 1 study. Accordingly, the cost of a Level 2 study is likely to be much higher than a Level 1 study. But with an increase in time, effort, and cost comes a significant reduction in uncertainty and a more narrow range of possible answers. The reduction in uncertainty is mostly attributed to use of the hydrodynamic models, which provide specific estimates of the critical regional coastal processes of interest, like water levels, wave heights and periods, velocities, etc. Note that the quality and utility of these estimates is not that they are necessarily “larger” values than those obtained in the Level 1 study, but rather that they are more accurate.

An example of a Level 2 assessment is highlighted in Section 5.2, Case Study: The Gulf Coast 2 Study – Mobile, Alabama. That study used original, high-resolution modeling to map storm surge and waves in extreme events for a variety of sea level rise and other climate change scenarios.

4.1.3 Level of Effort 3: Modeling in a Probabilistic Risk Framework

A “Level 3” study characterizes exposure in terms of probability and risk. While the general methodology is similar to that of a Level 2 study, each extreme event and climate change scenario is assigned a unique probability. The Level 3 study requires many more simulations in order to determine the probability of events. Whereas the Level 2 study is based on perhaps tens of unique event scenarios, this type of study may require on the order of one hundred simulations. This probabilistic approach is essentially the same as that currently used by FEMA for developing modern flood hazard maps (FEMA 2003) except here climate change scenarios must also be incorporated into the modeling.

The Level 3 study requires a significant investment. It takes longer to complete and has a higher cost than the Level 1 and Level 2 assessments. However, this highest level of effort also provides the greatest reduction in uncertainty and is the only one that explicitly accounts for probability in an objective manner. The number of simulations required in this analysis also allows for a range of return period events to be considered and the results may be applicable over a much larger area. For instance, a Level 2 study might consider storm events that lead to failure or damage of a specific asset, like a bridge. These results are valuable but only near that bridge. The event probabilities derived from a Level 3 assessment may be applicable to more than one area when multiple storm tracks or tsunami events are modeled.

A Level 3 study requires expertise in coastal engineering, numerical modeling, hazard analysis, probability and risk. Accordingly, such studies should be performed by accomplished engineers with demonstrated expertise in modeling extreme events as well as an understanding of the appropriate regional climate change scenarios.

An example of the Level 3 approach is highlighted in Section 5.3, Case Study: Synthetic Storm Analysis on the Florida Coast. That case study used high-resolution storm surge modeling to develop inundation maps for the 500-year flood with increased sea levels.

4.2 Gulf of Mexico and South Atlantic Coast

The multi-level approach to evaluating exposure is described on a regional basis in the sections that follow. Each region of the US experiences hazards, or combinations of hazards, that make the characterization of extreme events unique. Also, relevant climate change scenarios vary by region. Many of the critical regional coastal processes, numerical modeling of those processes and the impacts of climate change on those critical processes were identified previously in Chapter 2. Some simple, quantitative tools for estimating flow velocity not discussed in Chapter 2 are presented below. Some of the tools for assessing coastal vulnerability and risk were discussed in Chapter 3 and are also discussed below.

This section outlines the levels of effort, existing tools and data, appropriate models, and methodologies for determining exposure in the Gulf of Mexico and along the South Atlantic Coast. Some of the tools outlined below are also useful in the other regions of the country. In this region of the US, tropical storms and hurricanes are the predominant extreme events, and the storm surge and waves they generate are the critical coastal processes of interest. A multi-level approach for evaluating exposure to extreme events and climate change in the Gulf of Mexico and along the South Atlantic Coast is described in the subsections that follow.

4.2.1 Level of Effort 1: Gulf of Mexico and South Atlantic Coast

The major steps for developing the information needed to perform a Level of Effort 1 exposure assessment on the Gulf of Mexico and South Atlantic Coasts are summarized in Table 4.1. The steps shown assume that the processes of interest include:

- Flood depths (Step 6),
- Wave heights (Step 7),
- Wave crest elevations (Step 8), and
- Flow velocities (Step 9).

If only flood depths are required, steps 7-9 are not required.

A Level 1 approach in this region can be based upon the use of existing FEMA inundation maps, or FIRMs, to determine the exposure of infrastructure to coastal flooding. In this region of the US, the FEMA flood hazard maps delineate the 100-year (1 percent annual chance) flood plain and in some cases the 500-year (0.2 percent annual chance) flood plain. For coastal areas, these flood plains are mostly determined by storm surge from tropical storms and hurricanes. Existing flood hazard maps, however, do not account for future changes in sea level, nor do they explicitly provide information about wave heights or flow velocities.

As described in Section 3.1.6, FEMA FIRMs describe the 1 percent annual chance still water elevation at various locations throughout the flood plain, as well as the base flood elevations (BFE) at specific locations. The BFE accounts for the elevation of wave crests that could exist in the local flooded depth. Use of the FEMA products requires an understanding of their terminology (BFE, FIRM, etc.) as well as basic coastal engineering terminology (e.g. HEC-25).

Four of the critical, extreme event, coastal exposure processes can be evaluated in a Level 1 study:

1. spatial coverage of flooding,
2. depth of flooding,
3. wave characteristics, and
4. flow velocity.

Table 4.1. Exposure assessment steps for level of effort 1: Gulf of Mexico/South Atlantic Coast.

Step	Activity
1	Obtain appropriate FEMA flood map elevations for study area
2	Choose desired sea level change scenarios
3	Modify sea level change increments to account for nonlinearity
4	Add the result of Step 3 to the elevations obtained in Step 1
5	Obtain appropriate ground surface elevation maps for study area
6	Subtract ground elevations (Step 5) from values found in Step 4 to obtain flood depth
7	Multiply flood depths (Step 6) by 0.8 to determine maximum wave height
8	Multiply wave heights (Step 7) by 0.75, add to Step 4 for wave crest elevations
9	Use Equations 4.1 and/or 4.2 to estimate flood flow velocity
10	Consider shoreline retreat and erosion based on historic trends in study area
11	Map the damaging coastal processes (results from Steps 6-9)
12	Evaluate exposure of transportation infrastructure

Only the first of these is explicitly provided by the FEMA flood hazard maps. The most current FEMA flood hazard maps can be obtained from the FEMA Map Service Center (https://msc.fema.gov) for use in Geographic Information System (GIS) software applications. These maps are now part of what FEMA refers to as the National Flood Hazard Layer (NFHL). The maps describe the spatial coverage of the flood plain(s), as well as different flood hazard zones, in a geographic reference system. The flood hazard layer can be combined with other spatially-explicit data organized into GIS layers, like transportation systems, to quickly determine whether a specific area or asset falls within the FEMA flood plain. But this methodology does not immediately reveal whether an asset like a road or bridge will be affected by flooding, flood flows, or waves. It also does not account for increased exposure due to future sea levels and other climate change impacts.

After the appropriate FEMA flood map has been obtained for a study area, the effects of climate change may be incorporated by considering appropriate regional sea level change scenarios. In this region the relevant sea level change scenario is the local relative sea level rise that accounts for both land subsidence and global eustatic sea level rise. Appropriate regional relative sea level rise rates, increments, or targeted values at specific planning horizons (e.g., 2020, 2050, 2100, etc.), should be determined for the study area.

4.2.1.1 Relative Sea Level Rise Data

Some of the more widely adopted sources for sea level rise guidance are described in Section 2.3.1 Sea Level Rise. Other sea level change information can be found in USACE (2011) and is appropriate for most coastal transportation infrastructure. This guidance is also available in the form of an online sea level change calculator - http://www.corpsclimate.us/ccaceslcurves.cfm - that accounts for local rates of subsidence and eustatic sea level rise by using NOAA tide gages near any selected study area.

4.2.1.2 Increased Flood Levels: Nonlinear SLR-Surge Relationship

The effect of sea level rise on storm surge can be nonlinear (see Section 2.3.3 Storm Surge). In other words, if the depth of flooding under present-day conditions is *A* and the sea level rise increment is *B*, the resulting future flood depth may be less than or greater than *A+B*. If desired, this nonlinearity can be accounted for by multiplying each selected relative sea level change increment considered by a constant ranging from 1 to 5. A value of 1 represents a linear coupling while a value of 5 represents a strongly nonlinear coupling (i.e. the surge increases 5 times the sea level change increment). The degree of nonlinearity is likely both site and scenario specific, as described in Smith *et al.* (2010) who found only isolated cases of surge increasing 5 times the sea level rise increment. Instead Smith *et al*. (2010) found widespread areas where the surge increased 1 to 2 times the sea level rise increment. Therefore, an appropriate singular value to apply over an entire study area might be 1.5. There is currently very little guidance available about this nonlinearity and all of the existing published documentation comes from studies in the Gulf of Mexico. This is an area of research that needs more attention. Selection of a larger value could be justified to provide a more conservative estimate. This uncertainty is one of the limitations of a Level 1 approach.

After multiplying the selected sea level change increments by an appropriate nonlinear constant, the resulting values should be added to the still water elevations shown on the FEMA flood map for each climate change scenario considered. Recall that FEMA flood maps provide the elevation of the still water (i.e. waves removed) relative to a fixed vertical datum, like the North American Vertical Datum (NAVD). It is important to note that these values are elevations, not flood depths.

4.2.1.3 Coastal Land Elevation Data

In order to determine flood or total depths within the study area under the selected climate change scenarios, the local ground surface elevations must be known and subtracted from the modified still water elevations. Appropriate sources of information include USGS topographic maps for ground surface elevations (http://topomaps.usgs.gov/) and NOAA nautical charts for bathymetric elevations (http://www.nauticalcharts.noaa.gov/). Such maps, however, may not always provide the needed resolution to determine elevations near a specific asset. Many coastal areas of the US have been mapped using high-resolution light detection and ranging (LiDAR) systems that provide ground surface elevation values spaced a few feet apart. A good source for LiDAR and other coastal elevation data is the NOAA Coastal Services Center Digital Coast web data portal (http://www.csc.noaa.gov/digitalcoast/). Other excellent sources of combined topographic and bathymetric elevation data sets, commonly available as GIS layers, include the NOAA National Geophysical Data Center's Coastal Relief Models (http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html) and the USGS National Map Viewer (http://viewer.nationalmap.gov/viewer/).

4.2.1.4 Wave Characteristics

Wave characteristics and flow velocities can be determined as part of the exposure assessment once the spatial coverage and depth of inundation are estimated. In a Level 1 approach, waves can be assumed to be depth-limited and will break when their height is approximately 80 percent of the water depth. Thus, the wave height at each location can be conservatively assumed to the 80 percent of the local water depth. Depth-limited waves and wave characteristics are described in HEC-25 Chapter 4, Waves.

Also, the elevations of the wave crests under depth-limited conditions can be approximated by adding 75 percent of the maximum wave height to the still water elevation flood level. See Chapter 9, Coastal Bridges, in HEC-25 for more information about estimating wave crest elevations. This is essentially the same computation that FEMA uses to determine the base flood elevation (BFE) shown on many coastal flood maps.

4.2.1.5 Storm Surge Flow Velocity Estimates

The estimation of flood flow velocity magnitude and direction during a storm event is difficult. Conservatism and professional judgment should be applied when estimating and applying these values as part of a hazard analysis. General guidance on the estimation of flood flow velocity as a function of flood depth is provided in ASCE (2010). A recommended lower bound on the velocity is equivalent to the flood depth divided by one second:

$$V_{low} = d_S / (1\ \text{second}) \tag{4.1}$$

where:

d_s = design flood depth

For example, if the design flood depth is 5 ft, a low estimate of the velocity magnitude is 5 ft/s. A recommended upper bound on the velocity is given as the square root of the product of the gravitational constant and the flood depth:

$$V_{high} = \sqrt{g d_S} \tag{4.2}$$

where:

g = gravitational constant having a value of 32.2 ft/s^2 (9.81 m/s^2)

This equation is the same as that used to estimate the shallow-water wave celerity as described in HEC-25 Chapter 4, Waves. Using the same example as before, an upper estimate for the magnitude of flow velocity using a design flood depth of 5 ft is nearly 13 ft/s, more than twice the lower estimate.

4.2.1.6 Other Considerations in Level 1 Studies

The spatial coverage and depth of inundation, wave heights, wave crest elevations, and flow velocity for extreme events with selected climate change scenarios can be mapped and used for exposure assessments. This information can be used to determine if an area or asset falls within the modified 100-year flood plain, but it can also be used to determine the sensitivity of transportation infrastructure to waves and flow velocity. Some common types of damage are described in Section 3.3, Climate Change and Extreme Events: Damage Mechanisms, of this manual. The reader is directed to additional reference materials like HEC-25 and ASCE (2010) for more information about estimating hydrodynamic loads, wave loads on structures, scour, and other relevant coastal processes that lead to damage. Additional guidance for mapping hazards in sheltered waters, like coastal embayments, is available in FEMA (2008).

One specific limitation of this Level 1 approach is the inability to account for short- or long-term shoreline change. This may be a particularly important process to consider for highways near receding shorelines. The reader is encouraged to consider future shoreline positions that result from retreat and erosion in their exposure assessment. Additional information about where to obtain and how to use shoreline change data is provided in Chapter 7, Roads in Areas of Receding Shorelines, HEC-25.

4.2.2 Level of Effort 2: Gulf of Mexico and South Atlantic Coast

A Level 2 study requires some original modeling of storm surge and waves (and perhaps other processes) for selected extreme storm events under specific climate change scenarios. Climate change scenarios should include sea level changes and may include storm intensification through increased central pressure deficit and maximum winds. The fundamental steps in a Level 2 analysis for the Gulf of Mexico and South Atlantic coast are summarized in Table 4.2.

In the Gulf of Mexico and along the South Atlantic coast, storm surge and waves generated by tropical storms and hurricanes are the primary concerns. Episodic, storm-induced shoreline change may also be of concern for highways near receding shorelines, causeway islands, bridge approaches, etc. While the tide range in the Gulf of Mexico is generally small (less than 2 ft), it does grow larger moving north along the South Atlantic coast and should be considered in exposure assessments. This is especially true for low-lying areas that are particularly sensitive to the effects of sea level rise on tidal inundation (see Hagen and Bacopoulos 2012). Also, the contributions of coastal watersheds through increased stream flows may play an important role in the increase in local water levels, especially in areas distant from the coastline. Finally, the combination of the wind-driven storm surge, tidal stage, and river stage are of concern when they occur simultaneously.

Table 4.2. Exposure assessment steps for level of effort 2: Gulf of Mexico/South Atlantic Coast.

Step	Activity
1	Identify damaging coastal processes of interest (e.g. storm surge, waves, etc.)
2	Select and characterize storm and climate change scenarios of interest
3	Select, develop, and prepare appropriate numerical modeling tools
4	Validate and/or calibrate the models through hindcast simulations and analyses
5	Incorporate climate change scenarios into numerical model simulations
6	Perform model simulations of selected storm and climate change scenarios
7	Map the damaging coastal processes for each scenario
8	Evaluate exposure and sensitivity of transportation infrastructure for each scenario

4.2.2.1 Storm Selection and Characterization

A range of storm levels can be considered in a Level 2 study. The selection and characterization of storm events for a Level 2 study should not be based solely on the worst case scenario. Since risk is not a product of this approach it is important to consider the exposure and sensitivity of infrastructure to a wide range of storm and climate scenarios. The scenarios may include the frequent but low-intensity tropical storms, as well as infrequent but high-intensity hurricanes, that have previously impacted the study area. Other storms having properties that fall somewhere between these limits may also be considered, especially if they produced notable impacts to an area or piece of infrastructure in the past. This is the approach that was applied to the selection of storm events for the Gulf Coast 2 study described in Section 5.1 of this manual.

Some numerical models, like ADCIRC, require only basic storm parameters to develop meteorological forcing for the model. The time and geographic position of the storm, its central pressure, maximum winds, and radius to maximum winds generally constitute the minimum required information to model the storm. Some models also allow the user to characterize the asymmetry of a storm by defining winds in each of its four quadrants. Historic storm characteristics and information can be obtained from the NOAA National Hurricane Center (NHC) data archive (http://www.nhc.noaa.gov/data/). The NHC Best Track data archive provides general storm characteristics in six-hour increments for the duration of the storm event. Detailed storm characteristics are found in the archived NOAA NHC storm forecast and observation reports.

Synthetic storms, storms based on historic storms but with some possible differences, can be evaluated directly in a Level 2 modeling study. In particular, shifting the track of a storm is a common exercise in model studies because of the sensitivity of coastal storm surge to storm track. Other parameters which can be modified are storm movement speed, wind strength, etc., but care should be taken to alter only the characteristics of interest without affecting those that should remain constant. For example, shifting the track and landfall location of Hurricane Katrina for the Gulf Coast 2 study (Choate *et al*. 2012) required simultaneously preserving the storm's forward speed and decay characteristics.

4.2.2.2 Climate Change Scenarios

In this region, appropriate climate change scenarios that lead to considerable changes in the damaging coastal processes include relative sea level rise and storm intensification. While there is some variability in the global eustatic sea level rise rates in this region, the local rates of subsidence can be very different. Care should be taken when developing relative sea level rise scenarios for your study area. As in the Level 1 study, the USACE (2010) guidance on sea level change and their web-based tool can be used here to determine appropriate rates of relative sea level rise, or specific sea level targets at selected planning horizons, for the study area (http://www.corpsclimate.us/ccaceslcurves.cfm).

The selected sea level rise scenarios should be incorporated into the numerical model before the simulation is performed. Doing so provides the deterministic results required to capture the nonlinear effects of sea level rise on storm surge and waves. Incorporating relative sea level rise into hydrodynamic models can be achieved in two possible ways: first, the sea level position can be increased relative to its present-day elevation or; second, the ground surface elevations can be reduced relative to their present-day positions. If the model provides an option for the user to prescribe a sea level offset, this will generally be the simpler and preferred method for incorporating sea level change as it does not require one to modify the computational grid or mesh.

There are associated effects of increasing sea level in a model simulation that can be considered. Many hydrodynamic models require the user to prescribe frictional constants throughout the computational domain. Frictional constants for dry land are typically based on land use and land cover data and represent the "roughness" of coastal landscapes. As new, low-lying areas are inundated by each sea level rise scenario, their frictional resistance should be lowered to be consistent with values of the surrounding water body (Smith *et al.* 2010). It may also be appropriate to consider and incorporate other major changes to the newly-inundated landscape. Examples include the abandonment and/or removal of major infrastructure; the recession and erosion of barrier islands; and the incorporation of new coastal engineering defenses like sea walls, dikes, levees, and beach fill projects.

