Emerging Issues Associated with Sea Level Rise

August 8, 2018

FINAL

Prepared by:
Roger Kilgore
Kilgore Consulting and Management
2963 Ash Street
Denver, CO 80207

Prepared for:
Federal Highway Administration
Contract: DTFH61-16-D-00033
Subcontract: 469-HDL16-1-15

Table of Contents

TABLE OF CONTENTS I

LIST OF FIGURES II

LIST OF TABLES II

1. INTRODUCTION AND OBJECTIVES 1

2. WORKSHOPS 6

2.1. Presentations 7

2.2. Discussion Questions 8

3. FINDINGS 9

3.1. Common Themes 10

3.2. Regional Themes 11

3.3. Current Responses 12

3.4. Identified Needs 12

3.4.1 Science Guidance and Research 13

3.4.2 Engineering and Technical Guidance 14

3.4.3 Social Science and Economics Tools 15

3.4.4 Institutional and Coordination Strategies 15

4. RECOMMENDATIONS 16

REFERENCES 18

APPENDIX A. EMERGING CONSEQUENCES AND REPONSES 19

APPENDIX B. WORKSHOP ATTENDEES 23

APPENDIX C. PARTICIPANT PRESENTATIONS 27

List of Figures

Figure 1. Sunny day flooding in Annapolis Maryland (Photo credit: Joe Krolak). 2
Figure 2. Sunny day flooding in Olympia Washington (Sylvester Street) (Photo credit: City of Olympia). .. 2
Figure 3. Increases in flooding with relative sea level (RSL) at Norfolk Virginia (from Sweet *et al*. 2018). .. 3
Figure 4. High tide gauge locations (from Sweet *et al*. 2017). 4
Figure 5. Tally of minor high tide flooding at selected gauges (from Sweet *et al*. 2017). 5

List of Tables

Table 1. Projected high tide flood frequencies (from Sweet *et al*. 2018). 6
Table 2. Workshop attendees in Hanover Maryland. 23
Table 3. Workshop attendees in Tallahassee Florida. 24
Table 4. Workshop attendees in Olympia Washington. 25
Table 5. Workshop attendees in Boston Massachusetts. 26

Emerging Issues Associated with Sea Level Rise

Rising sea levels threaten existing coastal transportation infrastructure beyond storm-related flooding. These emerging threats include increases in nuisance flooding, backflows, water quality effects, changes in storage, saltwater intrusion, pavement impacts, etc. This report documents a series of workshops conducted across the country to identify and, where feasible, address these issues primarily as they pertain to the nation's transportation infrastructure.

1. Introduction and Objectives

The objectives of the workshops were to identify coastal concerns in each region and develop strategies for increasing resilience in coastal transportation infrastructure, particularly roadways, bridges, and tunnels. Prior to the workshops, the Federal Highway Administration (FHWA) compiled a list of emerging issues associated with sea level rise (SLR), their potential consequences, and possible responses. The emerging issues, beyond exacerbated storm-related flooding, included the following areas:

- Nuisance flooding.
- Increasing frequency of roadway overtopping and tunnel 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.

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

Increasing sea levels reduce the freeboard provided to protect roads, bridges, and tunnels from the negative effects of high water (e.g. reduced passage of debris, possible pressure flow and/or increased wave impacts, etc.). On navigable waterways, sea level rise reduces navigational clearances.

[1] Image downloaded from a 4/11/17 presentation to City Council found at: http://olympiawa.gov/city-utilities/storm-and-surface-water/sea-level-rise.aspx. Downloaded August 1, 2018.

