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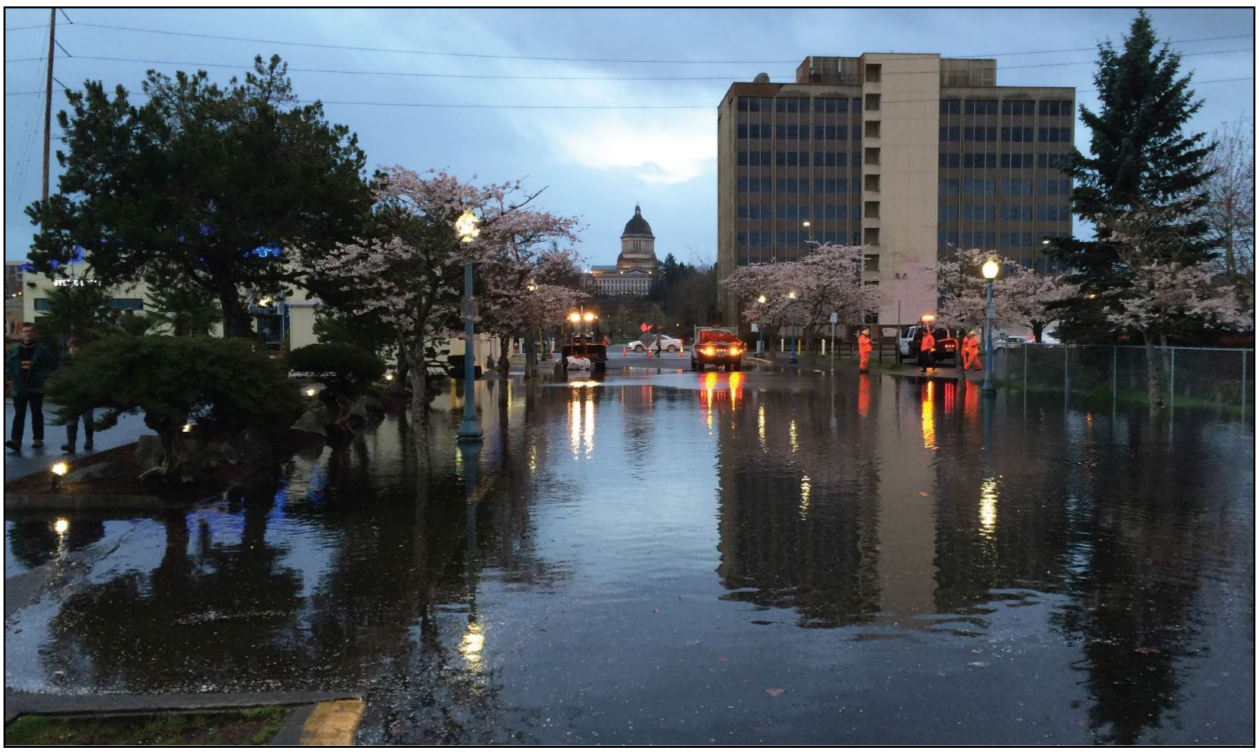

Emerging Issues Associated with Sea Level Rise

Findings from FHWA Peer Exchanges

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16. Abstract

Coastal transportation infrastructure is one of many important assets that DOTs seek to protect. In the last decade, there has been increasing concern for the vulnerability of coastal transportation infrastructure resulting from observed and projected relative sea level rise, particularly conditions of "nuisance" or "sunny day" flooding being experienced in a growing number of communities.

As a result, the FHWA sponsored a series of peer exchanges with coastal State DOTs, their partners, and experts in sea level rise to share experiences in characterizing and addressing these concerns. Objectives also sought to identify strategies for increasing resilience in coastal transportation infrastructure, particularly roadways, bridges, and tunnels. The FHWA convened these peer exchanges in four separate regions of the United States. Peer exchanges participants related their experiences and insights on these emerging issues regarding nuisance flooding and its impacts on their transportation programs. Discussion topics also included current and projected conditions of sea level rise as well as brainstorming potential solutions to reduce the vulnerability of coastal infrastructure.

Peer exchange participants expressed their opinions and recommendations, not only related to their particular communities, but for consideration by FHWA, other Federal agencies, State and local agencies, and other potential stakeholders. This document summarizes the presentations and discussions that took place during these peer exchanges. The recommendations are those of the participants, and do not necessarily align with FHWA authorities and policies.

17. Key Words
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Acknowledgments

The cover image is a picture of sunny day flooding in Olympia, Washington, taken by the City of Olympia. All photos and images are used with permission by the original author or agency.

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Supporting Purpose

The FHWA developed this document, in part, to support 23 U.S.C. § 503(b)(3)(B)(viii), that directs the Department of Transportation to *"… carry out research and development activities … to study the vulnerabilities of the transportation system to … extreme events and methods to reduce those vulnerabilities"* and the July 27, 2017 U.S. Senate Report 115-138 for the *"Transportation, and Housing and Urban Development, and Related Agencies Appropriations Bill, 2018" stated that FHWA "[is further directed to]… expand its technical assistance … to help coastal States, MPOs, and cities to revise their practices in all phases of transportation planning and asset management, project planning and development, and operations with the goal of improving the resiliency of our coastal highways and reducing the life-cycle costs for these natural disaster-prone roadways."*

List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
CFR	Code of Federal Regulations
DOT	Department of Transportation
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GW	Groundwater
MHHW	Mean Higher High Water
MPO	Metropolitan Planning Organization
NCHRP	National Cooperative Highway Research Program
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
OFR	Office of Federal Register
RSL	Relative Sea Level
SLR	Sea Level Rise
TRB	Transportation Research Board
U.S.	United States of America
USACE	U.S. Army Corps of Engineers
U.S.C.	U.S. Code (statutes/laws)
USCG	U.S. Coast Guard
USDOT	U.S. Department of Transportation
USGS	U.S. Geological Survey
USEPA	U.S. Environmental Protection Agency

Part 1 – Background, Review & Synopsis

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Chapter 1 Introduction

The FHWA regards coastal roads as those influenced by their presence in or near the water levels, tides, waves, and environment unique to the Nation's coast. The coastal transportation milieu includes the Pacific, Atlantic, Arctic Ocean and Gulf of Mexico shores, the Great Lakes and any other water bodies affected by coastal storms, waves, and sea level rise (NRC 2015). In the technical reference "Highways in the Coastal Environment" (HEC-25, 3rd edition), the FHWA describes the science and characteristics of the coastal environment, including extreme weather events, waves, and rising sea levels (FHWA, 2020).

Beyond coastal extreme weather events, rising sea levels threaten existing coastal transportation infrastructure in a less dramatic but still compelling manner. These emerging threats include increases in "nuisance flooding," backflows, water quality effects, changes in storage, saltwater intrusion, and pavement impacts, among others.

1.1 What is Sunny Day Flooding?

For the purposes of this document, nuisance – or "sunny day" – flooding is the increased frequency of flooding related to high tides primarily associated with an increase in sea level. Many examples of this exist today including in Annapolis, Maryland (Figure 1) and Olympia, Washington (Figure 2).

Figure 1. Sunny day flooding in Annapolis, Maryland (Photo credit: Joe Krolak. Used with Permission).

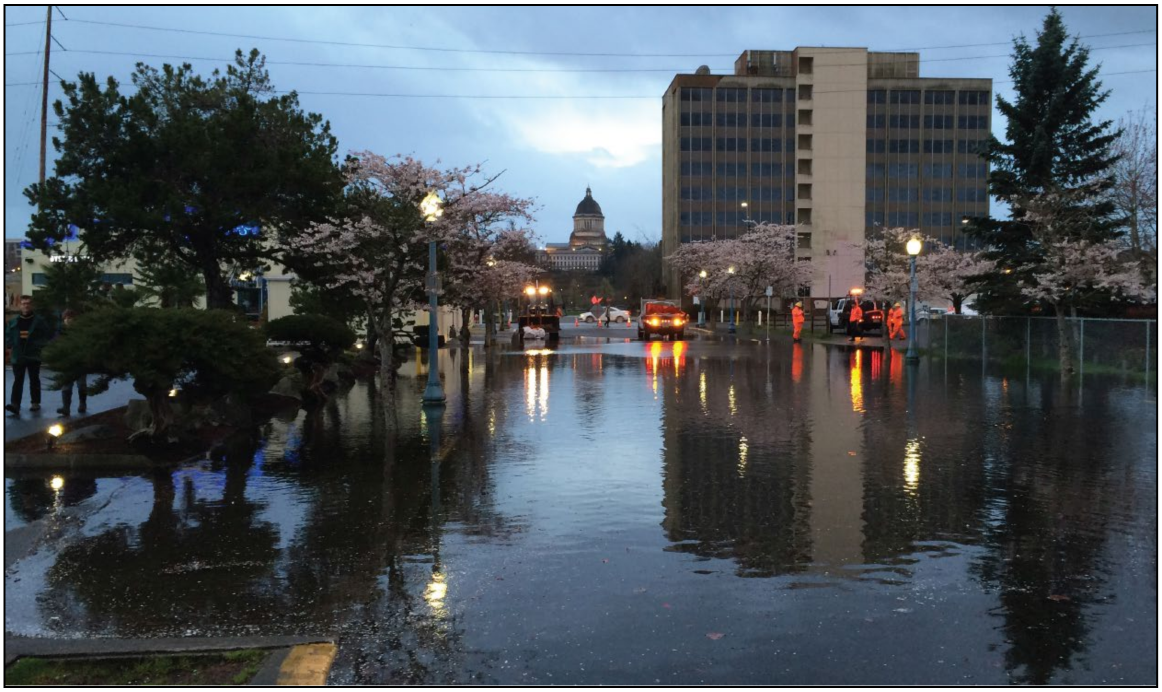

Figure 2. Sunny day flooding in Olympia, Washington (Sylvester Street) (Photo credit: City of Olympia. Used with Permission).

Increases in sea level also have the potential to increase the frequency[1] of roadway overtopping (i.e., when the water surface rises to and inundates the roadway) caused by coastal storms (e.g., from once in every ten years to several times in a year). This reduces access and safety on roadways and tunnels.