The expected impacts of climate change on storm frequency and intensity are briefly described in Chapter 2, Section 2.3.3 of this manual. While the intensification of storms due to climate change is still an area of ongoing research, limited guidance is available in Knutson and Tuleya (2004), Knutson *et al.* (2007), Knutson *et al.* (2010), and other documents. For example, Knutson *et al.* (2010) state that tropical storms and hurricanes will grow in intensity by +2 percent to +11 percent by the year 2100. This roughly corresponds to a +3 percent to +21 percent central pressure fall. This information can be used to alter storm characteristics like wind speed and central pressure in order to simulate the effects of climate change on storm intensity. This is described more fully in this manual in the Gulf Coast 2 case study in Section 5.1.3.

4.2.2.3 Surge and Wave Models

One or more numerical models will be required to perform a Level 2 study. Few models are capable of simulating storm surge, waves, and shoreline change in a fully-integrated package. The selection of appropriate modeling tools is somewhat dependent upon the regional coastal processes of interest, the type of extreme event being considered, and the spatial coverage of the region to be modeled. The common storm surge models are briefly described in Section 2.4.1 Storm Surge Models, of this manual. In the Gulf and South Atlantic region of the US, FEMA modeling contractors typically use the ADCIRC model to simulate storm surge from tropical storms and hurricanes because of its proven ability to model surge characteristics in a variety of complex situations. The case study described in Section 5.1 used the ADCIRC model to estimate storm surge.

There are a number of numerical models for simulating wave characteristics that may be used in a Level 2 study. See Section 2.4.2 Wave Models, for a discussion of the merits of some of the available wave models. The case study described in Section 5.1 used the STWAVE model to estimate wave height fields throughout the flooded areas. Any appropriate shallow water wave model can be used for Level 2 studies.

4.2.2.4 Mapping of Results

After the selected numerical models have been validated, the storm and climate change scenarios are modeled and the outputs saved for analysis. These model results constitute a major source of information needed to assess exposure and evaluate sensitivity. Pertinent model results, like maximum storm surge elevation (or depth), wave height and direction, or overland flow velocity, can be mapped in GIS software for use with other relevant spatial layers, like transportation systems, demographics, etc. Appropriate examples are found in Choate *et al.* (2012) and USDOT (2013). These results can be presented at discrete times throughout the duration of the model simulation, or simply as the maximum values of each quantity. Examples of each include the time history of wave characteristics at a particular location, and the maximum envelope of water (MEOW), respectively.

A unique mapping of the damaging coastal processes will be required for each storm and climate change scenario considered. The effects of climate change on these processes, and the subsequent exposure to them, can be evaluated through direct comparisons to the historic, or model hindcast, results. Furthermore, the degree to which various climate scenarios modify the degree of exposure can be determined through direct comparisons between them.

Maps of the damaging coastal processes can be used to assess exposure in different ways. For example, maps of storm surge can be used to determine the spatial coverage and extent of inundation within the study area; maps of wave characteristics can be used to determine if, and to what degree, a particular asset will experience wave forces and overtopping; and maps of velocity can be used to determine hydrodynamic loads, scour, and erosion of embankments. Accordingly, these data and maps may also be used to evaluate sensitivity when appropriate guidance is followed (e.g. USACE 2002, FHWA 2008, and ASCE 2010).

Caution should be exercised in the development of maps based on hydrodynamic model results, particularly those used to reference elevations. Hydrodynamic model results, like water levels, are commonly referenced to a vertical tidal datum (e.g. mean sea level). However, ground surface elevations and GIS layers containing transportation infrastructure are generally referenced to a vertical survey datum like NAVD. The difference between elevations referenced to either datum may be significant and must be accounted for prior to the mapping exercise. Model results referenced to a vertical tidal datum can be transformed to almost any vertical survey datum using NOAA's free software program VDATUM (http://vdatum.noaa.gov/). More information about tidal and survey datums is found in HEC-25 Section 3.1.2, Tidal and Survey Datums.

4.2.3 Level of Effort 3: Gulf of Mexico and South Atlantic Coast

The process of conducting a Level 3 study is almost identical to that of a Level 2 study. This type of assessment requires identification of the damaging processes; selection of storm and climate change scenarios; numerical modeling of the selected scenarios; and assessment of exposure, and perhaps sensitivity, based on model outputs. However, the fundamental difference between the Level 2 and Level 3 approaches is the ability to assign probability and risk to scenario outcomes (see Section 3.1.2 Coastal Storm Flood Frequencies). A Level 3 study will consider hundreds of unique storm and climate change scenarios, each having their own assigned probability of occurrence, as compared to the one or two historic storms used in a Level 2 study. As a result, the level of effort, difficulty, cost, and duration of study are all likely to be higher for a Level 3 study.

The major steps for developing the information needed to perform a Level of Effort 3 exposure assessment for the Gulf of Mexico and Atlantic Coasts are summarized in Table 4.3. The suggested methodology of a Level 3 study is very similar to the process used by FEMA to develop coastal flood hazard maps, or FIRMs and similar to the procedures used by the USACE in plan formulation of large coastal projects. Specific guidance and details about how the FEMA studies are conducted are available in FEMA (2003).

Table 4.3. Exposure assessment steps for level of effort 3: Gulf of Mexico/South Atlantic Coast.

Step	Activity
1	Identify damaging coastal processes of interest (e.g. storm surge, waves, etc.)
2	Select and characterize storm and climate change scenarios of interest
3	Select, develop, and prepare appropriate numerical modeling tools
4	Validate and/or calibrate the models through hindcast simulations and analysis
5	Incorporate climate change scenarios into numerical model simulations
6	Perform model simulations of selected storm and climate change scenarios
7	Derive probabilities associated with water levels, wave heights, velocity, etc.
8	Map the damaging coastal processes for each return period (probability) of interest
9	Evaluate exposure and sensitivity of transportation infrastructure for each return period
10	Estimate risk as a function of scenario probability and time-interval considered

The most significant differences between a Level 2 and Level 3 study, where storm surge and waves are the primary damaging coastal processes of interest, are related to the characterization of storm and climate change scenarios, as well as their results. Instead of modeling only one or two notable historic storms, dozens to hundreds of synthetic storms may be developed and modeled. The parameters of these synthetic storms are initially based on historic storms that impacted the study area, but are altered to yield hundreds, and possibly even thousands, of unique storm events. The storm's track, landfall location, forward speed, central pressure, maximum winds, and radius to maximum winds (i.e. size) are typically the parameters that are adjusted to generate the unique storm scenarios. Each of the synthetic storms must also be assigned a probability of occurrence based on its unique parameters. By doing so, the return period of each storm is known. FEMA has already performed this exercise in the process of updating flood hazard maps in many US coastal states and their counties, including many in this region. These storm characteristics, probabilities, and the associated model results are archived and stored by FEMA.

While previous FEMA coastal flood hazard studies represent excellent resources for the characterization of storm and surge frequencies they do not incorporate or account for the effects of climate change. Appropriate climate change scenarios could be incorporated into those synthetic storm scenarios, but the associated probabilities would generally be unknown. Until recently, most published sea level rise projections did not have associated probabilities. The IPCC (2007) published sea level rise projections for 2100 with 95 percent confidence intervals (2.5 percent probability of being equaled or exceeded) but those estimates did not fully account for the effects of ice sheet melting in Greenland or Antarctica. Houston (2013) provides updated sea level rise projections for the period 1990 – 2100 that appropriately account for these contributions as well as thermal expansion and the melting of glaciers and ice caps. The global sea level rise projections for the period 1990 – 2100, as determined by Houston (2013) at the 5 percent, 50 percent, and 95 percent confidence intervals, are 0.59 ft, 1.6 ft, and 2.7 ft, respectively. Houston (2013) also describes the steps required to determine sea level rise projections at other confidence intervals. Note, however, that these are global sea level rise projections and do not account for local subsidence. For a fully probabilistic characterization of relative sea level rise, the probabilities associated with local subsidence rates would also have to be known, or at least assumed to be constant and stationary.

Incorporating storm intensification in a probabilistic manner may not currently be possible. There are no probabilities associated with storm intensification at this time. Furthermore, there are currently no probabilities associated with future increases or decreases in landfalling storm frequency. There is some agreement, though, that the global frequency of all storms will decrease with a corresponding increase in the frequency of major storms (Knutson *et al.* 2010). Therefore, it may not be appropriate to assume that the probabilities of intensified storms will be equivalent to their present-day equivalent. This remains an area of needed research.

The inherent benefits in modeling hundreds of unique storm and climate scenarios, each with their associated probability, also represent serious obstacles. The level of effort, time, and cost to perform such a large number of model simulations may be prohibitive. Alternative strategies are presented by Hagen and Bacopoulos (2012) and Li *et al.* (2013). While neither approach is fully probabilistic in nature, these studies demonstrate how scenario outcomes can be associated to return period events without having to perform hundreds of model simulations. A more detailed description of Hagen and Bacopoulos (2012) is provided as a case study in Section 5.3 of this manual.

After all storm and climate scenarios have been modeled, the probabilities of each process of interest (e.g. water levels, wave heights, velocity, and shoreline change) must be derived from the model results. These probabilities are generally extracted from all model results at every geographic node or grid point in the computational domain. This is representative of the process that delineates a coastal flood plain for a specific return period event, as in the 100-year and 500-year flood plains. Statistical approaches for determining event probabilities are briefly described in Section 3.1.1, Return Period and Probability of Occurrence, and can also be found in most hydraulic engineering texts.

In contrast to a Level 2 study where outcomes are based on specific scenarios, the outcomes of a Level 3 study are based on the probabilities of all scenarios considered. Therefore, the model results capture the frequent, low-intensity events, as well as the infrequent, high-intensity events, and everything in between. Once the values of relevant processes are determined and associated with specific probabilities (i.e. 100-year water level, 100-year wave height, etc.), risk can be assigned as a function of the project duration, life cycle, or for specific planning horizons.

As in the Level 2 study, maps of storm water levels, waves, velocity, and possibly shoreline change are anticipated to be the primary products of the model simulations. Unlike the Level 2 study where maps of each process are generated for each scenario, the relevant coastal processes will be mapped only at desired return periods. Exposure assessment can then be generalized in terms of probability and risk, as can sensitivity analyses.

4.3 Mid-Atlantic and New England Coast

This section outlines the levels of effort, existing tools and data, appropriate models, and methodologies for determining exposure to extreme events along the Mid-Atlantic and New England Coasts. In this region of the US, tropical storms, hurricanes, and extratropical storms are the predominant extreme events, and the storm surge and waves they generate are the critical coastal processes of interest. Other processes of interest in this region include tides, episodic shoreline change, and runoff to coastal waters. A multi-level approach for evaluating exposure to extreme events and climate change along these coasts is described in the subsections that follow.

4.3.1 Level of Effort 1: Mid-Atlantic and New England Coast

The suggested methodology for performing a Level 1 study in this region is essentially the same as that described above in Section 4.2.1, Level of Effort 1: Gulf of Mexico and South Atlantic Coasts. The extreme events in this region are similar with the exception of extratropical storms. Accordingly, the damaging coastal processes of interest for this region are also basically the same: storm surge and waves generated by strong storms. The major steps for developing the information needed to perform a Level of Effort 1 exposure assessment along the Mid-Atlantic and New England Coast are summarized in Table 4.4.

The coastal flood hazard maps produced by FEMA (https://msc.fema.gov) in this region are developed similar to those for the Gulf of Mexico and South Atlantic coasts and give the same types of information. The flood hazard maps in this region show the 100-year return period still water elevations, relative to a survey datum, for different flood zones. In some locations, the BFE is also provided to show the elevation of probable wave attack. Detailed information about the mapping procedures is available in FEMA (2003). Additional guidance for mapping hazards in sheltered waters, like coastal embayments, is provided in FEMA (2008).

This region of the US corresponds to FEMA Regions 1, 2, 3, and part of 4 on the Atlantic coast. With the exception of northern Maine, flood map modernization has either been completed or is ongoing for most coastal counties along this coast. Many of the coastal counties that were impacted by Hurricane Sandy in 2012 were in the process of updating their coastal flood hazard maps. In limited cases, communities adopted “Advisory Base Flood Elevations” (ABFEs) after Sandy. Unlike the BFEs listed on published FEMA FIRMs, these ABFEs are not based on a standard deterministic or probabilistic protocol. ABFEs have been based on storm-specific surge or high water mark elevations plus some increment, e.g. 1 to 3 feet, of freeboard. In general, the published FEMA FIRMs for this region should be used instead of ABFEs in the Level 1 study, unless there is accepted technical logic to use the ABFEs.

Table 4.4. Exposure assessment steps for level of effort 1: Mid-Atlantic/New England Coast.

Step	Activity
1	Obtain appropriate FEMA flood map elevations for study area
2	Choose desired sea level change scenarios
3	Modify sea level change increments to account for nonlinearity
4	Add the result of Step 3 to the elevations obtained in Step 1
5	Obtain appropriate ground surface elevation maps for study area
6	Subtract ground elevations (Step 5) from values found in Step 4 to obtain flood depth
7	Multiply flood depths (Step 6) by 0.8 to determine maximum wave height
8	Multiply wave heights (Step 7) by 0.75, add to Step 4 for wave crest elevations
9	Use Equations 4.1 and/or 4.2 to estimate flood flow velocity
10	Consider shoreline retreat and erosion based on historic trends in study area
11	Map the damaging coastal processes (results from Steps 6-9)
12	Evaluate exposure of transportation infrastructure

The appropriate climate change process for a Level 1 study in this region of the US is sea level rise. Local rates of relative sea level rise and their future projections should be considered. All coastal areas in this region are experiencing relative sea level rise, with the Mid-Atlantic region having rates 2 to 3 times higher than those along the New England coast. As previously described in Section 4.2.1, the USACE (2011) guidance on sea level change can be used along with their web-based tool (http://www.corpsclimate.us/ccaceslcurves.cfm) in order to develop appropriate relative sea level rise rates and projections for a specific study area.

One issue that remains unclear for this region of the US is the degree of nonlinearity associated with the effects of sea level rise on storm surge. All published studies documenting this effect were conducted in the Gulf of Mexico. The offshore bathymetry and topography of the Mid-Atlantic and New England coasts are very different than those in the Gulf of Mexico, and they likely play an important role in determining how storm surge is affected by higher sea levels. This is a topic that requires future research and caution should be exercised when applying the multiplier of 1.5 suggested in Section 4.2.1.

4.3.2 Level of Effort 2: Mid-Atlantic and New England Coast

The process for conducting a Level 2 study in this region is almost identical to the one presented above in Section 4.2.2, Level of Effort 2: Gulf of Mexico and South Atlantic Coasts.

Exceptions include the selection and characterization of storm scenarios, as well as some of the physical processes that should be included in numerical model simulations. The general methodologies for conducting the study and assessing exposure are, however, essentially the same as before and they are not repeated but differences are outlined below. The major steps for developing the information needed to perform a Level of Effort 2 exposure assessment along the Mid-Atlantic and New England Coast are summarized in Table 4.5.

Table 4.5. Exposure assessment steps for level of effort 2: Mid-Atlantic/New England Coast.

Step	Activity
1	Identify damaging coastal processes of interest (e.g. storm surge, waves, tides, runoff, etc.)
2	Select and characterize storm and climate change scenarios of interest
3	Select, develop, and prepare appropriate numerical modeling tools
4	Validate and/or calibrate the models through hindcast simulations and analysis
5	Incorporate climate change scenarios into numerical model simulations
6	Perform model simulations of selected storm and climate change scenarios
7	Map the damaging coastal processes for each scenario
8	Evaluate exposure and sensitivity of transportation infrastructure for each scenario

Extreme events in this region of the US include tropical storms, hurricanes, and strong extratropical storms. Sometimes, combinations of these events are also possible as demonstrated by Hurricane Sandy in 2012. The selection of an appropriate extreme event or storm scenario might include historic storms of record, low-intensity storms producing notable impacts, or perhaps a synthetic storm that hasn't even occurred. For example, researchers at Stevens Institute and Rutgers University considered a model scenario that combined some properties of Tropical Storm Irene (2011), which produced significant precipitation, with the size and winds of Hurricane Sandy (2012). A separate scenario simulated the effects of Sandy making landfall at the same time as the astronomical high tide, which altered the spatial coverage and extent of flooding.

Since the extreme events in this region are not limited solely to tropical cyclones, simply knowing the historic storm parameters will generally not provide enough information to recreate the meteorological forcing. Instead, measured or reanalyzed meteorological data must be obtained or created for the selected storm scenarios.

Most coastal circulation and wave models accept meteorological input in terms of wind (or wind stress) and pressure fields. An excellent source of meteorological measurements in coastal areas is provided by the NOAA National Data Buoy Center (http://www.ndbc.noaa.gov/). These platforms commonly record and archive wind speed, wind direction, and atmospheric pressure at intervals ranging from 6 minutes to 1 hour. The averaging duration and measurement elevation should be noted and corrected based on the requirements of the numerical model being used (see HEC-25 Appendix C). While these platforms are robust, they do occasionally fail during extreme storm events, and sometimes their spacing is too coarse to resolve all characteristics of the meteorological forcing. The NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/) provides fully reanalyzed meteorological data at a range of spatial scales appropriate for use in numerical models. If these two options do not provide suitable information, there are companies that sell detailed ocean weather data.

Once the desired storms or storm parameters have been selected, the effects of climate change on those storms could be incorporated in addition to modeling sea level rise. A storm's maximum winds, pressures, size, and precipitation are parameters of interest, as well as storm speed, track and landfall location. Appropriate regional and local relative sea level rise rates and projections can be developed using guidance described in Section 2.3.1, Sea Levels, and elsewhere in this manual. Changes in surface roughness for areas inundated by sea level rise can be incorporated into the selected numerical models.

A Level 2 exposure assessment in this region of the US requires original numerical modeling of the selected storm and climate change scenarios. As described previously, the selected scenarios may require from a few to tens of simulations. The numerical models should be selected, developed, and implemented in a manner that ensures the relevant physical coastal processes are being simulated. For example, the contribution of wave setup to storm surge can become significant in this region of the US due to the offshore bathymetry. Numerical models, or combinations of models, that incorporate this additional forcing for storm surge should be used.

The effects of tides and runoff from coastal watersheds on storm surge and waves are especially important in this region and can be considered in model simulations. For example, developing a model scenario that considers the peaks of the local storm surge and stream flow hydrographs occurring simultaneously with the astronomical high tide will produce the maximum likely spatial coverage and depth of flooding. The increased flooding will subsequently allow wave impacts to reach further inland. Therefore, both the astronomical tides and stream flows should be included as boundary conditions in model simulations. Tidal characteristics are available at NOAA tide gage locations (http://tidesandcurrents.noaa.gov/). Historic stream flow data and statistics are provided by the USGS (http://waterdata.usgs.gov/usa/nwis/rt).