1.2 Why Is the FHWA Involved?

The July 27, 2017 U.S. Senate Report 115-138 for the *"Transportation, and Housing and Urban Development, and Related Agencies Appropriations Bill, 2018"* stated that FHWA *"[is further directed to] expand its technical assistance … to help coastal States, MPOs, and cities to revise their practices in all phases of transportation planning and asset management, project planning and development, and operations with the goal of improving the resiliency of our coastal highways and reducing the life-cycle costs for these natural disaster-prone roadways."*

Additionally, 23 U.S.C. § 503(b)(3)(B)(viii) directs the Department of Transportation to *"… carry out research and development activities … to study the vulnerabilities of the transportation system to … extreme events and methods to reduce those vulnerabilities."* This report is such a research study that investigates emerging vulnerabilities in the highway transportation study.

[1] In the context of this report, "frequency" denotes the number of occurrences of some event, rather than an explicit alignment with some probabilistic value (e.g., 10 percent annual exceedance probability). For example, if the number of days per year where observations of nuisance flooding occur increase from one year to a later year, the report describes this as an increase in the frequency of nuisance flooding.

1.3 Questions for Consideration

Such situations and Congressional direction led the FHWA to consider questions such as:

- What are emerging threats to coastal roadways associated with sea-level rise?
- How does the scientific literature describe these issues?
- How significant and extensive are these emerging threats?
- How might they differ across various coastal locations of the United States?
- What are potential resilience, adaptation, and mitigation approaches?
- What information can the FHWA obtain from our transportation partners, stakeholders, and others in the coastal community?

Therefore, to better understand these types of coastal flooding situations, the FHWA engaged in a study of such emerging issues in coastal roads and highways.

1.4 Seeking Answers and Insights

The study sought to answer these questions above vis-à-vis several tasks:

- Review of the relevant literature.
- Seek out insights, understandings, lessons, and recommendations from the transportation community, via four peer exchange workshops:
  - Mid Atlantic Coast, Maryland (March 8, 2018),
  - Gulf Coast, Florida (March 29, 2018),
  - Pacific Coast, Washington (April 12, 2018), and
  - North Atlantic Coast, Massachusetts (April 26, 2018).
- Synthesizing important takeaways from the first two tasks.
- Documenting this study, findings, and other information within this report.

1.5 Report Structure

The FHWA structured this report in the following manner:

Part 1 – Background, Review & Synopsis

- Chapter 1 provides an introduction, background, and overview of the study.
- Chapter 2 describes findings from research into the topic, focusing on the best available actionable scientific literature relevant to the United States.
- Chapter 3 provides a synopsis of these emerging issues.

Part 2 – Peer Exchanges

- Chapter 4 provides the peer exchange agenda, logistics, elements, and discussion framework.
- Chapter 5 synthesizes peer exchange themes, findings, and participant recommendations.

Part 3 – Syntheses and Summaries

- Chapter 6 synthesizes and summarizes the study.

Part 4 – References and Appendices

- Chapter 7 provides References
- Appendices sections provides additional information and details.

1.6 Role of FHWA

The FHWA is not a science agency, nor does it have authorities beyond those provided under statute or regulation. However, as described above, FHWA has a robust role providing technical assistance to coastal transportation stakeholders. The FHWA served as the facilitator of discussions, information exchange, and materials. The material herein represents the opinions of participants and describes results from authoritative scientific studies conducted by others. This study report does not contain any FHWA recommendations nor policies.

Finally, the information within this report represents a “snapshot” of a study occurring between 2017 and 2018. With some slight exceptions, the report attempts to describe the state of knowledge available during that period. The FHWA believes that the information remains relevant to such discussions that still occur to the present period. To illustrate, the Bipartisan Infrastructure Law (BIL), enacted as the Infrastructure Investment and Jobs Act (Pub. L. 117-58, November 15, 2021), introduced new initiatives (e.g., Promoting Resilient Operations for Transformative, Efficient, and Cost-saving Transportation (PROTECT) program [23 U.S.C. 176], which provides funds for resilience improvements through formula and discretionary grant programs) and amended the FHWA Emergency Relief statute [23 U.S.C. 125] to allow mitigation of risks of recurring damage to roadways because of flooding.

Chapter 2 Review of Scientific Literature

To better understand and characterize context and deliver background information to peer exchange participants, the FHWA conducted a review of the recent scientific literature in the study topic.

2.1 What Sources Help Inform the Topic?

The breadth of literature into sea level rise is quite significant, representing a myriad of groups, organizations, and nations; and spanning worldwide conditions. The FHWA focused on recent U.S. Government produced, authoritative, and scientific sources. The National Oceanic and Atmospheric Administration (NOAA) and the Transportation Research Board (TRB) of the National Academy of Science served as primary scientific sources. Specifically, sources from NOAA and TRB included:

- NOAA paper, published June 7, 2017 by William V. Sweet[2] (NOAA) *et al.* entitled "*2016 State of U.S. High Tide Flooding and a 2017 Outlook;"*
- NOAA technical report, published February 2018, by William V. Sweet, et al. entitled "*Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold;"* and
- TRB paper, dated March 13, 2018 by Jacobs, J.M., L.R. Cattaneo, and W.C. Sweet entitled *"Recent and Future Outlooks for Nuisance Flooding Impacts on Roadways on the East Coast."*

In the context in facilitating the study, an advantage of these sources was their consideration of transportation and highway implications within their respective bodies of research. The lead authors specifically provide seminal research into the topic of "nuisance" flooding. Additionally, the lead authors have collaborated with other U.S. Climate Scientists, Oceanographers, and affiliated Federal agencies, including the U.S. Army Corps of Engineers (USACE) and others. This cross-Federal collaboration also facilitated alignment to the areas desired within this study.

The intent was to present such current research relating to sea level rise during the actual peer exchange workshops. The research presents data verifying the trend of increasing coastal flooding events that many of workshop participants have experienced.

2.2 Findings from Literature

The literature review focused on two areas:

- The potential extent of potentially affected coastal roadways; and
- How science characterizes the potential changes in sea level rise applicable to the study.

2.2.1 Extent of Coastal Roads

There are thirty States that have coasts and shorelines (FHWA 2020). The 2010 census revealed that 39% of the U.S. population lived in the 452 coastal counties, those with shorelines on the major coasts and the Great Lakes (FHWA 2020). Population density in the coastal counties is six times greater than the inland counties (FHWA 2020). The literature revealed that approximately 60,000 road miles in the United States are occasionally exposed to coastal waves and surge (FHWA 2020). These values did not

[2] William V. Sweet is a researcher and oceanographer with NOAA's National Ocean Service. His works helped define and articulate the state-of-art and practice within this research topic.

consider any changes in sea level; instead assuming that those levels represent stationarity for the associated coastal waters.

2.2.2 Science and Nuisance Flooding

The scientific literature documents the growing problem of high tide (“sunny day”) flooding, e.g., Sweet *et al*. (2018) and Jacobs *et al*. (2018). For example, as depicted in Figure 3, Sweet *et al*. (2018) describes the problems associated with sea level rise on a range of flooding events in the historical record. In this figure, Sweet *et al*. illustrate that in the 1960s there was a probability of certain water levels occurring related to both storms and tides. In the 2010s, the record shows this probability distribution shifting to the right with increasing relative sea level (RSL) resulting in higher water levels associated with the same probabilities.

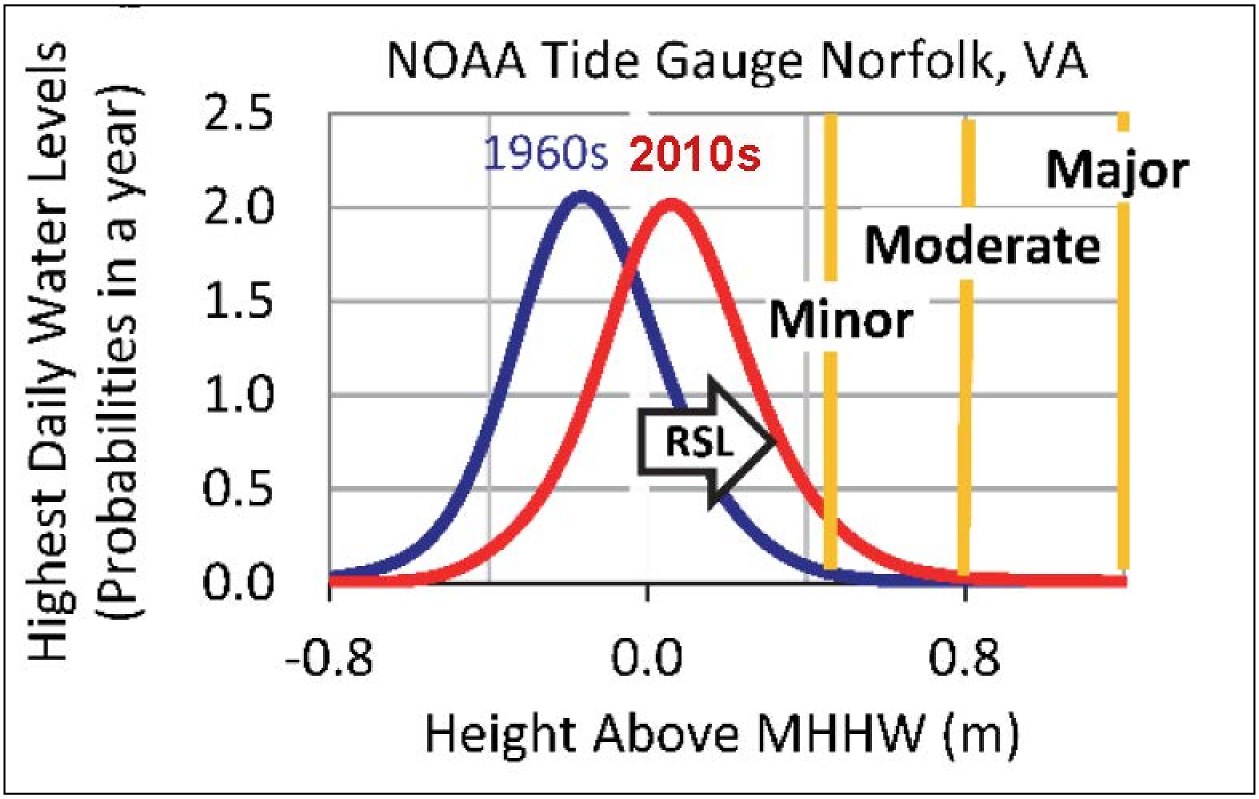

Figure 3. Increases in flooding with relative sea level (RSL) at Norfolk, Virginia (from Sweet *et al*. 2018).