If it is not possible to explicitly model the astronomical tides, one may consider an additional offset of the water level corresponding to the local mean higher high water (MHHW) elevation. Tidal datum information can be obtained from NOAA (http://tidesandcurrents.noaa.gov/). This is analogous to the process of changing the water level to account for higher future sea levels. The procedures for validating the numerical models, performing the simulations, interpreting the results, and mapping exposure are similar to those presented earlier.

4.3.3 Level of Effort 3: Mid-Atlantic and New England Coast

A Level 3, risk-based, exposure assessment in this region of the US would be performed in a manner similar to that described in above in Section 4.2.3, Level of Effort 3: Gulf of Mexico and South Atlantic Coast. The primary regional differences have been described in the previous two sections. Those differences include the selection and characterization of storms to include both tropical and extratropical events; incorporating regionally appropriate sea level rise values; prescribing appropriate boundary conditions like astronomical tides and stream flows; and using numerical models that explicitly account for wave effects on storm surge. The major steps for developing the information needed to perform a Level of Effort 3 exposure assessment along the Mid-Atlantic and New England Coast are summarized in Table 4.6.

In addition to modeling the storm surge and waves for each of the probability-based storm and climate change scenarios in a Level 3 study, predictions of storm-induced shoreline change may be important for this region of the US. Shoreline change could be estimated using approximations like the FEMA 540 rule; simple models like EDUNE and SBEACH; or sophisticated models like XBEACH, DELFT3D, and MIKE 21 (see Section 2.4.3, Coastal

Morphology Models). A risk-based model like Beach-*fx*, which is being used as part of post-Sandy recovery project design, could also be applied.

Table 4.6. Exposure assessment steps for level of effort 3: Mid-Atlantic/New England Coast.

Step	Activity
1	Identify damaging coastal processes of interest (e.g. storm surge, waves, tides, runoff, etc.)
2	Select and characterize storm and climate change scenarios of interest
3	Select, develop, and prepare appropriate numerical modeling tools
4	Validate and/or calibrate the models through hindcast simulations and analysis
5	Incorporate climate change scenarios into numerical model simulations
6	Perform model simulations of selected storm and climate change scenarios
7	Derive probabilities associated with water levels, wave heights, velocity, etc.
8	Map the damaging coastal processes for each return period (probability) of interest
9	Evaluate exposure and sensitivity of transportation infrastructure for each return period
10	Estimate risk as a function of scenario probability and time-interval considered

4.4 Great Lakes Coast

This section specifically outlines the levels of effort, existing tools and data, appropriate models, and methodologies for determining exposure to extreme events in the Great Lakes region. In this region of the US, frontal storms and extratropical storms are the predominant extreme events, and the storm surge and waves they generate are the critical coastal processes of interest. Other processes of interest in this region include changing lake levels, seiching, meteotsunamis, and bluff erosion. Many of these processes, as well as the expected impacts of climate change on them, have been described in Chapters 2 and 3 of this manual, and additional information is available in HEC-25.

A comprehensive coastal flood study of the Great Lakes region is currently underway. The goal of the study is to produce new flood hazard maps, which are expected to be published by 2016. The objectives of the study are to define and map the 10-, 50-, 100-, and 500-year return period flood hazards related to wind, surge, waves, and shoreline change. Some reports and guidance describing these processes on Lakes Michigan and St. Clair are available now. Additional documentation and technical resources are available on the Great Lakes Coastal Flood Study web site (http://www.greatlakescoast.org).

A multi-level approach for evaluating exposure to extreme events and climate change along the Great Lakes coasts is described in the subsections that follow. Each approach is described in terms of the existing guidance and technical resources available for the region. Some specific comments regarding how these methodologies may be affected by results of the ongoing flood study are provided.

4.4.1 Level of Effort 1: Great Lakes Coast

As in other regions of the US, a Level 1 exposure assessment in the Great Lakes might use existing FEMA flood hazard maps, or FIRMs, to determine the depth and spatial coverage of inundation (https://msc.fema.gov). The major steps for developing the information needed to perform a Level of Effort 1 exposure assessment on the Great Lakes Coast are summarized in Table 4.7.

Most of the developed and populated shorelines of the Great Lakes have been mapped by FEMA. These coastal areas are served by FEMA Regions 2, 3, and 5. There are considerable reaches of shoreline along Lakes Superior, Michigan, and Huron that remain unmapped.

Table 4.7. Exposure assessment steps for level of effort 1: Great Lakes Coast.

Step	Activity
1	Obtain appropriate FEMA flood map elevations for study area
2	Choose desired lake level change scenarios that account for seasonal variability
3	Subtract (or add) the result of Step 2 from (to) the elevations obtained in Step 1
4	Obtain appropriate ground surface elevation maps for study area
5	Subtract ground elevations (Step 4) from values found in Step 3 to obtain flood depth
6	Multiply flood depths (Step 6) by 0.8 to determine maximum wave height
7	Multiply wave heights (Step 7) by 0.75, add to Step 4 for wave crest elevations
8	Use Equations 4.1 and/or 4.2 to estimate flood flow velocity
9	Consider shoreline retreat and erosion based on historic trends in study area
10	Map the damaging coastal processes (results from Steps 6-9)
11	Evaluate exposure of transportation infrastructure

The methodology and resources for performing a Level 1 exposure assessment in the Great Lakes region are essentially the same as those for the regions described above for the other regions with one significant exception. In the Great Lakes region the expected impact of climate change is a decrease in lake levels, not an increase (see Section 2.3.2, Lake Levels). However, it is important to recognize that the projected lake level decreases are similar in magnitude to observed long-term oscillations. Lake levels also exhibit seasonal variability that should be considered. Historic and real time lake level data can be obtained from the NOAA Great Lakes Environmental Research Laboratory web site (http://www.glerl.noaa.gov/). Return period lake levels can be obtained from the US Army Corps of Engineers' coastal storm database (http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=SOFTWARE;46). The database, named CSTORM-DB, is being populated with return period storm, water level, and wave statistics derived from modeling and statistical analysis as portions of the Great Lakes Flood Study are completed.

Falling lake levels will alter how one evaluates exposure, sensitivity, and vulnerability in the Great Lakes region. The spatial coverage and depth of inundation are likely to decrease with falling lake levels. The wave impacts will generally be of a similar magnitude but will impact areas at lower elevations than present-day. This may expose foundations, embankments, revetments, and other structures to very high forces not accounted for in their design. Furthermore, falling lake levels may lead to undercutting of the shoreline and/or bluffs as highly erodible soil layers are directly impacted by wave action. For these reasons, consideration should be given to the extent of wave runup in the various climate scenarios.

Great Lakes water levels also exhibit season fluctuations that will be superimposed on the projected future trend. Therefore, as lake levels fall there will be times throughout the year when water levels and wave impacts occur at elevations below and above the annual mean lake level. Accounting for these seasonal fluctuations may make it necessary to consider a range of potential elevations that will be exposed to the damaging physical coastal processes.

When using the existing FEMA flood hazard maps for the Great Lakes in a Level 1 analysis, the stated still water elevations and base flood elevations could be incrementally shifted downward to reflect falling lake levels. The selection of appropriate increments should consider both the expected impacts of climate change described earlier, as well as the seasonal and long-term fluctuations that are known to exist. More information about the expected impacts of climate change on the Great Lakes can be found at the Great Lakes Integrated Sciences + Assessments web site (http://glisa.msu.edu/index.php).

In addition to the potential for falling lake levels, the application of the Level 1 methodology in this region is unique because there is no existing guidance on the potential nonlinear relationship between the effect of falling sea or lake levels on storm surge and waves. Therefore, a multiplier is not used for these locations. Further research is needed to quantify and describe these potential effects.

The estimation of shoreline change, dune erosion, and bluff erosion may not be possible using simple rules or historic trends. If they are of concern, some simple numerical modeling may be required. Appropriate guidance can be found on the Great Lakes Coastal Flood Study web site. A specific example includes use of the one-dimensional model CSHORE (Johnson *et al.* 2012) to estimate waves, water levels, and beach profile evolution. The Great Lakes Coastal Flood Study web site also provides links to oblique aerial photography, LiDAR bathymetry and topographic elevations, and geodatabases that will be useful for studies in this region of the US.

4.4.2 Level of Effort 2: Great Lakes Coast

A Level 2 exposure assessment or sensitivity analysis will require many of the same steps, and use many of the same models, described above for the other regions of the country (Sections 4.2.2 and 4.3.2). The major steps for developing the information needed to perform a Level of Effort 2 exposure assessment for the Great Lakes Coast are summarized in Table 4.8. As applied to the Great Lakes region, a Level 2 assessment will still require identification of damaging physical coastal processes; selection and development of relevant storm and climate change scenarios; selection and validation of numerical models; model simulations of the desired scenarios; and mapping of exposure. The primary differences in application of the Level 2 approach presented earlier is related to identification of the physical processes, the storm scenarios that create them, and the expected impacts of climate change on lake levels.

Extreme meteorological events in this region are characterized by frontal systems, extratropical storms, the remnants of tropical low pressure systems, and combinations thereof. Similar to other regions of the US, these extreme events produce wind-generated surge and waves that cause inundation and damaging wave forces to reach further inland and at higher elevations. In rare cases, these weather systems can produce seiching of the lakes. In even rarer cases, extreme weather systems have generated meteotsunamis that cause damage to infrastructure at higher elevations. These physical processes, as well as their effects on the shoreline, are modified in the winter seasons by the presence of lake ice. As climate change affects the extent and duration of ice coverage in the Great Lakes, so too will the physical processes and their impacts be modified.

Table 4.8. Exposure assessment steps for level of effort 2: Great Lakes Coast.

Step	Activity
1	Identify damaging coastal processes of interest (e.g. storm surge, waves, bluff erosion, etc.)
2	Select and characterize storm and climate change scenarios of interest
3	Select, develop, and prepare appropriate numerical modeling tools
4	Validate and/or calibrate the models through hindcast simulations and analysis
5	Incorporate climate change scenarios into numerical model simulations
6	Perform model simulations of selected storm and climate change scenarios
7	Map the damaging coastal processes for each scenario
8	Evaluate exposure and sensitivity of transportation infrastructure for each scenario

The selection of appropriate storm scenarios in the Great Lakes region can be treated as in other regions of the US. Extreme events of interest may include either infrequent but intense historic storms that have had significant impacts within the study area, or perhaps a frequent, low-intensity historic storm that had notable impacts. As in other regions, combinations of historic storm parameters may be considered in order to generate a synthetic storm.

Selection of an appropriate extreme event for a study area may also be a function of the damaging physical processes it produces. For example, if the inundation and high flood velocity attributed to a meteotsunami are of concern, then a storm event capable of (or known to have) producing one should be modeled.

As in other Level 2 assessments, a few storm scenarios representative of the study area, or reflective of the processes of interest, should be considered and later modified to account for the expected impacts of climate change in the region. Development of the meteorological forcing for the numerical model simulations will require some effort. The meteorological forcing can be reconstructed from measured winds and pressures in the study area, or from reanalyzed climate and environmental data. Note here that in addition to winds and pressures, precipitation, temperatures, and lake ice coverage may also be important. Real-time and historic meteorological and hydraulic measurements can be obtained from the NOAA Great Lakes Environmental Research Laboratory (http://www.glerl.noaa.gov/data/). The NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/), NOAA National Centers for Environmental Prediction (NCEP) (http://www.ncep.noaa.gov/), and NOAA NCEP Climate Forecast System Reanalysis (http://cfs.ncep.noaa.gov/cfsr/) serve as excellent sources for reanalyzed meteorological data. The Great Lakes Coastal Flood Study web site should also be consulted.

The relevant climate change scenarios to consider for the Great Lakes region are those that will significantly impact storm surge, waves, and shoreline change; and those that can be readily incorporated into hydrodynamic models. Here, the selected storm scenarios should be simulated on future lake levels, which are projected to be lower than their present-day elevations. The effects of climate change on lake ice coverage and duration may also be simulated by decreasing the spatial ice coverage and/or increasing the number of ice free days for storms occurring in the winter months. Ice coverage is generally accounted for as an increase in friction or drag coefficients in wind-stress formulations. Note that the model must be capable of accepting spatially variable coefficients for this to be possible.

Future lake levels can be incorporated into the selected models as a reduction in the mean lake level position: a negative offset of the present-day lake level. If such an offset is not possible in the numerical model, then all topographic and bathymetric elevations can be shifted upward (positive) by an equivalent amount. Either way, the net effect is that the lake levels will be lower relative to the land surface. Caution must be exercised when using the latter approach, as direct comparisons of model results to existing data referenced to its original vertical datum will not be possible. In this case, the elevations of either the modeled results or the existing infrastructure data must be altered. Preference should be given to correcting modeled results at the completion of the model study, but prior to exposure mapping, to avoid potential errors.

The modeling of storm and climate change scenarios, as well as the validation of selected numerical models, should be performed in a manner similar to what was described in Sections 4.2.2 and 4.3.2. However, the spatial coverage of the general circulation (storm surge) model should receive special attention in this region. It is likely that an entire lake must be modeled in order to properly simulate wind surge and waves. If the specific study area falls within Lakes Michigan or Huron, both lakes must be modeled to capture the coupling between them. The coupling may not impact wind-wave generation as much as it will the lake water levels, but if the contributions of wave setup to the total water level are of interest then they must be accounted for in this manner.

Upon completion of the storm and climate change scenario simulations, exposure of infrastructure to water levels, waves, velocity, and shoreline change should be mapped using a methodology consistent with descriptions provided in previous sections of this manual. As in other Level 2 assessments, exposure maps of each process will be generated for each scenario considered and are expected to be the primary products of the study. The maps can also be used to evaluate sensitivity of specific infrastructure to the relevant physical processes and the effects of climate change on them.

4.4.3 Level of Effort 3: Great Lakes Coast

The suggested methodology for performing a Level 3 assessment in the Great Lakes region differs from that described for the Gulf and Atlantic coasts. In the Great Lakes region, probabilities are associated with the storm response, e.g. resultant water level, rather than assigned to storm characteristics, e.g. wind speed. This methodology is what FEMA refers to as the “storm response method” or “total water level method.” The storm response method is more fully described in FEMA (2005). Additional guidance for mapping hazards in sheltered waters, like embayments, is available in FEMA (2008). The major steps for developing the information needed to perform a Level of Effort 3 exposure assessment in the Great Lakes region are summarized in Table 4.9.

The storm response method and original numerical modeling are being applied in the ongoing Great Lakes Coastal Flood Study to develop new maps that communicate risk related to the wind surge, wave, wave runup, and shoreline erosion hazards. These hazards will be communicated at probabilities defined by the 10-, 50-, 100-, and 500-year return period intervals. These correspond to the 10 percent, 2 percent, 1 percent, and 0.2 percent annual chance of exceedance, respectively.

Table 4.9. Exposure assessment steps for level of effort 3: Great Lakes Coast.

Step	Activity
1	Identify damaging coastal processes of interest (e.g. storm surge, waves, tides, bluff erosion)
2	Select and characterize relevant climate change scenarios (i.e. lower lake levels)
3	Select, develop, and prepare appropriate numerical modeling tools
4	Validate and/or calibrate the models through hindcast simulations and analysis
5	Model and derive hazard probabilities using the storm response method or use existing hazard values at design return periods as model boundary conditions
6	Incorporate climate change scenarios into numerical model simulations
7	Perform model simulations of selected storm and climate change scenarios
8	Map the damaging coastal processes for each return period (probability) of interest
9	Evaluate exposure and sensitivity of transportation infrastructure for each return period
10	Estimate risk as a function of scenario probability and time-interval considered

In the storm response method, event probabilities like return period water levels and waves, are generated through a combination of traditional frequency analysis, when measurements are available, and hindcast numerical modeling when they are not. Storm response records are reconstructed by considering peak values over specific thresholds. The storms that produced the peak values are simulated in hindcast mode to recreate the data needed to perform the frequency analysis.

Some probabilistic data are available for the Great Lakes through the USACE WIS and CSTORM-DB web data portals. These data are archived at a number of “save points” along the coast. The spacing of the save points is generally adequate to resolve detailed wave transformation and shoreline processes. Additional data will be added as it becomes available, which will precede the release of the flood hazard maps in 2016. A number of companion documents are also available through the study web site.

Regardless of whether your specific assessment will utilize the probabilistic hazard values determined by the Great Lakes Coastal Flood Study, an extensive amount of original numerical modeling will need to be performed. If the exposure assessment calls for the development of new or different hazard probabilities, then the modeling and frequency analysis inherent to the storm response method must be performed first. Such modeling would require the application of lake-wide surge and wave models to generate the data necessary to perform a frequency analysis.

The amount of modeling required to generate probabilistic hazard values can be substantially reduced if existing data are available and used in the study. In that case, the number of model scenarios is a function of the number of climate scenarios considered and/or the number of locations where the modeling is performed. For a Level 3 exposure assessment, the relevant climate change scenarios should consider future lake levels that are lower than their present-day elevations. The desired return period water levels can then be incrementally lowered for each scenario and applied as boundary conditions in one- and/or two-dimensional process models. The corresponding return period wave characteristics can be applied in a similar manner, as can any required meteorological forcing.

Appropriate numerical models for simulating storm surge, waves, and shoreline change in this region are similar to those listed elsewhere in this manual. In order to generate the probabilistic data necessary to perform a Level 3 assessment, the use of one- and/or two-dimensional models may be required. Application of two-dimensional models may reduce the total number of required simulations as they may resolve the entire study area; however, they typically take much more time to complete. As an alternative, a number of one-dimensional process models can be applied at desired transects, or shore-perpendicular reaches, within the study area. A specific example would be the application of CSHORE with the appropriate return period wave and water level values prescribed as boundary conditions.

A benefit of the storm response method is that probabilities are assigned to the hazards, not the storms that generate them. Therefore, the model results will inherently be probabilistic in nature and there is no longer a need to derive probabilities from model results. This constitutes a significant difference from the Level 3 methodology described in Sections 4.2.3 and 4.3.3. However, keep in mind that in order for the results of the climate change scenarios to be fully applied in a risk framework, the probabilities associated with future lake levels would also have to be known. Such information is not currently available and the subsequent limitations must be acknowledged and preferably accounted for as part of the Level 3 assessment.

Upon completion of the climate scenario simulations, mapping of exposure and sensitivity analyses can be performed in a manner similar to what has been described in previous sections of this manual. Particular attention should be given to the fact that as lake levels fall, areas not previously exposed to direct wave attack and high velocity flows will become vulnerable. As a consequence, sensitivity analyses in the Great Lakes region should include structure stability and foundation integrity.

4.5 Pacific Coast – Storms

This section specifically outlines the levels of effort, existing tools and data, appropriate models, and methodologies for determining exposure to extreme events along the Pacific Coast, including Alaska and Hawaii. In this region of the US, extratropical storms and tsunamis are the predominant extreme events. Although rare, southern California and Hawaii have occasionally experienced tropical storms and hurricanes.

This section of the manual will focus only on storms and their impacts. The coastal processes of interest in this region are water levels, large waves, wave setup, wave runup, tides, storm-induced shoreline change, bluff erosion, and runoff from coastal watersheds. Water levels and storm intensity in this region are strongly influenced by changes in the PDO and ENSO processes described previously in the manual. A multi-level approach for evaluating exposure to extreme storm events and climate change along these coasts is described in the subsections that follow. An approach for assessing exposure to tsunami hazards is provided in Section 4.6.

4.5.1 Level of Effort 1: Pacific Coast – Storms

Similar to other regions of the US, a Level 1 exposure assessment in this region might use existing FEMA flood hazard maps, or FIRMs, to determine the depth and spatial coverage of inundation (https://msc.fema.gov) at the 1 percent or 0.2 percent annual chance of flooding. Most of the developed and populated shorelines of Alaska, California, Hawaii, Oregon, and Washington have been mapped by FEMA. There are vast reaches of coastline in Alaska that remain unmapped, as well as some isolated areas in other states. These coastal areas are served by FEMA Regions 9 and 10.

The major steps for developing the information needed to perform a Level of Effort 1 exposure assessment for the Pacific Coast are summarized in Table 4.10. The process for developing flood hazard maps in this region of the US is essentially the same as that described in Section 4.4 for the Great Lakes region. The storm response method, or total water level method, is applied since the most extreme storm events are non-tropical and, therefore, difficult to assign probabilities to. Therefore, the 1 percent and 0.2 percent flood hazards delineated on the FEMA maps are derived from measurements or model hindcasts describing the response of coastal water levels to historic storms over a 30-, 40-, or 50-year period. More information about the mapping procedures and zones is available in FEMA (2005).

Table 4.10. Exposure assessment steps for level of effort 1: Pacific Coast.

Step	Activity
1	Obtain appropriate FEMA flood map(s) for study area
2	Choose desired regional sea level change scenarios (i.e. magnitude and direction)
3	Subtract or add the result of Step 2 from the still water elevations obtained in Step 1
4	Obtain appropriate ground surface elevation maps for study area
5	Subtract ground elevations (Step 4) from values found in Step 3 to obtain flood depth
6	Multiply flood depths (Step 5) by 0.8 to determine maximum wave height
7	Multiply wave heights (Step 6) by 0.75, add to Step 3 for wave crest elevations
8	Use Equations 4.1 and/or 4.2 to estimate flood flow velocity
9	Consider shoreline retreat and bluff erosion based on historic trends or modeling
10	Map the damaging coastal processes
11	Evaluate exposure of transportation infrastructure

The relevant climate change scenario to consider for a Level 1 assessment in this region is sea level change (http://tidesandcurrents.noaa.gov/sltrends/sltrends.html). However, the magnitude and direction are highly variable in some areas. Most of California, Hawaii, Oregon, and Washington are experiencing relative sea level rise having rates on the order of 0 to 2 ft per century. There are isolated portions of northern California, northern Oregon, and northern Washington that are experiencing relative sea level fall on the order of 0 to -1 ft per century. In Alaska, the relative sea level rates vary greatly from +1 ft/century to -6 ft/century.

The selection of an appropriate sea level change scenario will be a function of the study area location and regional extent. It may not be possible to cover large spatial regions in this type of exposure assessment if the sea level change rates are highly variable over the study area. The NRC has recently projected sea level rise rates for the US Pacific that should be used (NRC 2012). The USACE (2011) sea level change web-based tool can be used to develop appropriate relative sea level rise rates and projections for a specific study area (http://www.corpsclimate.us/ccaceslcurves.cfm).

The contribution of wind-driven surge to the total water level is much smaller in this region due to the steep coastal bathymetry and narrow continental shelf. However, the contribution of wave setup and wave runup is much more significant than in other regions. The nonlinear coupling between sea level change and wave characteristics is not well understood and only limited examples from the Gulf coast exist that quantify those effects. For example, the study of Smith *et al.* (2010) in Louisiana found the increase in wave heights to be equal to or less than the incremental change in sea level. Since only limited guidance is available, and the potential nonlinear coupling along the Pacific coast is currently unknown, a multiplier on sea level change should not be used.

Separate shoreline change modeling may be desired to capture the effects of climate change on beach profile evolution and bluff erosion. The recommendations provided in FEMA (2005) should be followed.

Most of the data resources presented in previous sections of Chapter 4 will also be useful for exposure assessments in these regions. Specific examples include the NOAA Coastal Services Center Digital Coast web data portal (http://www.csc.noaa.gov/digitalcoast/), the NOAA National Geophysical Data Center (http://www.ngdc.noaa.gov/mgg/bathymetry/relief.html), the USGS National Map Viewer (http://viewer.nationalmap.gov/viewer/), and the US Army Corps of Engineers' WIS database (http://wis.usace.army.mil/).

4.5.2 Level of Effort 2: Pacific Coast – Storms

The suggested methodology for a Level 2 study in this region is very similar to the process described in Section 4.4.2 for the Great Lakes. The major steps for developing the information needed to perform a Level of Effort 2 exposure assessment for the Pacific Coast are summarized in Table 4.11. The major differences here include the need to account for tides, water level fluctuations, and relative sea level rise (or fall) that is location-specific. Since the basic procedure requires most of the same steps outlined in previous Level 2 assessments, most of the data resources and models described earlier will also apply here.

Table 4.11. Exposure assessment steps for level of effort 2: Pacific Coast.

Step	Activity
1	Identify damaging coastal processes of interest (e.g. water levels, wave runup, erosion)
2	Select and characterize storm and climate change scenarios of interest
3	Select, develop, and prepare appropriate numerical modeling tools
4	Validate and/or calibrate the models through hindcast simulations and analysis
5	Incorporate climate change scenarios into numerical model simulations
6	Perform model simulations of selected storm and climate change scenarios
7	Map the damaging coastal processes for each scenario
8	Evaluate exposure and sensitivity of transportation infrastructure for each scenario

The selection and characterization of extreme storm events and climate change for this region will be somewhat unique from others. The selection of appropriate storm events should consider a range of possible intensities, as in other regions, but should also consider the timing of those events with the highest astronomical tides of the year (locally referred to as king tides). Because of the large tide range in Alaska, it may also be relevant to consider wave impacts at lower elevations, similar to the Great Lakes region. Contributions of runoff from coastal watersheds should also be considered in the selection of storm events or the development of synthetic storms.

It is anticipated that sea level rise will lead to much greater inundation, along with broader expanses of possible wave impacts, during astronomical high tides for even mild extratropical storms. Some of the anticipated effects of climate change on tidal elevations are documented in Zervas (2005). Once the selected extreme storm event scenarios have been selected, climate change can be incorporated by considering future sea level projections at desired time intervals or planning targets. Of the selected storm and climate scenarios, at least one should consider an historic storm on present-day sea levels to serve as a hindcast scenario for model validation.

The selection of appropriate numerical models should be based on the relevant processes of interest. Numerical models that simulate astronomical tides, waves, wave setup, wave runup, and shoreline change along the Pacific coast should be considered. Although wind surge is not a significant component of the total water level along the Pacific coast, it will typically be accounted for in most general circulation models used to simulate the astronomical tides. Such models are generally capable of accepting stream flows as non-oscillatory, or discharge, boundary conditions as well. As described in Section 4.2.2, changes in land surface roughness could be incorporated into the selected numerical models as areas are affected by sea level change.

In some cases it may be necessary to supplement the tide, wave, and shoreline modeling with other process-based modeling. For example, additional modeling may be required to capture wave transformations and runup in sheltered waters. These procedures are outlined in FEMA (2008). The use of equations may also be appropriate and necessary, as in the case of estimating wave overtopping rates. Such guidance is available in USACE (2002) and Pullen *et al.* (2007).

4.5.3 Level of Effort 3: Pacific Coast – Storms

The major steps for developing the information needed to perform a Level of Effort 3 exposure assessment for the Pacific Coast are summarized in Table 4.12. These steps are essentially the same as those described in Section 4.4.3 above for the Great Lakes. The regionally appropriate processes, storm events, and climate scenarios described earlier in Sections 4.5.1 and 4.5.2 should be accounted for and applied here.

Probabilistic flood hazards should be based on a storm response method that accounts for the frequency of all relevant processes. Much of this analysis is currently being performed as part of the ongoing FEMA California Coastal Analysis and Mapping Project: Open Pacific Coast study. Information about that study and the information being developed can be found on the study web site (http://www.r9map.org/Pages/CCAMP-Open-Pacific-Coast-Study.aspx). As new areas are studied in this region, the probabilistic hazard data will become part of the US Army Corps of Engineers' CSTORM-DB. Return period wave and wind characteristics are available at many save points along the Pacific, Alaskan, and Hawaiian coasts through the US Army Corps of Engineers' WIS database for the Pacific (http://wis.usace.army.mil/). Other relevant data resources for the Pacific coast include the NOAA Pacific Services Center (http://www.csc.noaa.gov/psc/), as well as many of the other NOAA and USGS resources identified elsewhere in this manual.

Table 4.12. Exposure assessment steps for level of effort 3: Pacific Coast.

Step	Activity
1	Identify damaging coastal processes of interest (e.g. water levels, waves, erosion)
2	Select and characterize relevant climate change scenarios (e.g. sea levels, runoff)
3	Select, develop, and prepare appropriate numerical modeling tools
4	Validate and/or calibrate the models through hindcast simulations and analysis
5	Model and derive hazard probabilities using the storm response method or use existing hazard values at desired return periods as model boundary conditions
6	Incorporate climate change scenarios into numerical model simulations
7	Perform model simulations of selected climate change scenarios
8	Map the damaging coastal processes for each return period (probability) of interest
9	Evaluate exposure and sensitivity of transportation infrastructure for each return period
10	Estimate risk as a function of scenario probability and time-interval considered

The selection and application of numerical models for this region should reflect the characteristics of the processes to be modeled. As previously mentioned, astronomical tides, water level fluctuations related to ENSO and PDO, wave transformation, wave runup, wave overtopping, and runoff from coastal watersheds should be simulated to determine the probabilistic flood, wave, and erosion hazards. Many of the numerical models described earlier could be applied appropriately in this region. One modeling system unique to this region is the USGS Coastal Storm Modeling System, or CoSMoS. The system is capable of simulating water levels, waves, coastal erosion and inundation. In addition to providing real-time forecasts of these processes, CoSMoS has also been successfully applied to recreate historic storms and synthetic scenarios (http://walrus.wr.usgs.gov/coastal_processes/cosmos/).

Application of the CoSMoS system to desired return period and climate change scenarios could provide the probabilistic hazard values required to perform a Level 3 risk-based exposure assessment in this region. Such detailed assessments will be greatly facilitated as additional flood hazard studies are completed by FEMA and USACE along the Pacific coasts.

4.6 Pacific Coast – Tsunamis

This section broadly outlines suggested levels of effort, existing tools and data, appropriate models, and methodologies for determining exposure to tsunami events along the Pacific coast, as well as the coasts of Alaska and Hawaii. Specific guidance for the determination of tsunami hazards is relatively new and only exists in limited forms. Probabilistic tsunami hazard assessments are even more limited, but a number of pilot studies are ongoing on the Pacific coast. Engineering guidance for the estimation of tsunami loads and effects is expected to be released in the 2016 edition of ASCE-7. For these reasons, the multi-level approach for evaluating exposure to tsunami events and climate change along these coasts is described only in general terms.

4.6.1 Level of Effort 1: Pacific Coast – Tsunamis

An appropriate Level 1 study of exposure in this region may be based upon existing tsunami inundation maps. Such maps are available for nearly all coastal areas of Alaska, California, Hawaii, Oregon, and Washington. Most of these inundation maps can be obtained through the National Tsunami Hazard Mitigation Program web site (http://nthmp.tsunami.gov/). The Pacific Northwest Seismic Network web site also contains links to many tsunami inundation maps and associated products (http://www.pnsn.org), as does the NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/index.html). The following sites provide access or links to the maps for each state:

- Alaska: http://www.dggs.alaska.gov/
- California: http://www.quake.ca.gov/gmaps/WH/tsunamimaps.htm
- Hawaii: http://www.scd.hawaii.gov/
- Oregon: http://www.oregongeology.org/tsuclearinghouse/pubs-inumaps.htm
- Washington: http://www.dnr.wa.gov/Publications/ger_tsunami_inundation_maps.pdf

Unlike FEMA flood hazard maps, tsunami inundation maps do not provide the information needed to estimate flood depth. This is because tsunami inundation maps show only the spatial coverage of inundation that would result from the most probable worst case tsunami (Bernard *et al.* 1996). The concept of a “still water elevation” does not necessarily apply for the description of tsunami hazards. A tsunami is a long period wave and not a wind-driven storm surge. As a result, the flood moves as a wave having a large amplitude, long period, and high speed. These properties allow the wave to reach a considerable distance inland, demonstrate considerable wave runup, and translate into very high flood velocities and hydrodynamic loads.

Tsunami inundation maps cannot be directly used to determine the spatial extent and depth of flooding, or expected flood velocity. A new tool for estimating some of these properties, based on existing tsunami inundation maps and land surface elevations, shows promise (Wiebe *et al.* 2013). The methodology applies an Energy Grade Line concept to describe the maximum expected flood depth, flow velocity, and momentum flux along chosen shore-perpendicular transects. The concept is somewhat similar to standard hydraulic equations for calculating water surface profiles that are available in most hydraulic texts.

Existing guidance for the assessment of tsunami hazards is not widespread. The reader is directed to Gonzalez *et al.* (2003) and FEMA (2005) for additional information on understanding and assessing tsunami hazards in this region. Suggested steps for performing a Level of Effort 1 exposure assessment to tsunamis with climate change are summarized in Table 4.13.

Table 4.13. Exposure assessment steps for level of effort 1: tsunamis.

Step	Activity
1	Obtain appropriate tsunami inundation maps for study area
2	Choose and incorporate desired sea level change scenarios
3	Apply an energy-based concept to estimate flood depth and velocity along a transect
4	Map the damaging coastal processes
5	Evaluate exposure of transportation infrastructure

Relevant climate change scenarios may be incorporated with incremental adjustments corresponding to higher or lower future sea levels. The potential nonlinear effect of future sea levels on tsunami propagation and transformation are likely insignificant, but the degree to which wave runup will be affected is currently unknown. Therefore, a multiplier should not be applied to the sea level change scenario.

Incorporating probabilistic tsunami hazards into FEMAs Risk Management, Assessment, and Planning (Risk MAP) program is the subject of pilot studies in Crescent City, California (Tsunami Pilot Working Group 2006; and Gonzalez *et al.* 2009) and Seaside, Oregon (CGS 2013). The probabilistic tsunami hazard maps for Seaside, Oregon have been developed and communicate flood risk for the 1 percent and 0.2 percent annual chance events. These levels were chosen to be consistent with existing FEMA guidance and requirements of the National Flood Insurance Program.

4.6.2 Level of Effort 2: Pacific Coast – Tsunamis

A suggested Level 2 study for mapping the exposure of transportation infrastructure to tsunami inundation is based on original numerical modeling of selected tsunamigenic events under appropriate climate change scenarios. Here, a tsunamigenic event could be a seismic event or landslide. The selection of an appropriate tsunami event could include consideration of those that have previously impacted the study area, or tsunamigenic events producing a credible worst-case scenario. Relevant climate change scenarios could include sea level rise or fall depending on the location of the study area and its corresponding sea level trends and projections.

Once the selected tsunami event and climate change scenarios have been developed, their effects can be simulated using an appropriate numerical model. There are a number of complex numerical models now being applied to the study, and forecasting, of tsunamis. Most of these modern tsunami models simulate three mostly independent processes: tsunami generation (i.e. earthquake), transoceanic propagation, and inundation of dry land. While the first and last processes are somewhat challenging to simulate, modeling the propagation of the tsunami is comparatively easy. In fact, tsunami waves propagate as surface gravity waves and undergo many of the same transformation processes as other ocean waves. The NOAA Center for Tsunami Research (http://nctr.pmel.noaa.gov/index.html) provides an overview of current tsunami forecasting and research efforts.

The NOAA Center for Tsunami Research specifically uses the Method of Splitting Tsunami (MOST) model (Titov and Synolakis, 1997; Titov and Gonzalez, 1997). The MOST model system is a suite of numerical models capable of simulating the three processes of tsunami evolution. The model has been extensively validated against previous tsunami events and is actively being implemented in tsunami forecast systems around the U.S.

There are numerous other tsunami models with capabilities similar to MOST, specifically the ability to model the tsunami propagation and inundation of dry land. Some of the more commonly used tsunami models include the TSUNAMOS model developed by Dr. Patrick Lynett and colleagues (http://coastal.usc.edu/plynett/TSUNAMOS/index.html); the GeoClaw model of Berger *et al.* (2011); the Cornell Multi-grid Coupled Tsunami (COMCOT) model of Liu *et al.* (1998); the TUNAMI model(s) documented in UNESCO (1987); the JRC Tsunami Model of Annunziato and Best (2005); and special applications of DELFT3D described in Gelfenbaum *et al.* (2006, 2007) and more recently Sasaki *et al.* (2012).

Some suggested steps for developing the information needed to perform a Level of Effort 2 exposure assessment related to tsunami hazards and climate change are summarized in Table 4.14.

Table 4.14. Exposure assessment steps for level of effort 2: tsunamis.

Step	Activity
1	Identify damaging processes of interest (e.g. flood depth, velocity, runup)
2	Select and characterize tsunamigenic and climate change scenarios of interest
3	Select, develop, and prepare appropriate numerical modeling tools
4	Validate and/or calibrate the models through simulation of historic tsunami events
5	Incorporate climate change scenarios into numerical model simulations
6	Perform model simulations of selected tsunami and climate change scenarios
7	Map the damaging coastal processes for each scenario
8	Evaluate exposure and sensitivity of transportation infrastructure for each scenario

The required procedures for mapping exposure to tsunami events and climate change will be similar to other regions of the US. One particular exception may be the communication of inundation as flood depths as opposed to still water elevations. The expected results of the model studies will be maps of inundation coverage and depth, flow velocity, and possibly momentum flux. As in other Level 2 studies, these maps are anticipated to be the primary products of the mapping effort. Exposure assessments and sensitivity analyses can be performed using the maps of each hazard for each scenario considered. New methods for evaluating tsunami loads and effects are anticipated for release in the 2016 edition of ASCE-7.