Higher water levels occur for minor (high tide), moderate, and major (storm-related) floods. The NOAA defines the flood thresholds based on the surrounding topography and the potential consequences of high-water levels. The NOAA defines a minor flood as minimal or no property damage, but possibly some public threat or inconvenience. While all types of flooding are affected by rising sea levels, this report is focused on the increasing occurrence of minor flooding.

The NOAA paper “*2016 State of U.S. High Tide Flooding and a 2017 Outlook”* (Sweet et al. 2017) and NOAA report “*Patterns and Projections of High Tide Flooding Along the US Coastline using a Common Impact Threshold” (*Sweet *et al*. 2018) analyzed trends in minor flooding at a set of 28 tidal gauges with a long period of record from 1950 to the present located as shown in Figure 4. This figure also shows the elevation that defines minor flooding relative to the current mean higher high water (MHHW) based on color-coded ranges. Red indicates that a minor flood is considered to occur at levels 0.15 to 0.3 m above

MHHW while the highest range is 0.76 to 0.90 m above MHHW. Areas in the red colored range can experience the consequences of a minor flood with relatively small exceedances of MHHW.

Sweet *et al*. (2017, 2018) tallied the frequency of minor floods (exceedance of a pre-defined elevation at each gauge) at the 28 tidal gauges[3] shown in Figure 4 as shown in Figure 5. For these gauges, the minor flooding events have increased from approximately 50 minor flooding events per year at all the gauges combined in the 1950s to approximately 400 events per year in the decade beginning with the year 2010. Averaged over the 28 gauges, this is an increase from an average of 2 minor flooding events to 14 at each gauge location. The changes at these gauges cannot be assumed to be representative of the coastline throughout the U.S. but are indicative of the growing problem.

Table 1 summarizes the analysis of Sweet *et al*. (2018) for projected conditions at coastal regions throughout the United States. Table 1 depicts two future scenarios (Intermediate Low and Intermediate) for two periods (2041-2050 and 2091-2100). For each coastal region, the table reports projected annual flooding events (plus or minus [±] one standard deviation) for each scenario and each period.

As previously defined, these flooding events include minor, moderate, and major events. For example, using the Intermediate Low scenario from 2041 to 2050, Sweet *et al*. (2018) estimates, on average, 44 annual flood events at locations in the Northeastern Atlantic region with a standard deviation on that estimate of 11 events per year. The report estimates further increases in the subsequent period of 234 annual flood events with a standard deviation of 56 events per year.

The percentage of those floods resulting primarily from tides (minor flood events) is also included in the table. The absolute numbers are less important than the clear indication that the high tide flooding experienced today is likely to worsen throughout this century. For example, in the NE Atlantic region, not only are the number of coastal flooding events from all sources projected to increase, but the number attributable primarily to tides increases from 31 percent in the decade beginning in 2041 to 95 percent in the decade beginning in 2091.

Table 1. Projected high tide flood frequencies (from Sweet *et al*. 2018).

	2041-2050 Average				2091-2100 Average			
U.S. Region	Int. Low Scenario	% tides	Int. Scenario	% tides	Int. Low Scenario	% tides	Int. Scenario	% tides
Northeast Atlantic	44±11	31%	132±26	46%	234±56	95%	363±2	100%
Southeast Atlantic	26±14	35%	85±33	65%	193±59	100%	364±2	100%
Caribbean	0±0	NA	6±3	11%	142±15	67%	365±0	100%
Eastern Gulf	23±29	2%	81±44	53%	199±66	79%	364±2	100%
Western Gulf	80±35	46%	184±45	79%	350±11	100%	365±0	100%
Southwest Pacific	13±9	75%	36±15	85%	84±29	100%	345±11	100%
Northwest Pacific	17±12	25%	32±21	66%	67±62	43%	281±58	100%
Pacific Islands	7±12	42%	44±27	66%	187±52	100%	365±0	100%

[3] NOAA uses the term "gauge" to refer to their record devices. This differs from the U.S. Geological Survey's (USGS) use of "gage." To reflect that this study applied NOAA information, it uses "gauges."

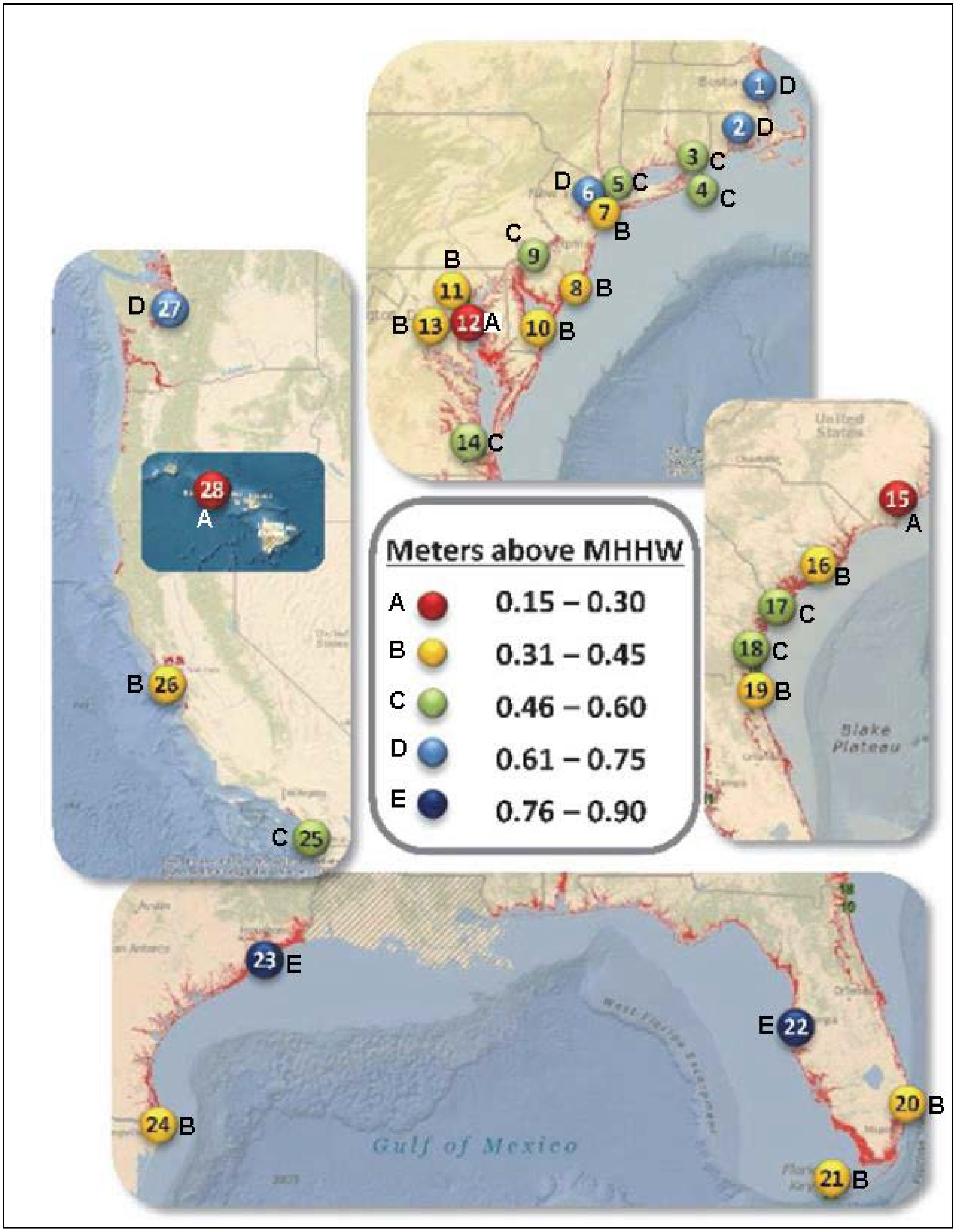

Figure 4. High tide gage locations (from NOAA [Sweet *et al*. 2017]).