4.6.3 Level of Effort 3: Pacific Coast - Tsunamis

Probabilistic tsunami hazard analysis is a relatively new concept. Tsunami hazards are often defined by the inundation resulting from a probable worst-case scenario for a particular area. However, there are no probabilities associated with such scenarios or the tsunami response. An accepted framework for the probabilistic description of tsunami hazards has been established and is consistent with seismic hazard analysis (Geist and Parsons, 2006). Application of the probabilistic analysis technique for California is described in Thio *et al.* (2010).

A suitable methodology for performing a probabilistic tsunami hazard analysis is described in Gonzalez *et al.* (2009). While the methodology was applied to a specific location, it could be replicated and used as the basis of a probabilistic Level 3 exposure assessment. The methodology was used to derive the 100- and 500-year tsunami inundation areas and elevations. Application and use of a numerical model (MOST), as well as the derivation of exceedance values, are described in Gonzalez *et al.* (2009). A similar technique is currently being used to develop probabilistic tsunami hazard maps for Crescent City, California (CGS 2013).

The probabilistic values of tsunami inundation must be determined through a joint probability analysis that considers both the probability of the tsunamigenic event (i.e. return period of the source event) and the flood exceedance (Gonzalez *et al.* 2009). The development of tsunami flood hazard maps currently defines flood levels for the 100- and 500-year return period events. Consideration could be given to the inundation from other return period events as well. For consistency with ASCE-7 seismic hazard analysis, a range of tsunami hazards is being considered including the 100-year low-level tsunami event and the 2500-year Maximum Considered Tsunami (Chock 2012).

As in other exposure assessments for the Pacific coast, appropriate climate change scenarios should be incorporated into the probabilistic tsunami modeling. The most relevant climate scenario is likely to be the local rate or future projections of relative sea level change. These changes in sea level can be incorporated into the numerical models using water level offsets as described previously. It may be possible to assign probabilities to sea level change scenarios using local rates or projections of subsidence in conjunction with the probability-based estimates of global eustatic sea level rise provided in Houston (2013).

Suggested steps for developing the information needed to perform a Level of Effort 3 exposure assessment for tsunami hazards with climate change are summarized in Table 4.15.

Table 4.15. Exposure assessment steps for level of effort 3: tsunamis.

Step	Activity
1	Identify damaging processes of interest (e.g. flood depth, velocity, runup)
2	Select and characterize tsunamigenic and climate change scenarios of interest
3	Select, develop, and prepare appropriate numerical modeling tools
4	Validate and/or calibrate the models through simulation of an historic event
5	Incorporate climate change scenarios into numerical model simulations
6	Perform model simulations of selected tsunami and climate change scenarios
7	Derive the joint probability, for multiple tsunami sources, of flood exceedance
8	Map the damaging tsunami processes for each return period (probability) of interest
9	Evaluate exposure and sensitivity of transportation infrastructure for each return period
10	Estimate risk as a function of scenario probability and time-interval considered

Chapter 5 – Case Studies of Exposure and Vulnerability Assessment

This chapter highlights three exposure and vulnerability assessment case studies that have generally used the analysis methods outlined in Chapter 4. The purpose is to demonstrate how climate change can be incorporated into assessments of exposure and vulnerability to extreme coastal events. Not all these case studies focus on transportation infrastructure, but the methodologies for quantifying exposure are similar. These case studies include regional variability (two in the east and one in the west) and examples of all three levels of analysis described in Chapter 4. Each of these case studies evaluated climate change scenarios that included sea level rise scenarios consistent with the guidance in this manual. Each of the study teams included coastal engineers and scientists with specialized training and experience in coastal modeling. The results of these case studies indicate that there is a high level of vulnerability of transportation assets to extreme events today and this level will increase with sea level rise and climate change.

Section 5.1 presents a Level 1 case study that used a form of basic inundation mapping (with modifications to approximate increased flooding from wave effects) for different storm and tide conditions with increased sea levels. Section 5.2 presents a Level 2 case study that used original, high-resolution storm surge and wave modeling and mapping with increased sea levels and storm strengths. Section 5.3 presents a Level 3 study that used high-resolution surge modeling to develop detailed maps of the 500-year flood plain with increased future sea levels.

5.1 Level 1 Example: Adapting to Rising Tides - San Francisco Bay

This section describes a case study of mapping the level of flooding exposure of transportation infrastructure to coastal extreme events and climate change in a region where coastal storms during El Niño episodes are the dominant destructive storms. This case study was the technical inundation mapping component of the "Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment" pilot project (ART 2011a). It is an example of a Level 1 study using the terminology outlined in Chapter 4 above. The approach was a form of basic inundation mapping to assess the depth of inundation along the Alameda County shoreline of San Francisco Bay. The purpose was to inform a vulnerability rating of transportation assets in the study area under future sea level rise scenarios considering different storm and tide conditions. Intended as a support planning efforts, the analyses were not intended to represent, or take the place of, detailed engineering analyses.

5.1.1 Background

This case study was one component of a multi-agency study to enable transportation planners in the San Francisco Bay regions to improve vulnerability and risk assessment practices and to help craft effective adaption strategies. Lead agencies involved in the study included the San Francisco Bay Conservation and Development Commission, the Metropolitan Transportation Commission, the California Department of Transportation (District 4) and the FHWA. The project stakeholder groups included twenty local, state, and federal agencies and governments. The overall goal of the Adapting to Rising Tides (ART) project was to increase the preparedness and resilience of Bay Area communities to sea level rise and other climate change-related impacts while protecting ecosystem and community services (ART 2011a).

This portion of the project was a pilot planning project on a sub-regional scale to test the FHWA Risk Assessment Model (a predecessor to the FHWA Framework presented in Section 3.2). The sub-region studied was the approximately 20-mile long Alameda County bay shoreline. The study included evaluation of potential shoreline impacts, vulnerabilities, and risks; identified adaptation strategies; and developed adaptation planning tools and resources. This case study is the component of the ART study focused on the methodology developed to produce the inundation maps for the pilot study (ART 2011b) and is not a review of the entire ART pilot study.

This pilot study was one of the FHWA-sponsored pilot studies on vulnerability and risk assessment conducted throughout the country in 2010-2011 (FHWA 2014). There were five of these FHWA pilot studies conducted by DOT's and MPO's. Each pilot study developed and used its own unique assessment methodology. The other pilot studies were in Washington, Hawaii, New Jersey, and Virginia. Four of the studies used some form of an inundation mapping approach for either sea level rise or storm surge. Of those four, two attempted to consider some combination of storm surge and sea level rise. A third study considered both separately. Only this ART study attempted to include the combination of sea level rise and storm surge with some influence of storm waves in their mapped areas. These pilot studies were intended to be planning level studies and not coastal engineering analyses.

5.1.2 Storm Selection and Climate Change Scenarios

The ART study focused on sea level rise as the primary effect of climate change because of its potential to cause major damage to residential, commercial, and industrial structures in low-lying areas near the shoreline as well as to important habitats and wildlife resources. Two sea level rise scenarios were selected based on a review of the literature (Section 2.3.1). The first scenario was an increase of 16 inches consistent with a high-end estimate for mid-century and the second scenario was an increase of 55 inches consistent with a midrange estimate for the end of the century (ART 2011b).

Three storm/tide conditions were evaluated for each of the sea level rise scenarios: a high tide (MHHW), a 100-year storm water level (still water level), and the 100-year storm water level increased by some effects of wind waves. These three storm/tide conditions were selected to represent a reasonable range of potential coastal flood levels. The high tide inundation is representative of the area that would be subject to frequent or permanent tidal inundation. The 100-year flood is representative of the area subject to flooding and wave damage in extreme storms. Thus, there were a total of six scenarios evaluated - the two sea level rise scenarios combined with three storm/tide conditions.

5.1.3 Inundation Mapping Approach

The method used to assess the vulnerability to climate change was a modified form of the basic inundation mapping (bathtub) approach. Six inundation maps were developed corresponding to the two sea level rise scenarios with each of the three storm/tide conditions. The maps were developed by estimating the water level of interest and then comparing that elevation to the existing upland topography to determine depth of flooding at all locations across the study area. The elevations of the water levels (MHHW, 100-year storm, and 100-year with some increase for wave effects) used for this inundation mapping were selected based on extensive modeling of the bay.

This pilot study was able to use results of two much more extensive modeling efforts focused on developing similar estimates around San Francisco Bay: a recently completed USGS modeling effort and an ongoing FEMA modeling effort to remap the coastal flood plain around the bay. The FEMA effort used a high-resolution hydrodynamic model, MIKE-21, which is comparable to ADCIRC and also includes a wave model. Estimates of the MHHW and the 100-year storm elevation were taken from the USGS modeling effort at 13 locations along the shore of Alameda County for use in this pilot study inundation mapping effort. These MHHW elevations ranged from +6.11 ft to +6.85 ft (NAVD) with the values consistently increasing farther to the south. This compares with a MHHW elevation at the Presidio of +5.83 ft (NAVD). This variation of high tides throughout San Francisco Bay is well-known and results from the bay's response to tidal waves. The tide is amplified in the bay and the amplification increases moving south from the Golden Gate area. The estimated 100-year storm still water elevations at those 13 Alameda County locations were also obtained from the USGS study results. Those values ranged from +9.2 ft to +10.42 ft (NAVD) and the variation was not consistent spatially along the coast.

This pilot study also then adjusted the 100-year still water levels upward an increment to account for the elevation of wave crests in depth-limited situations. These resulting elevation estimates were referred to as "wind waves" in the pilot study. This adjustment was essentially a professional coastal engineering judgment by the consultant team based on the available modeling results and consistent with the project purpose of a general screening-level tool. Inundation was then mapped as if the still water level was at that higher elevation and referred to as the "potential wind-wave zone." This adjustment is not standard coastal engineering practice. As stated in the report, the physics of overland wave propagation into the flooded areas is not modeled (ART 2011b). Similarly, this vulnerability mapping effort also includes a non-standard definition of "overtopping" based on whether the elevation of the shoreline feature along the bay is lower than the vertical elevation of the water surface.

5.1.4 Inundation Maps

Inundation maps were generated in the San Francisco Bay pilot study by overlaying the flood water elevations on detailed maps of the existing upland topography. The maps illustrate the potential for coastal flooding in relationship to transportation assets under the six scenarios discussed above (2 sea level rise scenarios with MHHW, 100-year flood levels, and 100-year flood levels including the "potential wind-wave zone").

Examples of the inundation maps from the pilot study showing the inundation areas estimated for the scenario of 16 inches of sea level rise with the 100-year storm levels adjusted upward to account for the "potential wind-wave zone." are provided in Figure 5.1 and Figure 5.2. Figure 5.1 shows the entire study area and Figure 5.2 shows the same information in more detail for the northernmost portion of the study area. The maps show the major transportation assets as well as the flooded areas. The extent of flooding is shown by the yellow hatching. Specific transportation assets are identified in Figure 5.2. Also shown on Figures 5.1 and 5.2 are the estimated flood depths. These mapping results were used to develop metrics of the level of exposure and vulnerability of the transportation assets (ART 2011a, ART 2011b).

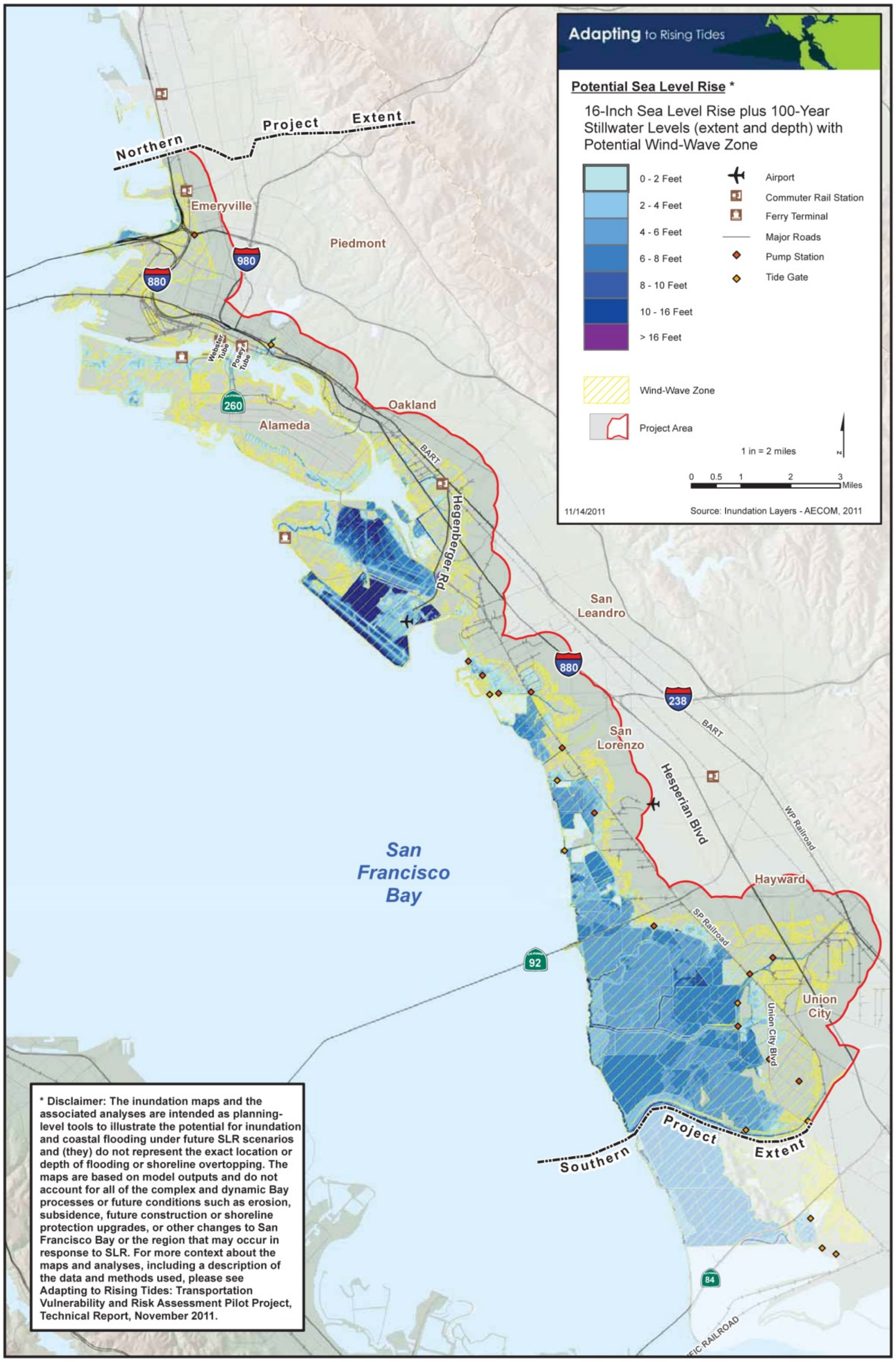

Figure 5.1. Inundation map of Alameda County for 100 year storm flood with 16 inches of sea level rise and additional elevation for wave effects (from ART 2011b).

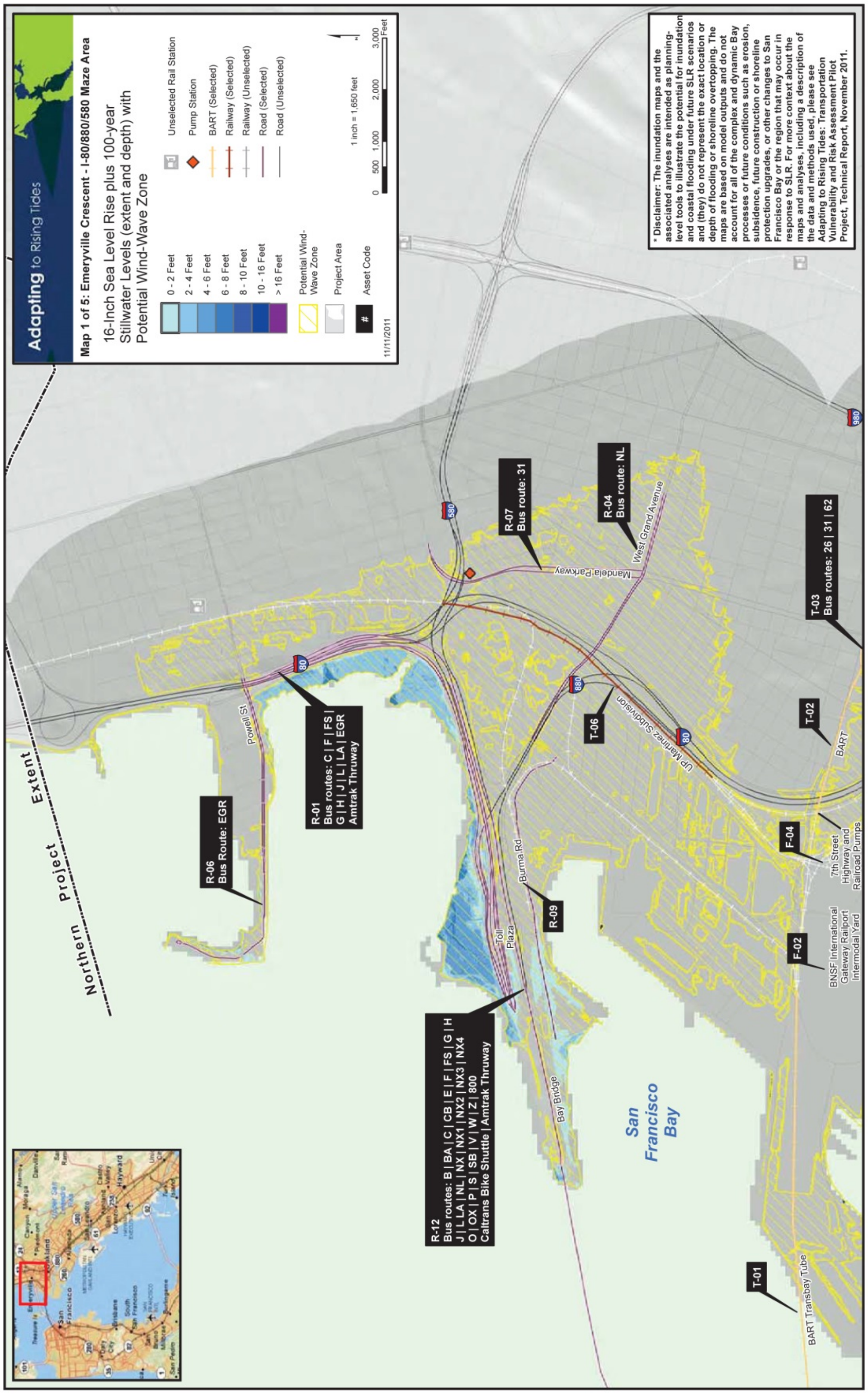

Figure 5.2. Detailed inundation map of the northern portion of Alameda County for the 100-year storm flood with 16 inches of sea level rise and additional elevation for wave effects (from ART 2001b).

5.2 Level 2 Example: The Gulf Coast 2 Study - Mobile, Alabama

This section describes a case study assessing the exposure of transportation infrastructure to coastal extreme events and climate change in a region where hurricanes are the dominant destructive storms. The approach was a scenario- and model-based analysis which used high-resolution storm surge and wave models. Storm surge flood elevation and wave height maps were produced for different possible future sea level and storm scenarios. The results were used to assess the vulnerability of road, bridge, tunnel, railway, port, and airport facilities as part of a larger comprehensive study. This case study is an example of a Level 2 type analysis as described in Chapter 4.

5.2.1 Background

The USDOT has been studying the impacts of climate change on transportation systems in the Central Gulf Coast Region in a multi-year study, "Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: the Gulf Coast Study" (USDOT 2013). This study had two primary phases. Phase 1 (completed in 2008) examined the impacts of climate change on transportation infrastructure at a regional scale. Kafalenos *et al.* (2008) mapped flooding of transportation facilities from Galveston, Texas to Mobile, Alabama by future sea levels. The exposure was determined by identifying areas with ground elevations below the future sea level rise projections/scenarios. Phase 2 was focused on a much smaller study area, Mobile County, Alabama. Phase 2, called the “Gulf Coast 2” or “GC2” study, is a more detailed study that developed and applied more complex methods for assessing climate change exposure and vulnerability.

This case study is a portion of the second major task, GC2: Task 2, which focused on scenario-based modeling of hurricanes with sea level rise. Additional detail on the study methods and results can be found in that task study report (Choate *et al.* 2012). Some of the model results developed in this case study below have been included in the NCA (Melillo *et al.* 2014).

5.2.2 Approach

This case study used storm surge and wave models with future climate scenarios. The results were maps of wave heights and water depths at transportation asset locations.

Hurricane impacts of surge and waves are the most important coastal process for this study area. Mobile County is susceptible to hurricane storm surge damage because of its location along the northern Gulf coast. The largest city in the study area, the City of Mobile, is in the northwest corner of Mobile Bay. Mobile Bay is a large, very shallow estuary with a very wide inlet to the Gulf of Mexico, Mobile Pass. Storm surge in the northern portions of the bay can be up to 6 ft higher than in the southern end of the bay. The north end of the bay is also where most of the transportation systems (roads, bridges, ports, and rails) are located. The area is frequently impacted by tropical storms and hurricanes. It has been impacted by at least one named storm in 12 of the last 17 years. Thus, proper estimation of hurricane impacts is vital for quantifying exposure to flooding and wave damage with climate change in Mobile, Alabama.

The storm surge model was validated by comparing simulated results with actual surge measurements for historic storms. The models were then used to simulate surge and waves under a variety of storm and climate change scenarios discussed below. The resulting water levels, velocities, and wave heights were mapped to quantify exposure within a GIS framework. The selection of storm and climate change scenarios and descriptions of the modeling approaches and validation are provided in the following sections.

5.2.3 Storm Selection and Climate Change Scenarios

Storms (in this case, hurricanes) and climate change scenarios were selected to bracket a reasonable range of expected conditions. The selected storms included a moderate strength hurricane and an extremely powerful hurricane. Sea level rise scenarios consistent with the projections presented in Section 2.3.1, Sea Level Rise, were considered. The storms and climate change scenarios were selected to address two main questions:

1. What are the implications of a moderate hurricane striking the region under a scenario of increased sea levels, and
2. What are the implications of a strike by a larger hurricane than the region has experienced in recent history?

Characteristics of two hurricanes which had notable impacts in Mobile County - Hurricane Georges (1998) and Hurricane Katrina (2005) - were used to address these questions. Hurricane Georges was used to evaluate the effects of a moderate storm and Katrina was used to evaluate the effects of a larger, rarer storm. Hurricane Georges made landfall near Biloxi, MS as a Category 2 hurricane. Hurricane Katrina, one of the most destructive hurricanes in US history, made landfall near Buras, LA as a Category 3 hurricane and then again near the Mississippi-Louisiana state line (over 100 miles from Mobile, Alabama). The use of these historic storms, or more correctly, the use of the characteristics of these historic storms (intensity, size, and track) was entered into the numerical models under the assumption that future storms will, in general, have similar characteristics as past storms. Additional scenarios included changes in both the storm track and the storm intensity.

The storm and climate change scenarios modeled in this case study are summarized in Table 5.1. The first two scenarios, with no sea level rise, were considered primarily for model validation (discussed later) and comparison purposes. However, their results show that the area is very exposed to extreme events today. Climate change was incorporated primarily by considering the storm effects with raised sea levels. All investigators agree that global sea levels will rise in the next century (see Section 2.3.1, Sea Level Rise). The selected sea level rise scenarios were 0.98 ft (30 cm), 2.5 ft (75 cm), and 6.6 ft (200 cm). These values were selected based on consideration of the published sea level rise projections as well as local vertical land movement estimates (see Choate *et al.* 2012).

Storm track and intensity were also modified in some scenario simulations to address the second question above. The historic storm track of Hurricane Katrina was shifted eastward such that the strongest onshore, northerly hurricane winds would be blowing up the length of Mobile Bay. This was done without modifying the forward speed of the storm or the rate of decay as the storm moved over the new landfall location.

Intensification of hurricane winds was considered. Some investigators have suggested that more intense storms may occur with climate change and there is a chance of a stronger storm than Katrina at any time. Storm intensification was simulated by considering the anticipated effects of climate change on storm winds and central pressure using guidance found in Knutson and Tuleya (2004) and Knutson *et al.* (2010). The wind speeds in Hurricane Katrina were increased by 6.5 percent. This value represents an average of the intensification range (+2 percent to +11 percent) suggested in Knutson *et al.* (2010) for hurricane wind intensification by 2100. The central pressure deficit (i.e. difference between ambient and storm central pressure) was decreased by 13 percent, which is consistent with the results of modeling in Knutson and Tuleya (2004), as well as guidance provided in Knutson *et al.* (2010).

In the final two scenarios listed in Table 5.1, the 150 mph maximum wind speeds of Katrina measured out away from land in the Gulf of Mexico were maintained in the computer simulations until the storm made landfall. More explanation of the selection of the scenarios summarized in Table 5.1 can be found in the GC2: Task 2 study report (Choate *et al.* 2012).

Table 5.1. Scenarios modeled in GC2 (modified from Choate et al. 2012).

Scenario Name	Sea Level Rise?	Track Shift?	Intensification?
Georges	No	No	No
Katrina	No	No	No
Georges+30	0.98 ft (30 cm)	No	No
Georges+75	2.5 ft (75 cm)	No	No
Georges+200	6.6 ft (200 cm)	No	No
Katrina+75	2.5 ft (75 cm)	No	No
Katrina-Shift	No	Yes	No
Katrina-Shift+75	2.5 ft (75 cm)	Yes	No
Katrina-Shift-Intensity+75	2.5 ft (75 cm)	Yes	Higher Winds, Reduced C.P.
Katrina-Shift-MaxWind	No	Yes	Maximum Winds
Katrina-Shift-MaxWind+75	2.5 ft (75 cm)	Yes	Maximum Winds

5.2.4 Storm Surge Modeling

Storm surge and the resulting inundation for each scenario were modeled with the Advanced Circulation model ADCIRC. The ADCIRC model is capable of simulating tides, instream flows, hurricane wind fields, and the subsequent water levels and velocities at discrete locations continuously over a specified duration (see Luettich *et al*. 1992; Westerink *et al.* 1994). The ADCIRC model is currently used as one of many tools to predict storm surge elevations in the development of flood insurance rate maps for FEMA.

Tides were not included in the surge simulations in this case study since the average tide range (about 1.2 ft) is much less than storm surge in the study area. Storm durations were modeled over a 2.5- to 3.0-day period prior to landfall. Storm histories were adapted from the official NOAA National Hurricane Center (NHC) storm database archives that give storm coordinates and characteristics at specified times. The internal wind models of ADCIRC were used to simulate the hurricane wind fields using these basic storm characteristics.

In the model scenarios considering sea level rise, the water level everywhere in the computational domain was increased by an amount equal to the sea level rise scenario. This procedure is analogous to lowering the earth surface elevations by an equivalent amount. The ADCIRC model has an option for specifying such adjustments without having to alter the digital elevation model.

The finite element mesh is shown in Figure 5.3. It had 446,459 nodes and 866,496 triangular mesh elements and included the entire Gulf of Mexico, Caribbean Sea, and much of the western North Atlantic Ocean. To account for upland surge flooding a seamless topographic-bathymetric mesh surface was developed for coastal Alabama as shown in Figure 5.4. Simulated water levels were saved frequently (e.g. hourly) at some discrete locations for comparison with tide gage measurements during the model validation process described below in Section 5.2.5. Simulated water surface elevations and flow velocities were saved at three-hour increments for every mesh node for the duration of the simulations. Other model output includes the recording of maximum water levels and velocities at each mesh node over the entire simulation. A map of the maximum envelope of water (MEOW) for each scenario was developed.

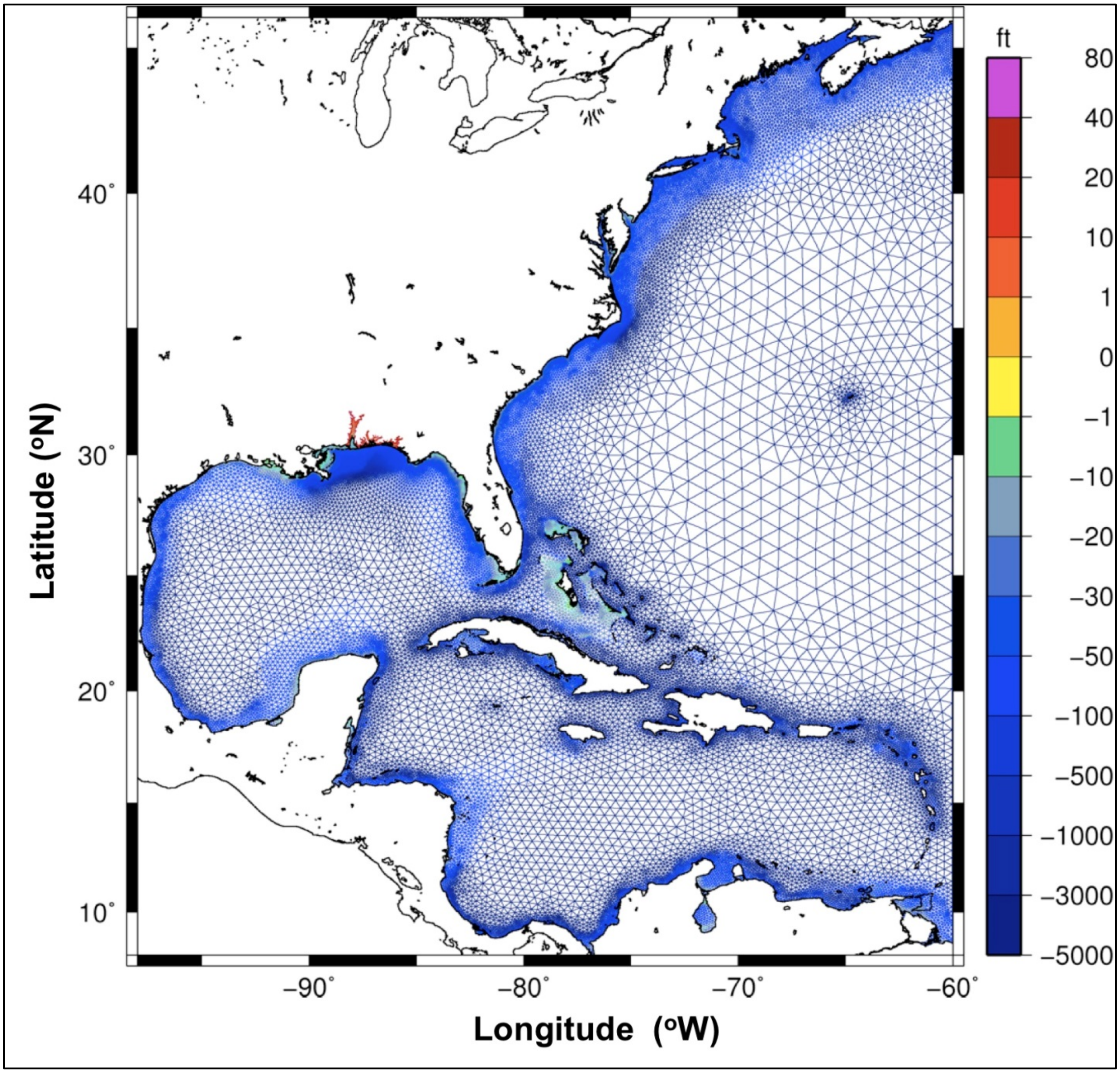

Figure 5.3. The ADCIRC mesh used in the GC2: scenario-based modeling.

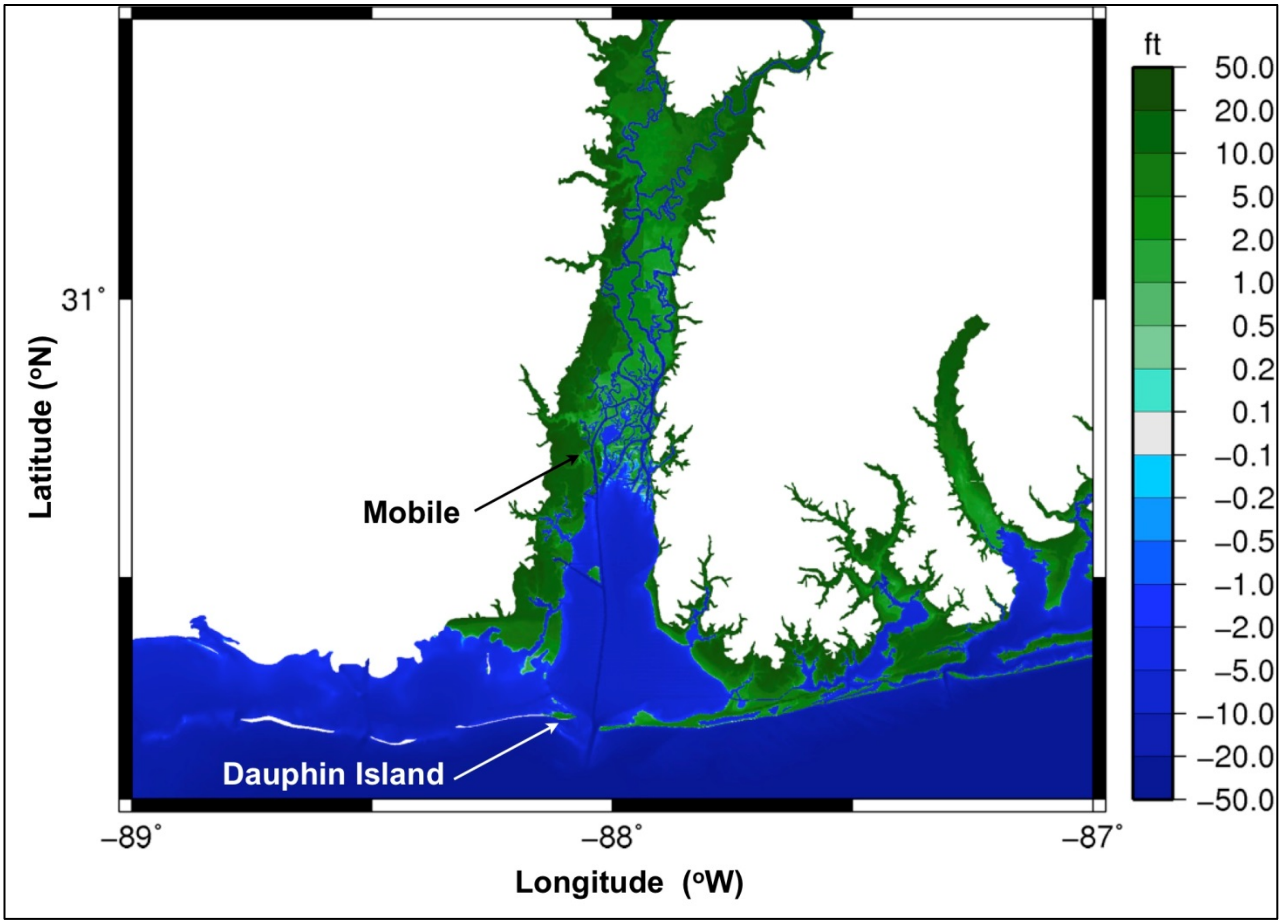

Figure 5.4. Detail of the seamless topographic-bathymetric mesh surface.

Figure 5.5 is an example of estimated surge depths across the study area for the scenario of a moderate hurricane like Hurricane Georges with 2.5 ft (75 cm) of sea level rise. Storm surge depth and inundation maps were generated by combining the ADCIRC model high water results with a GIS-based grid of ground surface elevations.

The implication of Figure 5.5 is that large portions of the study area near the bays and tidal creeks in the study area will be inundated. These areas include 33 miles of "critical" roads, 114 miles of rails, and 78 percent of port facilities. These values varied by scenario, as expected, with up to 117 miles of critical roads, 154 miles of rails, 100 percent of port facilities, and the downtown airport being inundated in the most extreme event scenarios. More examples of the maximum storm surge results can be found in the GC2: Task 2 study report (Choate *et al.* 2012).

The level of exposure and vulnerability resulting from extreme events today is one of the notable conclusions that can be drawn from this case study. For example, the road and rail inundation mileage results presented above for the scenario with 2.5 ft (75 cm) of sea level rise are only slightly higher than those for the same storm with today's sea level (see Table 25 of Choate *et al.* 2012). Similar results have been found in other vulnerability assessment studies (NJTPA 2011). The damage experienced in extreme events in the past decade, including Hurricane Sandy and Hurricane Katrina, is consistent with and confirms this conclusion. The modeling methodology outlined in this case study provides a way to quantitatively address the level of exposure and vulnerability to both extreme events and climate change.