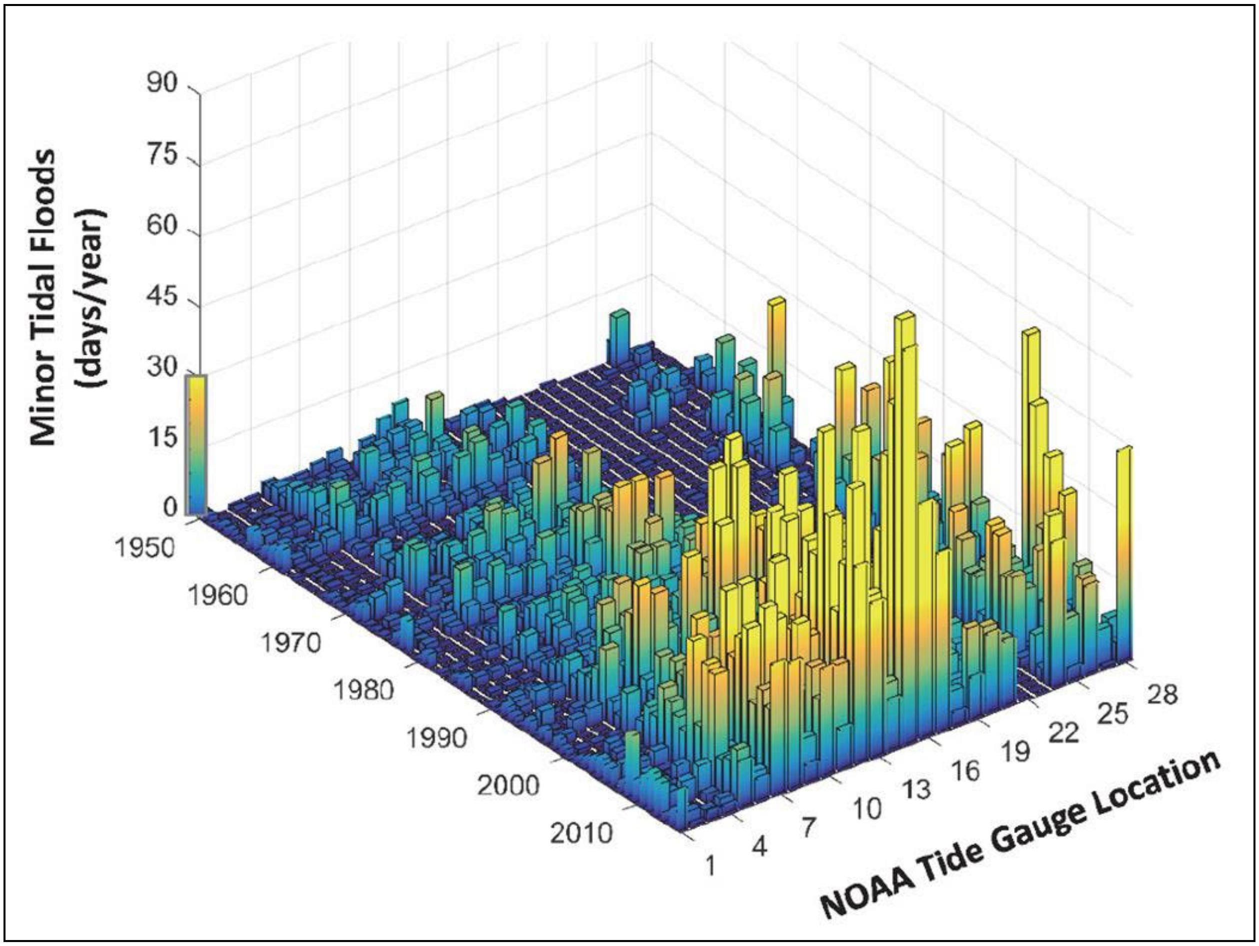

Figure 5. Tally of minor high tide flooding at selected gauges (from NOAA [Sweet *et al*. 2017]).

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Chapter 3 Science Review Synopsis

Using scientific literature and aligning these with areas where the FHWA has statutory and regulatory authorities, the study compiled a list of potential emerging issues associated with relative sea level rise, their potential consequences, and possible responses.

3.1 Some Potential Effects

The emerging issues, beyond exacerbated storm-related flooding, included the following areas:

- Nuisance flooding.
- Increasing frequency and duration of flooding.
- Loss of freeboard on roads, bridges, and tunnels.
- Reduced navigational clearances.
- Groundwater table rise.
- Groundwater quality changes, e.g., saltwater intrusion.
- Stormwater management performance and effects on hydraulic grade line (HGL).
- Effects on coastal ecosystems, e.g., saltwater marshes.

3.1.1 Increased Flooding Frequency or Duration

The consideration of a peak discharge, storm surge stillwater level, or wave crest remains a basis of transportation hydrologic and hydrodynamic design and analysis within U.S. practice. For example, the FHWA defines the term "design flood" in regulation 23 CFR 650.105(d) as *"the peak discharge, volume if appropriate, stage or wave crest elevation of the flood associated with the probability of exceedance selected for the design of a highway encroachment."*

However, as denoted by inclusion of the language *"volume if appropriate,"* the FHWA recognizes that some designs may wish to consider other aspects of hydrologic or hydraulic manifestations. As depicted in Figure 3, the frequency of an event may exhibit *nonstationarity* or a *"characteristic of time series data such that the data are heterogeneous. Trends over time prevent historical data from being used to estimate future conditions."* (FHWA, 2016). In other words, the 1960 era tidal data and statistics does not represent the 2010 era data. This has stochastic implications in regard to assumptions of probabilities of events, as this may preclude being able to associate the design flood with the "*probability of exceedance selected for the design*." [23 CFR 650.105(d)].

Another implication is that while a transportation structure may exhibit resilience from a few extreme events over its intended service life, the design may not yield the same resilience from increased instances (or frequency) of those same events (FHWA 2016). For example, some scour formation might result from repeated hydrodynamic loadings upon the channel bed material (Krolak and Henderson 2016).

3.1.2 Reduced Freeboard

The FHWA defines "freeboard" as *"the vertical clearance of the lowest structural member of the bridge superstructure above the water surface elevation of the overtopping flood."* [23 CFR 650.105(g)]. Regarding application of freeboard, the FHWA's regulations provide that freeboard *"shall be provided … to protect bridge structures from debris and scour-related failure."* [23 CFR 650.115(a)(3)]. In other words, freeboard is some distance between water surface and the structure, usually specified in a State DOT design manual or specification, that affords the protection described at 23 CFR 650.115(a)(3)

(FHWA, 2012). Additionally, such a definition and usage align with typical practice applicable to roadways, tunnels, and other hydraulic structures (FHWA, 2012). The FEMA's floodplain management regulations at 44 CFR, sections 59 through 80 may also offer insights on this topic.

Therefore, logically, increasing sea levels reduce the freeboard provided to protect roads, bridges, and tunnels from the negative effects of high water. Manifestations of these reductions or losses in freeboard may include, depending on location and circumstances, situations such as reduced passage of debris, possible pressure flow and/or increased wave impacts.

3.1.3 Navigable Water Clearances

The General Bridge Act of 1946 [33 U.S.C. § 525 through 533] requires the location and plans of bridges and causeways across the navigable waters of the United States be submitted to and approved by the U.S. Coast Guard (USCG) prior to construction. [33 U.S.C. § 525; see also 33 CFR Parts 114 and 115]. In addition, the Transportation Act of 1966 [Public Law 89-670] made the USCG responsible for ensuring that bridges and other waterway obstructions do not interfere with the navigability of waters of the United States without express permission of the United States Government[4]. The USCG generally focuses on two bridge dimensions: horizontal clearance (i.e., width of the bridge span over waters, usually for vessel maneuverability) and vertical clearance (the distance from water to the low portion of the span over the channel) (USCG 2004). The USCG and FHWA have variously estimated that there may be many thousands of coastal bridges subject to such permits (USCG 2013, FHWA 2022). On such coastal navigable waterways, sea level rise reduces vertical clearances of those bridges.

Additionally, these bridges may be susceptible to vessel collision concerns. Typical practice reduces the risk of vessel impacts by using pier protection and fendering systems[5]. The design of such systems assumes load impact from the vessel to the bridge element at certain water surface elevations. Increased water surface elevations, because of sea level rise, could exacerbate such impacts as the locations of the vessel/bridge collision could transfer forces onto substructure elements not designed for such loads.

3.1.4 Groundwater Effects

Increasing sea levels may also affect groundwater levels and groundwater quality, as well as the performance of stormwater management systems. The hydraulic grade line performance of storm drains may be adversely impacted by raised tailwater conditions at outfalls. These effects may warrant some brief scientific and engineering discussion.

Distinct from surface waters, the level of groundwater is generally a function of either spring/seepage flow or surface water infiltration (FHWA, 2002). The surface flow infiltration may be from (1) rainfall permeation into the soil or (2) the interchange/interflow between groundwater and waterbodies. In keeping with principles of the conservation of mass (i.e., water), the term "water budget" describes the

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[4] Subsequent legislation amended 23 U.S.C. § 144 to provide certain exceptions to USCG's authority under 33 U.S.C. § 401 and 33 U.S.C. § 525 for bridges constructed, reconstructed, rehabilitated, or replaced using Federal-aid funds. [23 U.S.C. § 144(c)(2)].

[5] 23 CFR 650.807(f) provides that where the risk of ship collision is significant, highway agencies shall consider, in addition to USCG requirements, the need for pier protection and warning systems as outlined in FHWA Technical Advisory 5140.19, Pier Protection and Warning Systems for Bridges Subject to Ship Collisions, dated February 11, 1983. The nonbinding LRFD Bridge Design Specification Guide (AASHTO 2020) and nonbinding AASHTO vessel collision guide specification (AASHTO 2009) also provide useful information on vessel collision design and analysis for bridges on the National Highway System (NHS).

analytical framework for the inflow, storage, and outflow constituents of such groundwater levels (FHWA 2002). The interchange between the groundwater level and surface water level (e.g., ocean, or river) helps dictate those inflow and outflow constituents.

To illustrate, should a drought reduce the water levels in a river or lake, that reduction may manifest itself with a reduction of groundwater levels. In the scenario of sea level rise, the increase of surface waters will result in a corresponding increase in groundwater levels as well.

In such a sea level rise scenario, over time, this reduces the overall storage capacity of the groundwater water budget system. The implications of such loss of storage means a reduction in the ability of the soil to allow rainfall infiltration; in turn resulting in larger surface runoff flows (and potential surface flooding).

The water quality aspects of increases of sea level rise into groundwater is a result of the interchange constituent described above. In this case, the salinity associated with the oceanic surface waters enters as an inflow and can contaminate the groundwater system.

As many stormwater quality and best management practices also rely on infiltration to mitigate water quality issues, such increased groundwater levels affect those capabilities as well (FHWA 2009). For example, reductions in efficiencies by infiltration trenches to remove fine particulates and soluble pollutants (FHWA 2009).

The increased groundwater has impacts on storm drains both via infiltration into the pipe joints (seepage) and, potential buoyancy issues (the pipes acting via Archimedes principle). The infiltration scenario reduces the potential hydraulic capacity of the network and may contribute to loss of pipe embedment because of fine soil intrusion. The hydrostatic forces may induce structural and geotechnical instability of the network.

Finally, storm drain surcharge conditions are a potential issue. For example, as a result of tidal conditions, coastal storm drain outfalls may employ a flap gate for the purpose of preventing back-flooding of the drainage system (FHWA 2009). However, to function for drainage, flap gates require enough differential pressure to allow discharge in the desired direction. Increases in the outfall water levels may affect the differential pressure, paradoxically preventing outflows and, thus surcharging the pipe network.

3.1.5 Ecosystem Effects

Another emerging issue is the effect of sea level rise on coastal ecosystems (e.g., saltwater marshes). Beyond potential ecological effects resulting from ecosystem disturbance as these natural features are diminished, these coastal ecosystems may lose some ability to buffer coastal transportation infrastructure against storm surge and waves.

For example, the marshes or mangrove systems may serve to dissipate wave energy prior to reaching the roadway embankment. As depicted in Figure 6, in 2004, after Hurricane Jeanne struck the east coast of Florida, portions of a local roadway with riprap experienced more significant damage than adjacent locations with mangroves and “offshore” natural species.

Fortunately, recent collected materials on use of natural and nature-based features and solutions for coastal areas provide insights and approaches relevant to nuisance flooding issues and sustainability of some environments (USACE 2015). Additionally, many of these materials specifically include information on sea level rise and other resilience concepts related to these effects.