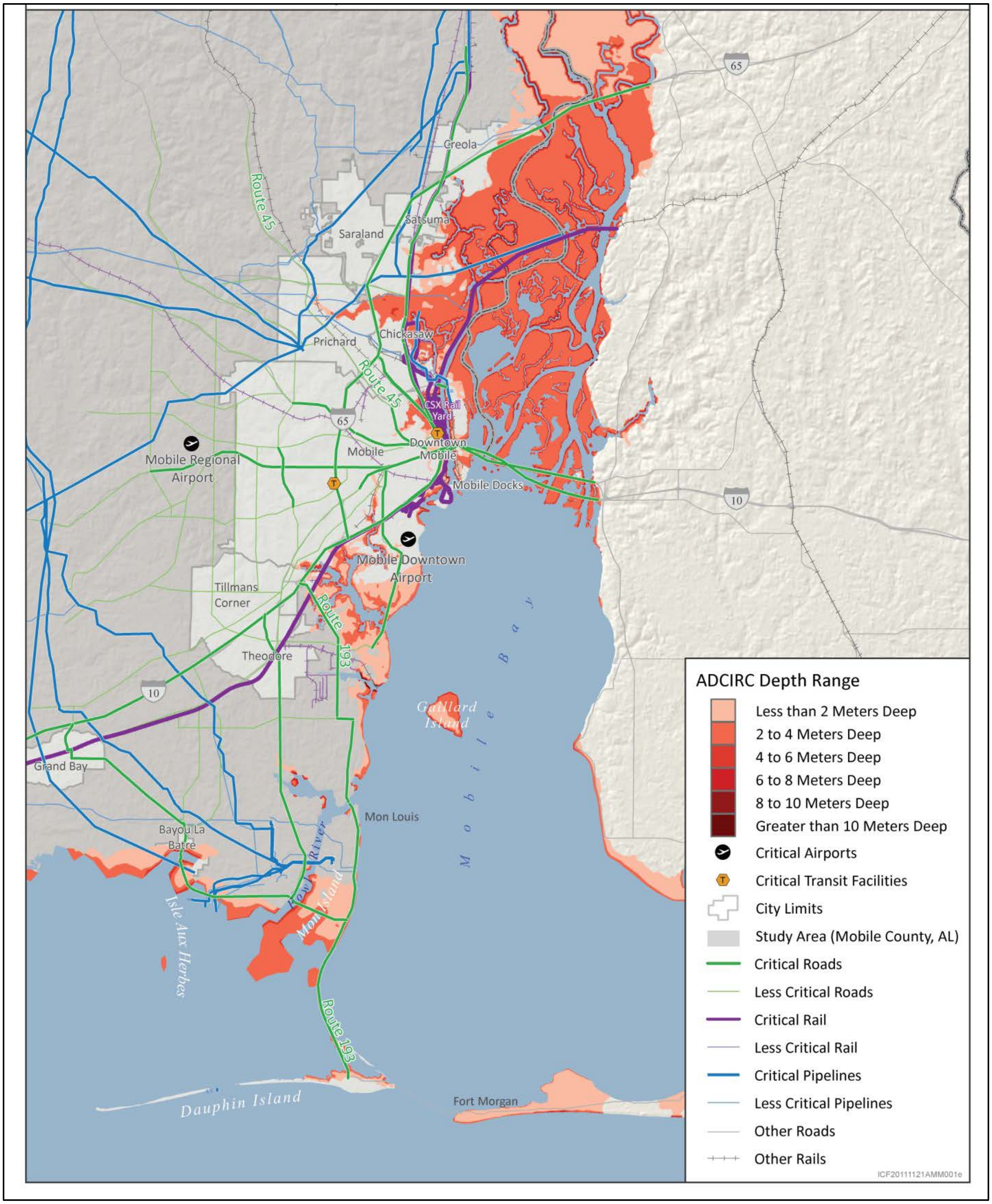

Figure 5.5. Modeled storm surge depths in Mobile County, AL for the scenario of Hurricane Georges conditions with 2.5 ft (75 cm) of future sea level rise (from Choate *et al.* 2012).

5.2.5 Validation of Storm Surge Model

The storm surge model was validated as part of this case study investigation before simulating the impacts of climate change on storm surge. The ADCIRC model and mesh were validated by hindcasting Hurricanes Georges and Katrina. Hindcasting is the use of a model to simulate a past time period, i.e. not a forecast. It is a common way to validate that a hydrodynamic model, like ADCIRC, and the project-specific input mesh are working correctly. An example of this model's hindcast of surge elevation during Hurricane Katrina is shown in Figure 5.6. The modeled surge matches the actual storm surge well.

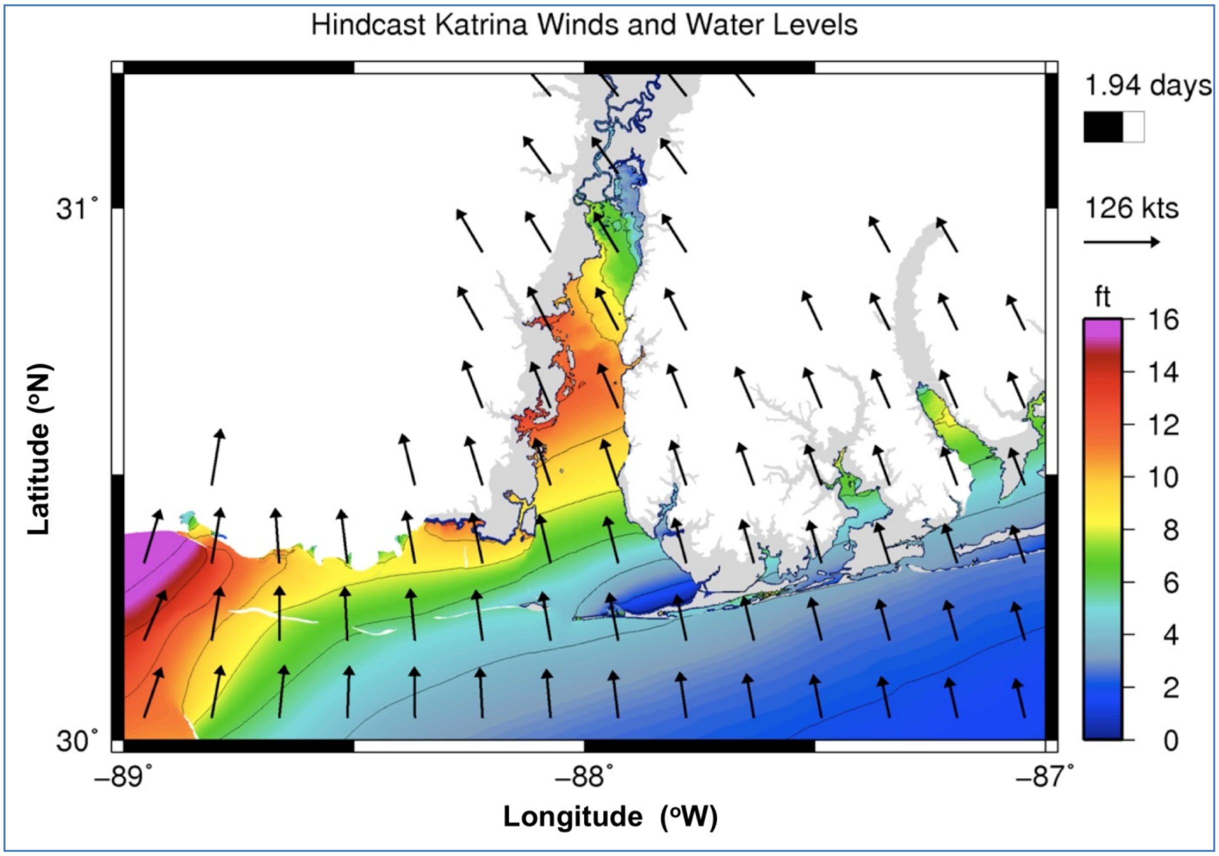

Figure 5.6. Modeled storm surge during Hurricane Katrina in Mobile Bay.

Time histories of simulated water levels were compared to NOAA tide gage measurements within and close to the study area. An example comparison of simulated and measured storm surge hydrographs is shown in Figure 5.7 for the Katrina hindcast. Such comparisons show the model's ability to faithfully recreate the time-dependent nature of storm surge. However, this is only useful in locations with tide gages in the study area.

A comparison of simulated and measured high water marks (HWMs) was also performed for each storm hindcast to evaluate the potential spatial variability of model errors throughout the study area. An example is provided in Figure 5.8 for the Hurricane Katrina hindcast. The values shown represent the difference in magnitude between simulated and measured maximum still water elevations. Comprehensive documentation of HWMs is available for many recent storms. However, the reporting of HWMs involves subjective determinations that make direct comparisons with simulated water levels difficult.

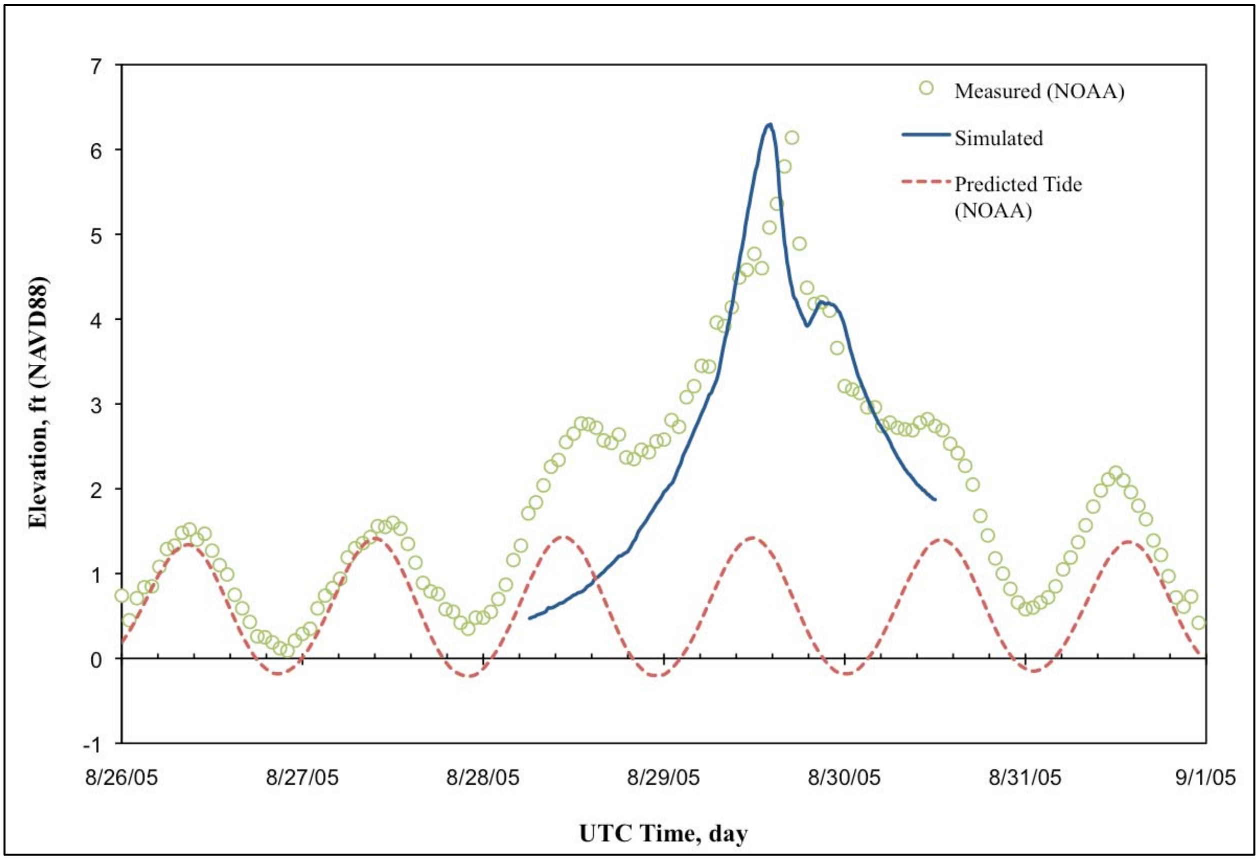

Figure 5.7. Validation of ADCIRC surge estimates by comparison with a tide gage at Dauphin Island, Alabama.

Additional analysis of the storm surge hydrographs and HWM comparisons was performed to evaluate a range of possible model errors. Calculated model errors are shown in Table 5.2. The root-mean-square (RMS) error provides an error magnitude based on direct comparisons between modeled and measured data over time, in the case of storm surge hydrographs, and in space for the HWM comparisons. An additional error estimate was expressed as the "Percent of Peak," which is the ratio of the RMS error to the measured maximum water level.

Whether the validation is adequate is a matter of professional judgment. The agreement between model and measured surge shown here was acceptable for the purposes and scope of this case study evaluation. The model was then used for the global climate change simulations as discussed.

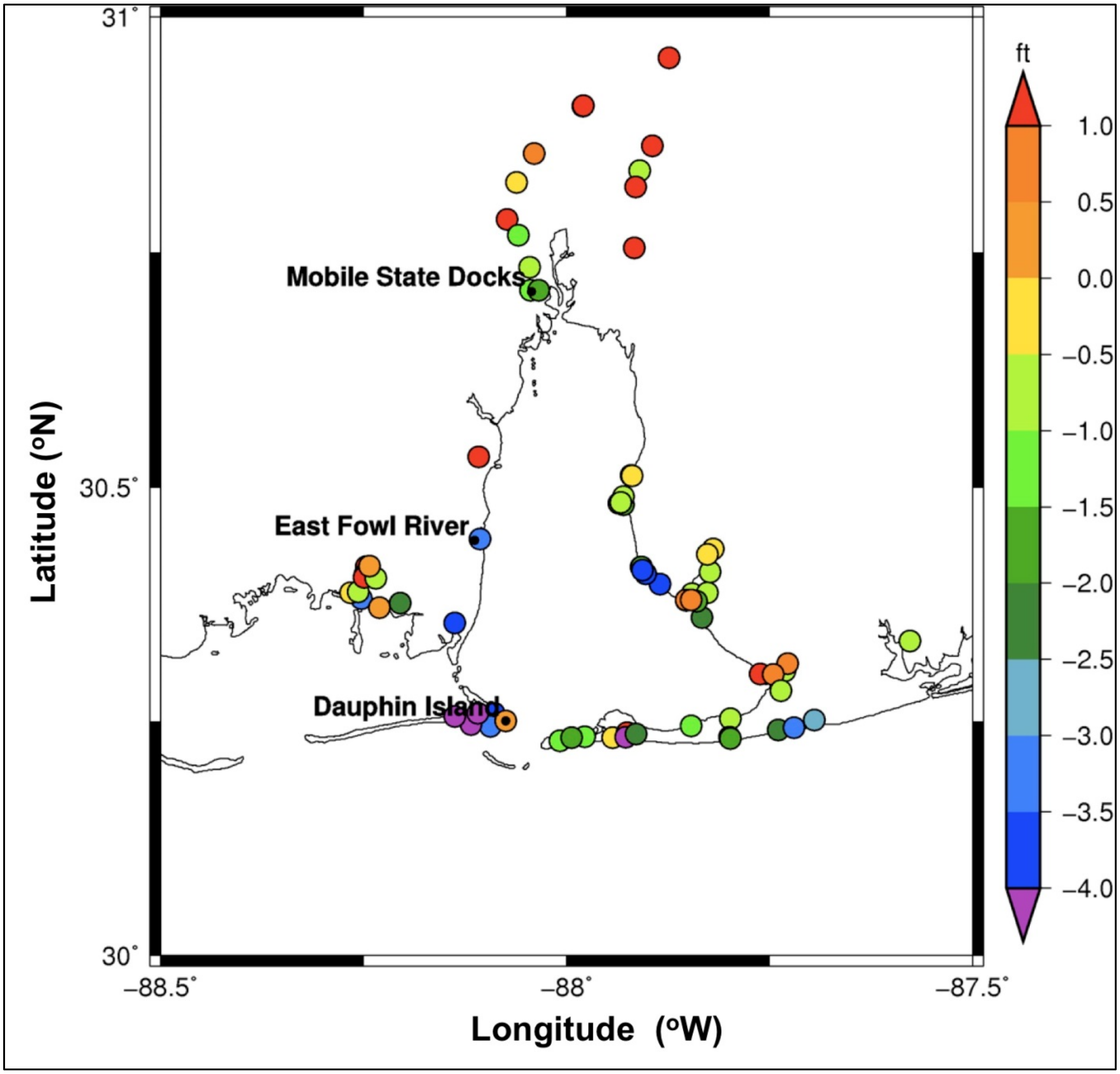

Figure 5.8. Validation of ADCIRC storm surge estimates by comparison with measured high water marks.

Table 5.2. Validation analysis of ADCIRC model storm surge estimates.

"Metric"	RMS Error (ft)	Percent of Peak (%)
78 High Water Marks	1.98	13.2
Hydrographs at Pensacola, FL	1.20	19.8
Hydrographs at Dauphin Island, AL	1.00	16.4

5.2.6 Wave Modeling

Storm waves were modeled with the Steady-State Spectral Wave model STWAVE. The STWAVE model simulates the generation and transformation of waves over variable bathymetry

(Smith *et al.* 2001). The model estimates wave characteristics at every grid point in the model domain assuming waves have come to a steady state.

The input included the ADCIRC surge simulations, measured winds in Mobile Bay, and measured waves in the Gulf of Mexico. The computational domain for the wave model was developed from a portion of the same digital elevation model used in the ADCIRC simulations but focused on a much smaller area including the bay and offshore into the Gulf. The resulting grid provided wave characteristics at a regular spacing of about 300 ft (100 m). This resolution was sufficient for subsequent exposure and sensitivity analyses in this case study.

Storm waves were simulated for the scenarios outlined in Table 5.1 using the maximum surge depths from the ADCIRC simulation. Input winds for wave generation in the bay were the maximum observed wind speed and direction. Boundary input waves were measured wave characteristics in the Gulf of Mexico during the peak of each historic storm. The results from each wave model scenario included estimates of significant wave height, peak wave period, dominant wave direction, and wave breaking throughout the model domain.

No direct measurements of waves were available within the study area to validate the STWAVE model predictions in this study. Direct measurements of wave characteristics are rarely available close to the coast where comparisons are most useful. However, the model has been extensively validated and those results are available in the published literature.

An example of the significant wave heights estimated by the STWAVE model is shown in Figure 5.9. This example is the scenario of a moderate hurricane (Georges) with 2.5 ft (75 cm) of sea level rise. Essentially, these are the waves riding on the surge shown in Figure 5.5. The wave heights are much larger in the Gulf of Mexico but the model estimates the regeneration of waves across Mobile Bay and into the areas inundated by storm surge. More examples of the wave field results corresponding to the scenarios evaluated in Table 5.1 can be found in the GC2: Task 2 study report (Choate *et al.* 2012).

The significant wave heights at one downtown Mobile location will increase from 2 ft (0.6 m) for a moderate hurricane today to over 4.3 ft (1.3 m) for some of the more severe scenarios. This is a particularly important increase because most built urban infrastructure will be severely damaged or destroyed with wave heights around 1 to 3 ft.