Figure 6. Local roadway damage from Hurricane Jeanne (FHWA photo).

Part 2 – Peer Exchanges

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Chapter 4 Peer Exchange Workshops

This Chapter describes the background, presentations, discussions, and themes that took place during four peer exchange workshops. The objectives of the peer exchange workshops (workshops) were to identify coastal concerns in each region and develop strategies for increasing resilience in coastal transportation infrastructure, particularly roadways, bridges, and tunnels.

4.1 Workshop Background

4.1.1 Locations

Four workshops were conducted in different coastal regions of the U.S. These were facilitated by FHWA and hosted by the respective State DOTs at the following locations and dates:

- Mid Atlantic Coast, March 8, 2018 (Hosted by Maryland State Highway Administration, Elizabeth Habic)
- Gulf Coast, March 29, 2018 (Hosted by Florida Department of Transportation, Carl Spirio)
- Pacific Coast, April 12, 2018 (Hosted by Washington Department of Transportation, Carol Lee Roalkvam)
- North Atlantic Coast, April 26, 2018 (Hosted by Massachusetts Department of Transportation, Steven Miller)

4.1.2 Participants

The invitation lists for each workshop included numerous stakeholders in the region including State DOTs, FHWA, State environmental agencies, local and regional agencies, and tribes. Appendix A provides the participants that attended at each workshop.

This report summarizes the discussions and findings of the workshops and synthesizes the outcomes into a series of recommendations from the participants.

4.2 Presentations

An important part of the workshops were informal presentations from participants related to their experiences on emerging issues resulting from sea-level rise. The presentations for each workshop were as follows:

4.2.1 Maryland workshop

- “Delaware Floodplain: Impacts of Severe Storms on Infrastructure in a Low Lying State,” LaTonya Gilliam, Delaware Department of Transportation.

4.2.2 Florida workshop

- “Broward County Florida Experience with Sea Level Rise Issues,” Samantha Danchuk, Broward County.
- “Sea Level Rise Update,” Carlos Ribbeck (consultant), Georgio Tachiev (consultant), and Florida Department of Transportation (District 6).
- “King Tide Flooding in South Florida (2015),” Jayantha Obeysekera, South Florida Water Management District.

4.2.3 Washington workshop

- "Sea Level Rise Response Planning," Andy Haub, City of Olympia.
- "Washington DOT Experience with Sea Level Rise," Carol Lee Roalkvam, Washington Department of Transportation.

4.2.4 Massachusetts workshop

- "Sea Level Rise and Storm Surge Vulnerability along Route 1A," Kirsten Howard, New Hampshire Coastal Program.
- "Assessing Vulnerability of Municipal Assets and Resources to Climate Change," Julie LaBranche, Rockingham Planning Commission.

4.2.5 Framing Questions

The first set of discussion questions pertained to the identification of potential consequences of sea level rise experienced or anticipated by the participants[6]. The discussion questions[7] were:

- Which of the potential consequences of sea level rise have you experienced and what have you experienced that is not on the list?
- What are the most important consequences of sea level rise that are not addressed in your budget?
- Are there research needs that you see to better anticipate and/or quantify the consequences of sea level rise?
- Does your organization have the technical and financial resources to address the potential consequences of sea level rise?

4.2.6 Open Questions and Discussions

Against this backdrop, the study posed the following questions to the participants:

- Which of these statutes or regulations have you experienced as barriers and what have you experienced that is not on the list?[8]
- Which of these statutes or regulations have facilitated a response to sea level rise?
- Is lack of leadership an institutional barrier for responding to the challenges of sea level rise?
- Who is not here (local, State, Federal agencies, business, etc.) that should be?
- Is there an appropriate balance between long-term and short-term decision making in your organization or among collaborating organizations?

4.2.7 Breakout Group Activities

After the open discussion periods, each peer exchange divided participants into three breakout groups for more detailed discussion to identify the most pressing needs and the most useful tools or strategies

[6] Appendix B (which is based on peer exchange workshop participant comments and information from relevant literature discussed in Part I, Chapters 2 and 3 of this report) provides a listing of potential consequences of sea level rise.

[7] The basis of the initial list referred to in this question was information and findings from relevant literature discussed in Part I, Chapters 2 and 3 of this report.

[8] The statutes and regulations referred to in this question included those discussed in Part I, Chapters 3 of this report.

for addressing those needs. The peer exchange asked breakout groups to consider and address the following questions and then report back to the rest of the workshop participants:

- Which potential consequences of sea level rise would you rank as the most important to you? Why?
- Which responses to those consequences have you found to be most effective? Least effective?[9]
- What areas of research would you identify as "low hanging fruit" for addressing the emerging issues associated with sea level rise?
- What areas of guidance (programmatic or technical) from appropriate local, State, or Federal authorities would be most helpful?

4.2.8 Workshop Closeout

The workshops closed with a recap of the major discussion items and reflections from each participant regarding their most significant take-aways from the workshop.

The next Chapter summarizes the results of the discussions, themes, responses, and findings from the workshops.

[9] Appendix B also provides a listing of possible Federal, State, or local responses to prevent or mitigate the consequences of sea level rise (also based on input from workshop participants and the relevant literature).

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Chapter 5 Themes, Responses, and Needs

The participants were highly engaged in their interest and involvement in the topics. They also generally recognized the effects of sea level rise now occurring in their communities or venues. They also expressed an expectation, expressed through their comments, that the effects of sea level rise will intensify in the future. Furthermore, participants generally shared a belief that many organizations responsible for, or influencing the development of, transportation infrastructure do not have all the tools and resources needed to address the effects of sea level rise.

5.1 Common Themes from Participants

The participants generally shared a belief, expressed in their comments, that sea level rise is affecting all U.S. coastal regions. Common themes emerged among participation comments, including:

- Communities are recognizing short-term changes associated with sea level rise, but are slow to react because, while the changes are incremental now, the potentially larger impacts over longer horizons are less visible.
- All four regions expressed an increase in high tide (sunny day) flooding resulting in traffic disruptions, including road closures.
- Raising roads[10] is a common strategy (already implemented or in planning) to keep out high tides. However, participants identified several issues with, or limitations of, this strategy, including inadequate right of way, the danger of roads serving as water barriers[11], differences in service levels and purposes of roadways, difficulty tying-in to the adjacent landscape, multiple ownership of road networks (e.g., State and local governments), drainage impacts, and environmental impacts.
- Consistent design guidance, particularly quantitative sea level rise estimates, may be beneficial in responding to the emerging issues related to sea level rise.
- Roadways are often viewed by elected officials and the public as fixed assets that should provide a given level of service indefinitely regardless of changing conditions.
- Multiple agencies must coordinate with State DOTs and FHWA to successfully implement and maintain the transportation network[12]. However, few agencies fully recognize or see the larger context (over extended time horizons and across regions and disciplines). Each sees the emerging issues related to sea level rise in different ways, depending on that agency's particular mission.
- Few State DOTs have staff dedicated to – or at least highly focused toward – adapting to sea level rise, specifically, and climate change more generally.
- Finding adequate funding for sea level rise adaptation continues to be a challenge, leaving State DOTs to rely on flood emergencies to fund adaptation, when feasible.

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[10] Participants also mentioned raising bridges, but they mentioned raising roads to keep them dry and as a water barrier much more often.

[11] In a September 10, 2008 Memorandum, the FHWA discusses the use of road embankments as water barriers or levees. The FHWA discourages such use for reasons discussed in the Memorandum, including safety and suitability (FHWA 2008) (Many participants referred to the potential use of road embankments as levees.)

[12] Discussion included not only the transportation network, but also other sectors such as water, power, and communications.

- Most regions have conducted vulnerability assessments/studies of some sort, but few efforts to implement adaptation strategies have been made, largely because of resource limitations.

5.2 Regional Themes

Some issues were unique to a particular coastal region or regions. These themes also depended on the relationship between the coast and the proximity of the transportation infrastructure.

Mid Atlantic (Maryland) Workshop. The Maryland State Highway Administration reported that it is designing for 2 feet of sea level rise by 2050 as a consistent approach to considering the future across projects. Based on observed trends, participants stated an expectation that extensive areas of low-lying land, including, e.g., that area of Dorchester County (Maryland) may be underwater by mid-century. Participants also reported that septic systems are failing because of rising groundwater and access for emergency services is impaired by more frequent flooding. Participants explained that to help communicate the immediacy of the issue to the public, there have been many efforts to bring public attention to the coming changes in the Mid-Atlantic area including a documentary film entitled “High Tide I Dorchester.”

Gulf and South Atlantic (Florida) Workshop. Participants from coastal counties and the State DOT discussed the threat of sea level rise to poorer communities, as well as areas of high value residential and business properties. Based on the experience of the participants, installing new - or raising the height of existing - sea walls is a common solution in these areas. They explained that sea walls involve extensive check valves and pumping systems to balance the need to prevent sea water flooding while providing a path for stormwater to escape.

The Florida DOT (FDOT) indicated districts have some flexibility to modify roadway and bridge designs to accommodate sea level rise, but there is no consistent basis for those modifications. In general, FDOT described that its present design process does not account for sea level rise when determining bridge clearances.

Pacific (Washington) Workshop. A major concern expressed by participants was that existing roads and bridges block natural sediment and woody debris paths to the ocean. They described how sea level rise, glacial retreat, and potential changes to precipitation patterns may be compounding these blockage issues. The participants described concerns that tidal areas have increased sediment deposits from rivers and streams. The sediment sources include areas of glacial retreat exposing erodible unconsolidated materials; increased flow (transport capacity) due to changes in the proportions of the watersheds dominated by either snow or rain processes and must overcome increasingly high tailwater elevations at the coast. The Washington State DOT (WSDOT) cited culvert maintenance as a major problem expected to worsen with sea level rise.

The City of Olympia reported that it has prepared strategies for adapting to sea level rise in its low-lying urban areas. Participants described that establishing long-term governance and financial mechanisms will be essential for implementation.

North Atlantic (Massachusetts) Workshop. Participants reported that regional solutions (e.g., a seawall) have been discussed to protect large areas of the coastline. Existing tidal culverts currently limit the upstream migration of tidal effects into embayments, but the increasing tides are changing the hydraulic performance of this infrastructure. A theme at this workshop was the importance of establishing a clearinghouse of climate information and tools that can be used State and region wide. Also, participants noted navigational hazards previously visible are being submerged and becoming problematic.

5.3 Participant Responses to Past and Current Issues

The workshop participants shared some of the responses to the emerging issues of sea level rise being taken by their organizations currently and in the recent past. Some, such as raising roads, have been mentioned in the previous sections on common and regional themes. The responses reported can be categorized in the following groups:

- Regulatory and institutional;
- Planning and analysis;
- Operational; and
- Engineering solutions.

Regulatory and institutional responses are those where changes to the context in which the transportation (or another sector) infrastructure operates. Workshop participants described their efforts in setting quantitative sea level rise targets for design and revising flood ordinances. In both cases, these responses provide new frameworks for a wide variety of other activities.

Workshop participants also reported responses associated with planning and analysis efforts. These efforts include modeling of possible exposure of assets to changing climate, hazard mitigation planning, and vulnerability/risk assessments. These actions assist in the identification of the extent of the potential response required to protect transportation infrastructure.

Participants identified numerous operational responses. These include road closures, road abandonment, as well as enhancing current practices in slope stabilization, stormwater controls, and roadside vegetation management. They noted that they have used most of these responses for reasons other than climate change but have been adapted for climate change.

Finally, as sea level rise increases, engineering solutions have been implemented by various organizations and governments. These include raising existing features such as roads, sea walls, landscape features, and buildings. They include installing new features including sea walls, replacement culverts, pumping systems, tide gates/valves, stormwater storage, and living shorelines. Engineering responses also included adjusting design criteria such as tailwater levels for storm drain design.

Appendix B provides many of the responses described by participants (as well as listing and summarizing other responses).

5.4 Participant Identified Needs

Discussions and presentations at the workshops covered a wide range of topics pertinent to the emerging issues related to sea level rise for transportation infrastructure. This report groups them in four basic categories:

- Science guidance and research;
- Engineering and technical guidance;
- Social science and economics tools; and
- Institutional and coordination strategies.

These areas include needs ranging from applied research and technical guidance to approaches for better management and communications. Each of the four categories is discussed in the following sections.

5.4.1 Participant Views on Science Guidance and Research

Participants observed that there is a wide range of projections for sea level rise by mid or late century, but no common authoritative scientific and methodological guidance. To illustrate:

- The State of Maryland has selected a rise of 2 feet by 2050 and 4 feet by 2100 as design targets.
- Several southern Florida counties have adopted 2 feet by 2060 for design purposes.
- The City of Olympia considers the year 2100 as the appropriate time horizon for evaluating sea level rise but does not have a quantitative design value.

Most workshop participants said national quantitative sea level rise design standards would stimulate design and adaptation work that would increase transportation infrastructure resilience. These participants further emphasized that the standards should be mandatory rather than suggestions and fully backed with the credibility and authority of a federal or national entity (e.g. FHWA, AASHTO, NCHRP).[13] The participants described that regional standards would be better than the current patchwork of guidance and suggestions, but not as effective as national standards.

The participants also described a second area of needed science-based and methodological guidance and research: the projection of groundwater rise rates and saltwater intrusion. The participants mentioned tools, such as groundwater models or regional studies, as being helpful in anticipating the effects on the operations and maintenance of various components of the transportation infrastructure.

The participants described a third area related to science and methodology would consist of focused applied research related to effects of a changing environment on transportation systems. Their ideas included better understanding of the impacts of the following:

- Frequent flooding on roads and the road base.
- Saltwater intrusion on materials, particularly metal culverts, foundations, and retaining walls.
- Sea level rise and groundwater (GW) level increases on foundation design.
- Sea level rise and GW level increases on seismic impacts.

A fourth science-based area, expressed frequently by participants, pertains to the ecological and geomorphological responses of natural systems to sea level rise. They recognized that relative importance varies by coastal region, but the list included:

- Identification of the effects of flooding changes and sea level rise on the transport of woody debris and sediment movement especially at the freshwater – coastal interface.
- Identification of how shoreline changes resulting from sea level rise may propagate upstream.
- Understanding of the evolutionary transitions of freshwater marshes to saltwater marshes and saltwater marshes to open water.
- Identification of the effects of sea level rise on coastal scour and shoreline erosion processes.
- Identification of the effects of sea level rise on saltwater and freshwater fish habitats.

5.4.2 Engineering and Technical Resources

Workshop participants also identified specific information needs in engineering and other technical areas. In many cases, these areas reflected the need for design resources to facilitate applying the scientific information to planning and engineering processes.

[13] NCHRP projects 15-61 and 15-61A evaluate development of quantitative sea level rise design recommendations. Such NCHRP studies inform, but do not bind the FHWA to any findings or recommendations.

A common engineering need expressed by participants was for resources that describe how to raise roads to limit inundation from rising sea levels while ensuring embankment stability during overtopping and resisting the negative effects of higher levels of saturation. Related to this, they expressed a need for technical strategies for raising roads incrementally as sea levels rise.

A second engineering gap participants described related to the effects of sea level rise and storm surge on bridges. Participants noted that a common strategy for designing new or replacement bridges is to attempt to place them sufficiently high that storm surge and waves pass under them. Participants expressed interest in potential strategies to design bridges “low and strong” so that they can be submerged during the height of storms but returned to service quickly after the storm passes.

Several participants expressed the need for tools to analyze the joint probability of contributions to coastal flooding – including those contributions from tides, storm surge, and rainfall). During discussions, participants referred to this topic as “compound flooding” and “coincident frequency analysis.” Participants noted that some research has been completed in this area (e.g. Kilgore *et al*. 2013), but more work is needed.

Participants also described a need for information and tools for estimating projected precipitation from coastal storm events to better estimate stream flooding.[14]

Participants further identified the need to provide more technical resources on the design of the interface between stormwater/storm drains and the tidal environment. With sea level rise, the participants explained that there is a need to adjust the tailwater design assumptions at the outlets of storm drains to insure continued drainage. They also identified a need to consider design approaches for tide gates, backflow controls, pump stations, and auxiliary power.[15] Participants stated improved resources will allow for more resilient design of these structures.

Participants described needs for other improved technical resources that included:

- Underdrain design with rising groundwater.
- Potential use of non-corrosive materials to replace metals in salt environments.
- Living shorelines for more nature-based shoreline protections.
- Seawall design and adaptation to rising sea levels.
- Rock and sediment size selection for beaches and gravel bed streams.
- Placement of electrical and mechanical components above flood level (e.g. signal boxes).

5.4.3 Social Science and Economics Tools

The participants expressed many needs not related directly to science or engineering. The participants discussed the following needs at multiple workshops:

- Communications tools to introduce concepts that may be unwelcome, e.g. sea level rise, in a positive manner that inspires constructive responses.
- Communications tools to expand awareness of the current experiences of sea level rise and potential changes.
- Training for regional, State, and local personnel responsible for adaptation covering how to recognize coming changes and how to prepare.

[14] Part of NCHRP 15-61 is directed to providing methods for estimating projected precipitation.

[15] *Highway Stormwater Pump Station Design,* Hydraulic Engineering Circular 24, (P.N. Smith 2001) provides technical information in some of these areas.

- Cost/benefit analysis tools to analyze and communicate the trade-offs between investments now and reactions later.
- Case studies of successful programs/strategies/pilot projects that can be used to illustrate the growing threats and workable strategies for responding to those threats.

5.4.4 Institutional and Coordination Strategies

The final category of needs pertains to intra institutional issues and coordination between various levels and types of organizations and institutions. As an example, participants frequently cited impediments to development of effective response strategies to sea level rise might consist of issues related to:

- Different levels of government (e.g. State versus local);
- Different agency missions (e.g. transportation versus emergency preparedness versus environmental protection); and
- Different levels of understanding around sea level rise complicate.

Participants expressed a major need for additional financial and personnel resources. They described potential use of such resources to promote more comprehensive asset management systems, monitoring programs, and investments in more resilient infrastructure. Such resources, participants noted, would have benefits throughout their organization beyond a more effective response to sea level rise.

The participants frequently cited a need for better intra- and inter-agency communication. This ranged from abolishing – or at least perforating – the decision-making silos that exist within many agencies and between agencies. They also raised a need for broader participation in the discussion about responses to sea level rise to remove barriers to the development of effective adaptation strategies. For example, including other regulatory agencies (e.g. FEMA and the USACE) and other stakeholders affected by sea level rise (e.g. utilities and water/wastewater providers) may provide a better understanding of the overall effects of sea level rise and potentially enable identification of more robust solutions. Participants also recognized the importance of Tribal outreach as they may also contribute to better solutions.

Also, related to communications, the participants described the need to consider transportation as a network that serves a particular function rather than considering a specific roadway segment, bridge, or culvert in isolation. This was identified as a key need especially when abandonment of certain parts of the transportation system might be the best long-term adaptation strategy. Strategies for how to implement abandonment strategies in the face of political and understandable public resistance are also needed. Effective strategies will also likely rely on cooperation between multiple jurisdictions and with sectors beyond the transportation sector.

The participants cited a need for sharing of information and data. They described setting up interagency data sharing of sea level rise projections, monitoring information, adaptation cases studies, design approaches, and other information.

A specific theme related to resources addressed the use of emergency response resources to build in more resilience when reconstructing damaged infrastructure. Participants noted that program requirements and the need for quick action often limit the opportunity for rebuilding with adaptation in mind. However, they also believed that with advanced planning, emergency resources could be better used in responding to and rebuilding after major flooding or storm damage.

Finally, the participants discussed the role of leadership in building resilience into the transportation infrastructure. Examples ranging from strong to weak leadership in the area of adaptation and resilience were available. But there was general agreement that strong leadership is essential to provide for investments today to protect people and property against sea level rise.

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Part 3 – Synthesis & Summary

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Chapter 6 Summary

This Chapter provides a summary of the study into emerging issues associated with transportation infrastructure and seal level rise. The objectives of this study, especially the peer exchange workshops, were to:

- Identify coastal concerns in different coastal regions of the United States each region; and
- Synthesize strategies for increasing resilience in coastal transportation infrastructure, particularly roadways, bridges, and tunnels.

The study convened peer exchange workshops in the States of Florida, Maryland, Massachusetts, and Washington with participants coming from wide geographic locations and diverse coastal milieus.