Results like Figures 5.5 and 5.9 can be examined to quantify the exposure of specific transportation assets to the primary damaging mechanisms: storm surge and waves. Thus, this type of Level 2 scenario- and model-based analysis provides tools for exposure and vulnerability assessments. In summary, model-based analysis, like this case study from GC2, can provide quantitative estimates of exposure which account for the complex physics of coastal storm surge and wave propagation under different climate change scenarios. It can also provide quantitative estimates of exposure to today’s climate.

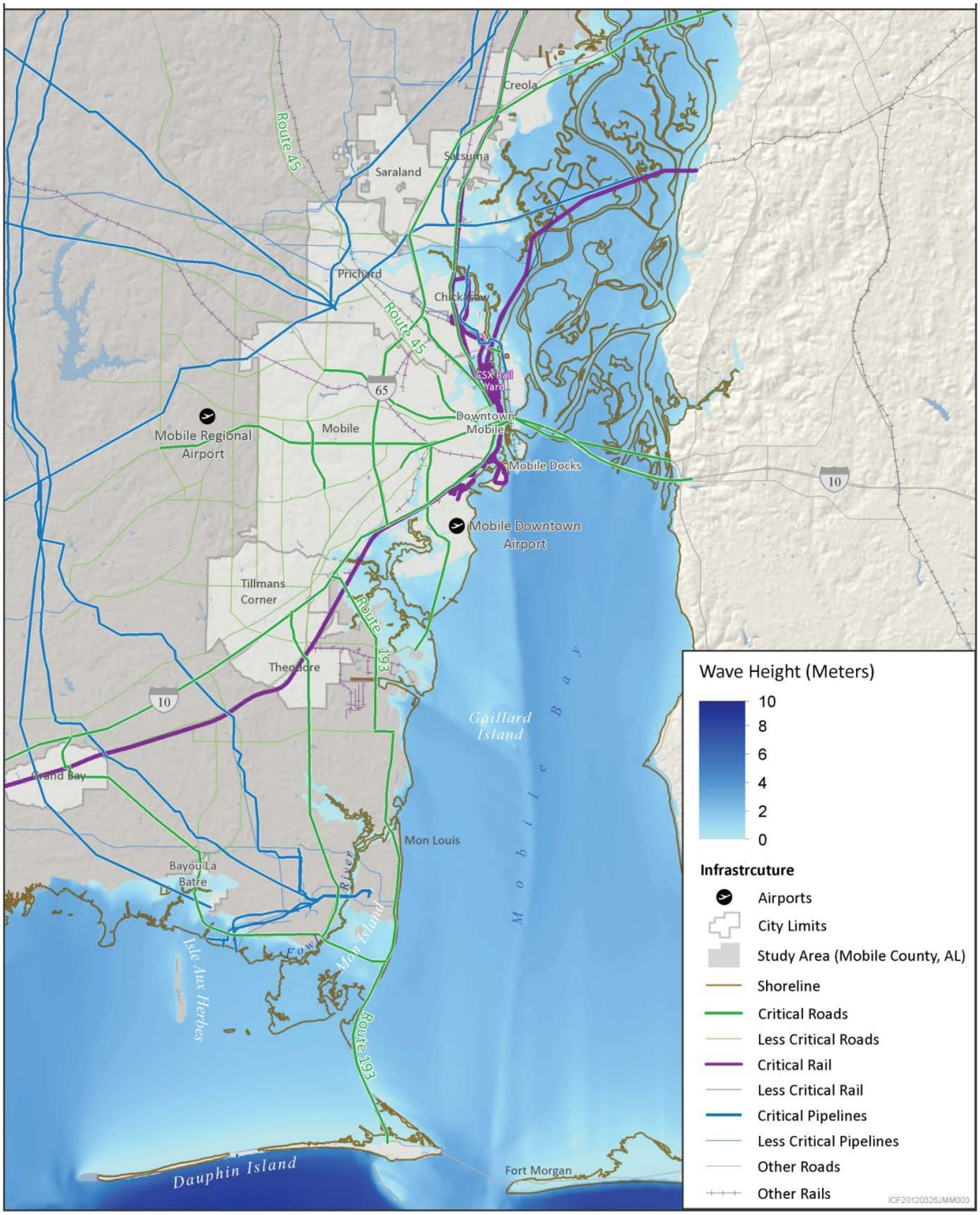

Figure 5.9. Modeled wave heights for the scenario of Hurricane Georges conditions with 2.5 ft (75 cm) of future sea level rise (from Choate *et al.* 2012).

5.3 *Level 3 Example: Synthetic Storm Analysis on the Florida Coast*

This section provides a case study of high-resolution modeling of storm surge, waves and tides, with and without future sea level targets, in the northeastern Gulf of Mexico. The case study is based on the work of Hagen and Bacopoulos (2012) and more specific details can be found there. This case study serves as an example of a Level 3 approach to mapping the extents of inundation in coastal areas under future sea level rise scenarios. Two very important outcomes are explained in this work First, the use of existing data generated through FEMA coastal flood map modernization efforts is described and a methodology presented for the reduction of the total number of synthetic storms to something more reasonable. Second, the nature of the dynamic (or nonlinear) response of surge, waves and tides to sea level rise is generalized for the study area.

5.3.1 Background

This case study demonstrates how existing data, generated through the FEMA coastal flood map modernization program, can be used along with high-resolution surge, wave, and tide models to estimate the extent and coverage of inundation under sea level rise scenarios. The study by Hagen and Bacopoulos (2012) focused on the extent of flooding due to tides, tropical storms, and hurricanes under future sea levels for three coastal counties in Northwest Florida: Franklin, Wakulla, and Jefferson. In the study, this area is referred to as the Big Bend Region of Florida. The study was made possible by the recent modernization of FEMA Flood Insurance Rate Maps (FIRMs) in these three coastal counties. More detailed information about the entire flood map modernization project can be found in Gangai *et al.* (2011).

The objectives of the study by Hagen and Bacopoulos (2012) were twofold: first, to develop a methodology whereby hundreds of existing synthetic storm scenarios could be systematically reduced to a smaller suite of storms that contribute to the majority of inundation coverage and extent defined by the 500-year return period (0.2 percent annual exceedance probability) flood plain; and second, to determine the magnitude and characteristics of the dynamic response of tide, hurricane, and tropical storm flooding to sea level rise. In the study, the terms “dynamic response” and “static response” are used to describe the sea level rise impact on inundation when the behavior is modeled deterministically (dynamic) or accounted for through a direct summation of expected water level and sea level rise increment (static).

As an example of a Level 3 analysis, this case study:

- provides an established methodology for using existing storm characterizations produced through rigorous and defensible applications of science and engineering;
- demonstrates the use of high-resolution tide, surge, and wave models for mapping the extent and coverage of inundation in coastal areas;
- describes the significance of modeling the dynamic response of flooding to sea level rise as compared to simply estimating the static response; and
- presents an example of how the effects of sea level rise on inundation, under both tidal and storm conditions, can be mapped in a probabilistic fashion.

5.3.2 Storm Selection and Climate Change Scenarios

A suite of 159 synthetic hurricanes and tropical storms was used in the original FEMA study to model the inundation hazards due to storm surge and waves. Storm characteristics such as size, translation speed, central pressure deficit, wind speed, and landfall location were chosen to simulate a broad range of flood hazards. The synthetic storm characteristics were developed through statistical analysis of regional historical storms for the years 1940 to 2008. A description of this process can be found in Toro *et al*. (2011). As a requirement for estimating the 100-year (1 percent exceedance probability) and 500-year (0.2 percent exceedance probability) flood surfaces for the FEMA FIRMs, the frequency, or return period, of each synthetic storm is also determined.

In their investigation, Hagen and Bacopoulos (2012) chose not to simulate the effects of sea level rise for each of the 159 synthetic storms used in the FEMA study. Instead, the authors analyzed the Maximum Envelope of Water (MEOW) outputs for each of the 159 storms to determine which, and how many, of the storms were responsible for generating the 500-year flood plain. The authors determined that just 14 of the 159 storms were responsible for generating full (100 percent) coverage of the 500-year flood plain. The top two storms accounted for over 40 percent coverage of the 500-year flood plain. The top five storms were responsible for 76 percent coverage of the 500-year flood plain and were selected to evaluate the effects of sea level rise on changes to the extent of inundation.

Two future sea level rise increments were considered in the study. Sea level rise increments of 0.5 ft (15.2 cm) and 1 ft (30.5 cm) were applied to represent linear and second-order (acceleration) increases of sea level, respectively. Hagen and Bacopoulos note that these values were comparable to a sea level rise forecast in Florida for the years 2006 – 2080 performed by Walton (2007). Each of the top five storms contributing to 76 percent of the 500-year flood plain was rerun under present (baseline) and future (+0.5 ft and +1 ft) sea levels. The sea level rise adjustment was made before the simulations were performed, so the effects of sea level rise on storm flooding were deterministic in nature. Additional model simulations were performed to determine the effects of sea level rise on inundation due to astronomical tides only. No storm forcing was incorporated in those simulations.

5.3.3 Hydrodynamic Models

The hydrodynamic models applied in the study by Hagen and Bacopoulos (2012) were essentially the same used during the original FEMA flood map study. Storm surge, circulation, and tides were simulated using ADCIRC and waves were simulated using SWAN. More specific details about application of these models to the original FEMA study, including their validation results, can be found in Atkinson *et al.* (2011), Salisbury *et al.* (2011), and Slinn *et al.* (2011).

As part of the original FEMA study, hydrodynamic modeling of the 159 synthetic storms was performed with and without the effects of waves. Hagen and Bacopoulos (2012) compared the extent and coverage of inundation on a node-by-node basis for each set of data. Their investigation revealed that the wave effects only contributed to 1 percent of the total flood plain coverage; and that the relative difference in water levels between the two cases ranged from 0 percent to 20 percent. Hagen and Bacopoulos (2012) speculate that while the broad and shallow nature of the continental shelf in this part of the Gulf of Mexico contributes to an amplification of wind-driven storm surge, it effectively reduces the impacts of waves by forcing the larger ones to break further offshore (i.e. through depth- or steepness-limited breaking). Therefore, the authors only used the ADCIRC model to determine the effects of sea level rise on flooding due to storms and tides.

5.3.4 Inundation Mapping

An objective of the study by Hagen and Bacopoulos (2012) was to determine the effects of sea level rise on the coverage and extent of inland flooding within a defined flood plain. Therefore, the contributions of all five simulated storms to the resulting flood surface were considered for each sea level scenario. The resulting flood surfaces were developed by capturing the

Maximum of Maximum (MOM) water levels from all five storm scenarios on a node-by-node basis.

Results for each of the two future sea level scenarios were plotted in terms of a flooding surface, generated by the MOM values, under present day sea level; and another flood surface showing the additional inundation due to sea level rise. The presentation of results clearly demonstrated that the effect of sea level rise was to increase the spatial coverage of the flood plain, as well as the depth of flooding. These flood surface maps were generated for the sea level rise increases of +0.5 ft and +1 ft for the top five storms as well as for astronomical tides alone.

Additional flood maps were produced to demonstrate the difference between a dynamic and static response of flooding to sea level rise under storm conditions and astronomical tides. The dynamic response is the flooding predicted by incorporating sea level rise into the hydrodynamic model. The static response is the flooding estimated by a simple summation of the sea level rise increment and predicted water levels on present day sea levels. Here, the flooding surface for the static response was approximated as the intersection of the estimated flood level (e.g. model result plus SLR increment) with the local terrain. When compared, the dynamic and static flood surfaces reveal differences mainly along the edge of the flood plain, and some localized differences within the interior of the defined flood plain.

5.3.5 Engineering Implications

The work of Hagen and Bacopoulos (2012) serves as a valuable example of utilizing a publicly available and highly defensible inventory of data generated through a community effort. Furthermore, the methodology used in similar FEMA flood map modernization projects is rooted in probability, making the storm and water level data appropriate for consideration in a Level 3 exposure assessment. The authors describe a sound methodology for significantly reducing the number of synthetic storms, by 97 percent, to only those contributing to a majority of the 500-year flood plain. Such a reduction results in significant cost and time savings when considering the number of model simulations that must be performed and analyzed to assess the impact of sea level rise on flooding.

Hagen and Bacopoulos (2012) clearly demonstrated that the role of sea level rise was to increase the spatial extent and characteristics of a defined flood plain. For the scenarios considered in their study, increases of approximately 10 mi^2 and 20 mi^2 to the spatial extent of the flood plain were attributed to sea level rises of +0.5 ft and +1 ft, respectively, over present day levels. And although they determined that the total area flooded did not change significantly when comparing the dynamic and static response under storm conditions (< 1 mi^2), the specific locations flooded did change. There were considerable differences in the areas flooded by tides. Overall, the dynamic response predicted as much as 1.5 times the amount of flooded area as did the static approach. Accordingly, Hagen and Bacopoulos (2012) suggest considering the dynamic response of flooding to sea level rise over a static response, particularly since their specific results are very much dependent upon the local bathymetry and terrain.

Chapter 6 – References

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Appendix A – Metric System and Conversion Factors

In SI there are seven base units and two supplemental units (Table A.1). Base units uniquely describe a property requiring measurement. One of the most common units in civil engineering is length, with a base unit of meters in SI. Decimal multiples of meter include the kilometer (1000 m), the centimeter (1 m/100) and the millimeter (1 m/1000). The second base unit relevant to highway applications is the kilogram, a measure of mass that is the inertia of an object. For temperature degrees Celsius (°C) has a more common usage than kelvin.

There is a subtle difference between mass and weight. In SI, mass is a base unit, while weight is a derived quantity related to mass and the acceleration of gravity, sometimes referred to as the force of gravity. In SI the unit of mass is the kilogram and the unit of weight/force is the Newton. Table A.2 illustrates the relationship of mass and weight. The unit of time is the same in SI as in the Customary (English) system (seconds). The measurement of temperature is Centigrade. The following equation converts Fahrenheit temperatures to Centigrade, °C = 5/9 (°F - 32).

Derived units are formed by combining base units to express other characteristics. Common derived units in highway drainage engineering include area, volume, velocity, and density. Some derived units have special names (Table A.3).

Table A.4 provides the standard SI prefixes and their definitions. Table A.5 provides useful conversion factors from Customary to SI units. The symbols used in this table for metric (SI) units, including the use of upper and lower case (e.g., kilometer is "km" and a Newton is "N") are the standards that should be followed. The multiplier in the table is given with 4 significant figures; an underline denotes an exact conversion.

Table A.1. Overview of SI.

Unit Category	Unit Measure	Units	Symbol
Base units	Length	meter	m
	Mass	kilogram	kg
	Time	second	s
	temperature	kelvin	K
	electrical current	ampere	A
	luminous intensity	candela	cd
	amount of material	mole	mol
Supplementary units	angles in the plane	radian	rad
	solid angles	steradian	sr

Table A.2. Relationship of mass and weight.

System	Mass	Weight or Force of Gravity	Force
Customary	slug	pound	pound
	pound-mass	pound-force	pound-force
Metric	kilogram	newton	newton

Table A.3. Derived units with special names.

Quantity	Name	Symbol	Expression
Frequency	hertz	Hz	s^{-1}
Force	newton	N	$kg \cdot m/s^2$
Pressure, stress	pascal	Pa	N/m^2
Energy, work, quantity of heat	joule	J	$N \cdot m$
Power, radiant flux	watt	W	J/s
Electric charge, quantity	coulomb	C	$A \cdot s$
Electric potential	volt	V	W/A
Capacitance	farad	F	C/V
Electric resistance	ohm	Ω	V/A
Electric conductance	siemens	S	A/V
Magnetic flux	weber	Wb	$V \cdot s$
Magnetic flux density	tesla	T	Wb/m^2
Inductance	henry	H	Wb/A
Luminous flux	lumen	lm	$cd \cdot sr$
Illuminance	lux	lx	lm/m^2

Table A.4. Prefixes.

Submultiples			Multiples		
Text	Exponent	Symbol	Text	Exponent	Symbol
Deci	10^{-1}	d	deka	10^{1}	da
Centi	10^{-2}	c	hector	10^{2}	h
Milli	10^{-3}	m	kilo	10^{3}	k
Micro	10^{-6}	μ	mega	10^{6}	M
Nano	10^{-9}	n	giga	10^{9}	G
Pica	10^{-12}	p	tera	10^{12}	T
Femto	10^{-15}	f	peta	10^{15}	P
Atto	10^{-18}	a	exa	10^{18}	E
Zepto	10^{-21}	z	zeta	10^{21}	Z
Yocto	10^{-24}	y	yotto	10^{24}	Y

Table A.5. Useful conversion factors.

Quantity	From English Units	To Metric Units	Multiplied by
Length	mile	km	1.609
	yard	m	0.9144
	foot	m	0.3048
	inch	mm	25.4
Area	square mile	km^2	2.590
	acre	m^2	4047
	acre	hectare	0.4047
	square yard	m^2	0.8361
	square foot	m^2	0.092 90
	square inch	mm^2	645.2
Volume	acre foot	m^3	1 233
	cubic yard	m^3	0.7646
	cubic foot	m^3	0.028 32
	cubic foot	L (1000 cm^3)	28.32
	100 board feet	m^3	0.2360
	gallon	L (1000 cm^3)	3.785
	cubic inch	cm^3	16.39
Mass	lb	kg	0.4536
	kip (1000 lb)	metric ton (1000 kg)	0.4536
Mass/unit length	plf	kg/m	1.488
Mass/unit area	psf	kg/m^2	4.882
Mass density	pcf	kg/m^3	16.02
Force	lb	N	4.448
	kip	kN	4.448
Force/unit length	plf	N/m	14.59
	klf	kN/m	14.59
Pressure, stress, modulus of elasticity	psf	Pa	47.88
	ksf	kPa	47.88
	psi	kPa	6.895
	ksi	MPa	6.895
Bending moment, torque, moment of force	ft-lb	N A m	1.356
	ft-kip	kN A m	1.356
Moment of mass	lb · ft	kg · m	0.1383
Moment of inertia	lb · ft^2	kg · m^2	0.042 14
Second moment of area	In^4	mm^4	416 200
Section modulus	In^3	mm^3	16 390
Power	ton (refrig)	kW	3.517
	Btu/s	kW	1.054
	hp (electric)	W	745.7
	Btu/h	W	0.2931
Volume rate of flow	ft^3/s	m^3/s	0.028 32
	cfm	m^3/s	0.000 471 9
	cfm	L/s	0.4719
	mgd	m^3/s	0.0438
Velocity, speed	ft/s	m/s	0.3048
Acceleration	f/s^2	m/s^2	0.3408
Momentum	lb · ft/sec	kg · m/s	0.1383
Angular momentum	lb · ft^2/s	kg · m^2/s	0.042 14
Plane angle	Degree	rad	0.017 45
		mrad	17.45