6.1 Synthesis of Participant Recommendations

The knowledge and experience of peer exchange workshop participants provided the primary basis for a synthesis of their collective insights and recommendations on emerging issues for transportation infrastructure resulting from sea level rise. The study also obtained additional information from existing applicable scientific literature. The recommendations integrate the workshop participant perspectives on their needs for better incorporating resilience into the transportation infrastructure.

The benefits of this series of four workshops was explorations from different regions of the country; obtaining consistent trends of the emerging issues related to sea level rise threatening the transportation infrastructure and the identification of needs by those who have responsibility for adapting to a changing sea level.

The common themes described by participants provide a conceptual framework that could inform the selection of appropriate next steps to improve infrastructure resilience against sea level rise and high tide flooding. Those themes include: 1) a recognition of historical sea level rise and an increase in high tide flooding, but a difficulty in responding now to conditions decades in the future, 2) the need for multiple agencies at local, State, and Federal levels to coordinate, 3) the lack of broadly accepted design criteria, including future sea level rise estimates, 4) the lack of staffing dedicated to – or at least informed about – responding to sea level rise, and 5) the need for additional resources to prepare for increasing sea levels. Based on these common themes and the needs identified by workshop participants, the following section provide a synthesis of their recommendations (grouped by needs areas):

6.1.1 Scientific tools and research

- Developing national technical reference materials addressing quantitative sea level rise estimates as tools for State and local communities to use for adaptation designs. The reference materials would be most beneficial if they are adaptable to local and regional differences in relative sea level rise.
- Conducting synthesis studies, including literature reviews, on the identified scientific research needs. AASHTO and Transportation Research Board (TRB) (through coordinated research programs) are examples of organization that might sponsor/conduct this type of research. Prioritization of these efforts could be determined, in part, by polling potential users for priorities.

6.1.2 Engineering and technical reference material.

- Developing national technical reference materials on the use of raised roadways to limit inundation caused by flooding including that caused by sea level rise.
- Developing national technical reference materials for estimating joint probabilities for high tides, storm surges, and rainfall.
- If requested by coastal States, collaborating with AASHTO and other organizations to prioritize and develop national technical reference materials for the remaining identified information needs.

6.1.3 Social science and economics tools.

- Considering expanding FHWA websites on resilience and adaption to refer to non-Federal studies related to adapting to sea-level rise that promote actionable practices. Participants noted that these FHWA websites have been useful to practitioners but suggested potential improvements (as described below).
- Updating National Highway Institute (NHI) training course 135082 “Highways in the Coastal Environment” to include lessons on adaptation and more broadly promote the course. Institutional and coordination strategies[16].
- Improving Federal interagency coordination. Participants believed it would be beneficial for FHWA to propose a collaboration between Federal agencies to discuss joint action on sea level rise issues.
- Improving State interagency coordination. Participants believed it would be beneficial for each State to encourage collaboration of State agencies to discuss joint action on sea level rise issues.

6.1.4 Institutional and coordination strategies.

- Improving Federal interagency coordination. Participants believed it would be beneficial for FHWA to propose a collaboration between Federal agencies to discuss joint action on sea level rise issues.
- Improving State interagency coordination. Participants believed it would be beneficial for each State to encourage collaboration of State agencies to discuss joint action on sea level rise issues.

[16] As of publication of this report, the FHWA is developing new NHI courses and materials covering the broader topic of “Resilient Highways.”

Part 4 – References & Appendices

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Chapter 7 References

AASHTO. 2009. *"Vessel Collision Design of Highway Bridges. Guide Specifications and Commentary."* AASHTO. Washington D.C.

AASHTO. 2020. "LRFD Bridge Design Specifications." 9th edition. Publication Code: LRFDBDS-9. AASHTO. Washington D.C.

Cole, W. D. October 2008. *Sea Level Rise: Technical Guidance for Dorchester County*, Maryland Department of Natural Resources Coastal Zone Management Division.

FHWA. February 2001. "*Highway Stormwater Pump Station Design"* Hydraulic Engineering Circular 24. FHWA-NHI-01-007. Washington D.C.

FHWA. September 2002. *"Highway Hydrology"* 2nd edition. Hydraulic Design Series 2. FHWA-NHI-02-001. Washington D.C.

FHWA. June 2008. "Highways in the Coastal Environment." 2nd edition. Hydraulic Engineering Circular 25. FHWA-NHI-07-096. Washington D.C.

FHWA. September 10, 2008. *"Highway Embankments versus Levees and other Flood Control Structures."* FHWA Memorandum. Washington D.C.

FHWA. September 2009. "Urban Drainage Design Manual." 3rd edition. Hydraulic Engineering Circular 22. FHWA-NHI-10-009. Revised August 2013. Washington D.C.

FHWA. January 2012. "Highway Hydraulics State of Practices, 50 US States and Puerto Rico." FHWA Resource Center, Hydraulics Technical Service Team.

FHWA. June 2016. *"Highways in the River Environment - Floodplains, Extreme Events, Risk and Resilience."* 2nd edition. Hydraulic Engineering Circular 17. FHWA-HIF-16-018. Washington D.C.

FHWA. January 2020. "Highways in the Coastal Environment." 3rd edition. Hydraulic Engineering Circular 25. FHWA-HIF-19-059. Washington D.C.

FHWA. June 2022. "National Bridge Inventory (NBI)." 2022 NBI ASCII files. Washington D.C. https://www.fhwa.dot.gov/bridge/nbi/ascii2022.cfm.

Kilgore, R. T., D. B. Thompson, and D. T. Ford. March 2013. *"Estimating Joint Flow Probabilities of Design Coincident Flows at Stream Confluences,"* Transportation Research Board of the National Academies, Web-only document 199, Project No. 15-36. Washington D.C.

Krolak, J.S. and D. Henderson. 2016. *"Implementing a Successful Risk-Based, Data-Driven Scour Program."* Transportation Research Record: Journal of the Transportation Research Board, No. 2588, Transportation Research Board, Washington, D.C., pp. 163–171. DOI: 10.3141/2588-18

National Research Council. (2015) *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences*. The National Academies Press, p. 86. Washington D.C. https://doi.org/10.17226/21655

NOAA. 2017. Sweet, W. V., J. J. Marra, and G. Dusek. "*2016 State of U.S. High Tide Flooding and a 2017 Outlook"* [supplement to State of the Climate: National Overview for May 2017]. https://www.ncdc.noaa.gov/monitoring-ccontent/sotc/national/2017/may/2016_StateofHighTideFlooding.pdf

NOAA. 2018a. Jacobs, J.M., L.R. Cattaneo, and W. Sweet *"Recent and Future Outlooks for Nuisance Flooding Impacts on Roadways on the East Coast," Transportation Research Record*, Transportation Research Board of the National Academy of Sciences.

NOAA. 2018b. Sweet, W. V., G. Dusek, J. Obeysekera, and J. J. Marra 2018. "*Patterns and Projections of High Tide Flooding Along the U.S. Coastline Using a Common Impact Threshold"*, Technical Report NOS CO-OPS 086. Washington D.C.

Office of the Federal Register, April 1, 2020, *"Code of Federal Regulations, Title 23 – Highways,"* U.S. Government Publishing Office, Washington D.C.

USACE. January 2015. Todd Bridges, P.W. Wagner, K.A. Burks-Copes, M.E. Bates, Z.A. Collier, C.J. Fischenich, J.Z. Gailani, L.D. Leuck, C.D. Piercy, J.D. Rosati, E.J. Russo, D.J. Shafer, B.C. Suedel, E.A. Vuxton, and T.V. Wamsley. "*Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience.*" ERDC-SR-15-1. Vicksburg, MS.

USCG. March 26, 2004. *"Bridge Administration Manual."* (See Chapter 2). COMDTINST M16590.5C. Washington D.C.

USCG. April 2013. Mid-Atlantic Waterways Conference. Personal Correspondence. Baltimore, MD.

Appendix A. Workshop Attendees

This Appendix provides tables of participants during the peer exchange workshops. All participants provided their permission to appear in these tables within this report. The FHWA appreciates their contributions to this study.

Table A 1. Workshop attendees in Hanover, Maryland.

Last Name	First Name	Title	Affiliation
Beucler	Brian	Senior Hydraulics Engineer	FHWA
Brown	Eric	Hydraulic Engineer	FHWA
Cox	Brian	TMDL Coordinator	Maryland DOT (State Highway Administration)
Douglass	Scott	President, South Coast Engineers	South Coast Engineers
Gilliam	LaTonya	Engineer	Delaware DOT
Goettler	Gina	Transportation Engineer (Hydraulics)	Maryland DOT (State Highway Administration)
Graff	Robert	Manager, Office of Energy and Climate Change Initiatives	Delaware Valley Regional Planning Commission
Habic	Elizabeth	Climate Risk and Resiliency Program Manager	Maryland DOT (State Highway Administration)
Hodges	Tina	Sustainable Transportation and Resilience Team	FHWA
Kafalenos	Robert	Air Quality Specialist	FHWA
Kapoor	Abhishek	Hydraulic Engineer	FHWA
Lauffer	Matt	Assistant State Hydraulics Engineer	North Carolina DOT
Liang	Joy	Environmental Specialist	FHWA
Lupes	Becky	Air Quality Specialist	FHWA
Mattejat	Peter	Environmental Manager	Maryland DOT (Maryland Transportation Authority)
McDaniel	Andrew	Manager, Highway Stormwater Program	North Carolina DOT
Michalski	Michael	District Operations Engineer	Maryland DOT (State Highway Administration)
Neighorn	Jim	Hydraulic Engineer	FHWA
Pujara	Karuna	Deputy Director	Maryland DOT (State Highway Administration)
Seiger	William (Bill)	Division Chief, Waterway Construction	Maryland Department of the Environment
Singleton	Eileen	Principal Transportation Engineer	Baltimore Metro Council
Sisson	Steve	Sussex County Review Coordinator	Delaware DOT
White	Ryan	Director of Public Works	Dorchester County, MD
Yurek	Russ	Director	Maryland DOT (State Highway Administration)

Table A 2. Workshop attendees in Tallahassee, Florida.

Last Name	First Name	Title	Affiliation
Beucler	Brian	Senior Hydraulics Engineer	FHWA
Bowman	Jenna	Engineering Specialist	FDOT
Carver	Jennifer	Growth Management Coordinator	Florida DOT
Claridge	Kevin	Director of the Florida Coastal Office	Florida Department of Environmental Protection
Danchuk	Samantha	Assistant Director	Broward County, FL
Dominguez	Mario	Assistant District 6 Drainage Engineer	Florida DOT
Douglass	Scott	President, South Coast Engineers	South Coast Engineers
Earp	Katey	Drainage Design Engineer	Florida DOT
Gray	Whitney	Administrator, Florida Resilient Coastlines	Florida Department of Environmental Protection
Jenkins	Rick	Drainage Design Engineer	Florida DOT
Kafalenos	Robert	Air Quality Specialist	FHWA
Knight	Chase	Composite Materials Research Specialist	Florida DOT
Konyha	Kenneth	Principal Hydrologic Modeler	South Florida Water Management District
Maamar-Tayeb	Abderrahmane	Transportation Engineer	Texas DOT
Nolan	Steve	State Structures	Florida DOT
Nurmi	Cynthia	Hydraulic Engineer	FHWA
Obeysekera	Jayantha	Chief Engineer	South Florida Water Management District
Poole	James	District 4 Drainage Engineer	Florida DOT
Ribbeck	Carlos	Consultant for District 6 Drainage Department	Florida DOT Consultant
Salazar	Ricardo	District 6 Drainage Engineer	Florida DOT
Spirio	Carl	State Drainage Engineer	Florida DOT
Tachiev	Georgio	Consultant for District 6 Drainage Department	Florida DOT Consultant

Table A 3. Workshop attendees in Olympia, Washington.

Last Name	First Name	Title	Affiliation
Assink	Luke	Hydraulics Engineer	Washington DOT
Beucler	Brian	Senior Hydraulics Engineer	FHWA
Boone	Craig	Bridge Engineer	Washington DOT
Douglass	Scott	President, South Coast Engineers	South Coast Engineers
Fletcher	William	Water Resources Program Leader	Oregon DOT
Fox	Peggy		Washington DOT
Haub	Andy	Director of Water Resources	City of Olympia
Heilman	Julie	Chief Hydraulics Engineer	Washington DOT
Himmel	John	Emergency & Security Specialist	Washington DOT
Hyman	Robert	Environmental Protection Specialist	FHWA
Knapp	Mike	Alaska DOT	Alaska DOT
Kramer	Casey	Principal, NHC	Northwest Hydraulic Consultants
Love	Sharon	Environmental Program Manager	FHWA
Mobbs	Mark		Quinault Tribe
Myhr	Gregor	Maintenance and Water Quality Specialist	Washington DOT
Page	Simon	Hydrologist	Washington DOT
Roalkvam	Carol Lee	Chair, WSDOT Climate Committee	Washington DOT
Rudolph	Jeff	Environmental Biologist III	Pierce County
Russel	Steve	Maintenance Superintendent, Port Angeles Region	Washington DOT
Steely	Alex	Mapping Supervisor	Washington DNR
Struthers	James	Chief Engineering Geologist	Washington DOT
Talebi	Babbak	Coastal Planner	Washington Dept. of Ecology
Turpin	Theresa	Planning and Environmental Leader, Olympic Region	Washington DOT
Wimberly	Susan	Field Operations Team Leader	FHWA

Table A 4. Workshop attendees in Boston, Massachusetts.

Last Name	First Name	Title	Affiliation
Arpino	Michael		FHWA (Massachusetts Division)
Bartha	Stephen	Tunnel/Structural Engineer	FHWA
Belanger	David	District Operation/Maintenance Engineer, District 6	Massachusetts DOT
Beucler	Brian	Senior Hydraulics Engineer	FHWA
Collette	Peter	Maintenance Engineer, District 4	Massachusetts DOT
Crean	Teresa	Coastal Community Planner	Univ. of Rhode Island Coastal Resource Center
Douglass	Scott	President, South Coast Engineers	South Coast Engineers
Dvelis	Jason	Environmental Protection Specialist	FHWA
Fouad	Hanan	Hydraulic Engineer	Massachusetts DOT
Griffin	Mark	District Inspection Engineer/Bridge & Tunnel Inspector, District 6	Massachusetts DOT
Hebson	Charlie	Chief Hydrologist	Maine DOT
Hogan	Mike	Transportation Supervising Engineer - Hydraulics & Drainage	Connecticut DOT
Howard	Kirsten	Coastal Resilience Coordinator	New Hampshire Coastal Program
Jacobs	Jennifer	Professor, Dept. of Civil and Environmental Engineering	Univ. of New Hampshire
Knisel	Julia	Coastal Shoreline and Floodplain Manager	Massachusetts Office of Coastal Zone Management
LaBranche	Julie	Senior Planner	Rockingham Co. (NH) Planning Commission
Lupes	Becky	Air Quality Specialist	FHWA
Mallette	Timothy	Hydraulic Engineer	New Hampshire DOT
McCullough	Rick	Director of Environmental Engineering, District 6	Massachusetts DOT
Mecray	Ellen	Regional Climate Services Director, Eastern Region	NOAA
Miller	Norm	District Drainage Engineer - Maintenance Division	Connecticut DOT
Miller	Steven	Supervisor, Environmental Management and Sustainability	Massachusetts DOT
Paris	Timothy	Project Development Section	Massachusetts DOT
Vieira	Daniel	Assistant District 5 Maintenance Engineer	Massachusetts DOT

Appendix B. Consequences & Reponses

As a result of the information gleaned from the peer exchange workshop participants; buttressed by the information from the literature review described in Part I, Chapters 2 and 3 of this report, this appendix documents a listing of potential consequences of sea level rise and possible Federal, State, or local responses to prevent or mitigate the consequences.

The study initially developed some of these materials through review of relevant literature; supplemented them through professional knowledge and experiences of the study's author; and augmented those materials using information and insights provided by the participants during the peer exchange workshops. These listings provide a general overview of the broad range of consequences and responses to sea level rise. They do not represent any official FHWA policies or guidance. They also do not have the force and effect of law and are not meant to bind the public in any way.

B.1 Potential Consequences

Potential consequences of sea level rise to roads, bridges, tunnels, culverts, stormwater quantity management, stormwater quality management, and other transportation-related infrastructure include loss of function and/or increased maintenance in areas as described in the following list:

B.1.1 Roads

- Roadbed saturation causing pavement degradation, sinkholes, and service life reduction
- Rutting asphalt causing hydroplaning issues
- Increased frequency of embankment overtopping
- Increased frequency of temporary road closures
- Reduction in visits for businesses

B.1.2 Bridges

- Navigational clearances compromised
- Loss of freeboard
- Altered risk of wave loading that is sensitive to sea level and bridge height
- Increased deterioration of undersides of decks and damage to (fixed) under-bridge utilities because of saltwater exposure
- Increased risk to mechanical/electrical systems because of saltwater exposure

B.1.3 Tunnels

- Increased frequency of flooding
- Increased potential for infiltration
- Increased risk to mechanical/electrical systems because of saltwater exposure

B.1.4 Culverts

- Pipe floatation/settlement
- Tidal erosion of end treatments or support
- Infiltration/exfiltration
- Sedimentation

B.1.5 Stormwater Quantity Management

- Pipe floatation
- Infiltration into the storm drain system
- High tailwater
    - Storm drain backflows
    - Increased frequency of flooding during rainstorms
    - Increased sunny day flooding
    - Decreased velocities and increased sediment deposition
- Storage losses in dry/wet ponds resulting from rising groundwater
- Interference of backflow prevention or tide gates by barnacles
- Saltwater damage to pipes, junctions, and inlets

B.1.6 Stormwater Quality Management

- Reduced infiltration capacity because of high groundwater affecting stormwater infiltration facilities and septic systems
- Storage losses in water quality ponds resulting from rising groundwater
- Saltwater intrusion interfering with biological processes
- Shortcutting loading of fertilizers and herbicides to receiving waters
- Increased frequency of combined sewer overflows
- Increased frequency of high tailwater preventing releases of combined sewer overflows and the associated health issues
- Loss of coastal wetlands

B.1.7 Other

- Seawalls
    - Piping behind seawalls in porous soils
    - Boat wakes more frequently overtopping seawalls
- Increased maintenance costs to keep roads functioning. Considerations may include when to draw the line? Who decides?
- Ecological effects on coastal ecosystems, e.g. saltwater marshes
- Widening of FEMA (or locally regulated) floodplains, rising Base Flood elevations
- Extension of tidal influenced zone upstream
- More vulnerability during storms, smaller storms more damaging, further inland, breaching barrier islands
- Loss of beaches
- Deterioration of concrete, metals, and other materials increasingly exposed to saltwater
- Groundwater supply contamination
- Changes to liquefaction of underlying soils during seismic events
- Effects on septic systems

B.2 Potential Responses

Potential responses to negative consequences of sea level rise to roads, bridges, tunnels, culverts, stormwater quantity management, stormwater quality management, and other transportation-related infrastructure includes items in the following list:

B.2.1 Roads

- Temporary road closures
- Permanent road closure
- Raising roads
    - May cause increased damage to roadbeds during storms
    - May cause unintended flooding consequences upstream
- Relocate roads
- Reclassify functional class of roads
- Rerouting of emergency vehicles, school busses, transit
- Parking restrictions to avoid flooded cars
- Sealing/armoring of embankments
- Seawalls
- Use of non-metallic MSE wall straps

B.2.2 Bridges

- Temporary or permanent closures

B.2.3 Tunnels

- Temporary or permanent closures
- Increased flood proofing

B.2.4 Culverts

- Watertight joints to prevent infiltration/exfiltration

B.2.5 Stormwater Quantity Management

- Watertight joints to prevent infiltration/exfiltration
- Installation of pumping systems and check valves
- Installation of tide gates/valves
- Adding offline storage volume (or larger diameter culverts), allowing for surcharge
- Making watershed modifications/storage upstream/flow reduction through low impact development strategies

B.2.6 Stormwater Quality Management

- Modify vegetation to include salt tolerant plants and other bio-habitat changes
- Inject stormwater underground
- Apply stormwater to irrigate maintenance yards/golf courses/ROW
- Reduce use of fertilizers and herbicides to establish and maintain roadside vegetation
- Relocate wetlands to higher ground

B.2.7 Other

- Evaluate whether the need for the infrastructure still exists?
- Accurately map flooded areas during high (king) tides and rainstorm/tide/high wind coincidences