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

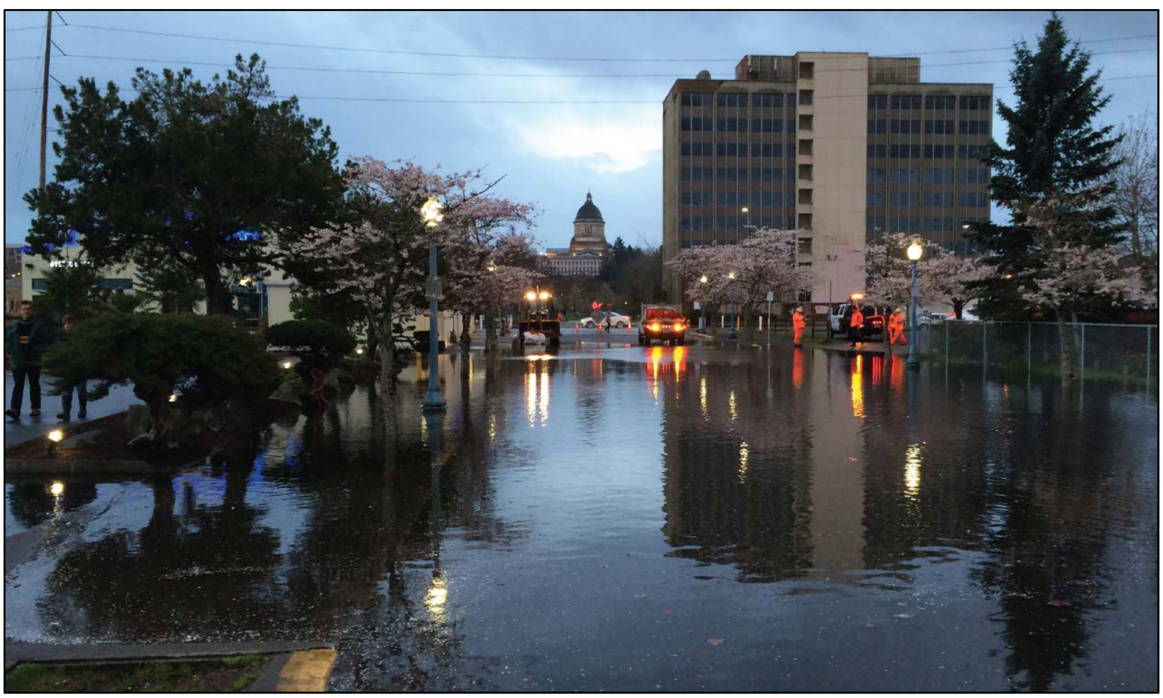

Figure 2. Sunny day flooding in Olympia Washington (Sylvester Street) (Photo credit: City of Olympia).

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.

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, they may lose some ability to buffer coastal transportation infrastructure against storm surge and waves.

Overall, the potential consequences of all of these emerging issues resulting from sea level rise may affect roads, bridges, culverts, stormwater management facilities, and other transportation system components. A detailed list of these effects and consequences is provided in Appendix A. Many of these effects are highlighted in a documentary film "High Tide in Dorchester County,"[2] which was discussed at the Mid-Atlantic workshop held in Hanover, Maryland.

The growing problem of high tide ("sunny day") flooding has been increasingly described in the scientific literature, e.g. Sweet *et al*. (2018) and Jacobs *et al*. (2018). Sweet *et al*. (2018) describes the problems associated with SLR on a range of flooding events in the historical record as shown in Figure 3. 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.

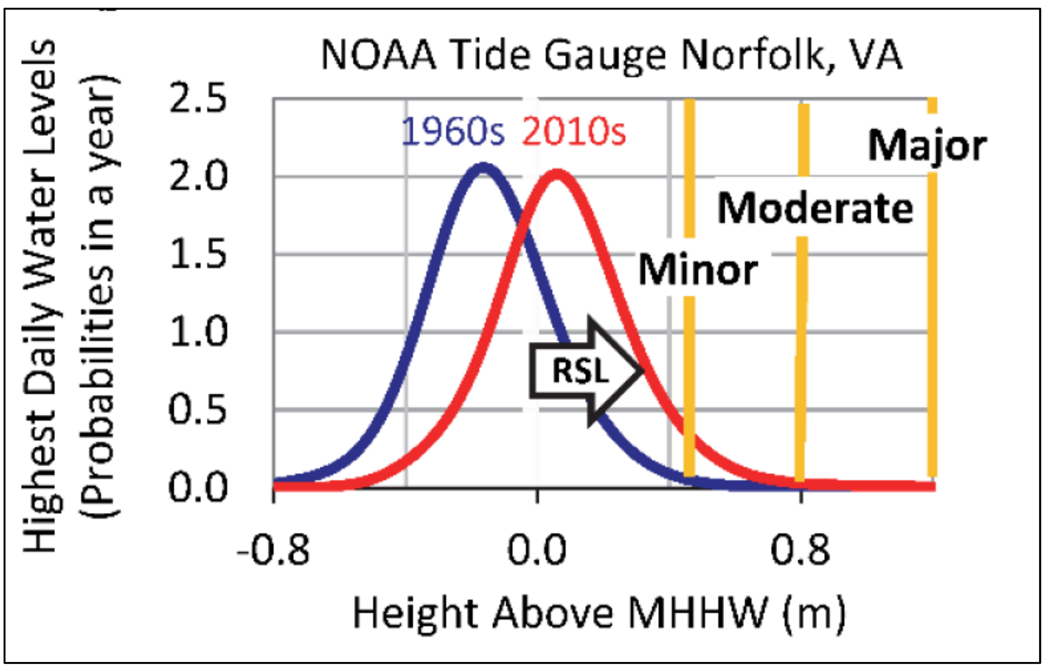

Figure 3. Increases in flooding with relative sea level (RSL) at Norfolk Virginia (from Sweet *et al*. 2018).

[2] http://hightidedorchester.org/

Higher water levels occur for minor (high tide), moderate, and major (storm-related) floods. The National Oceanic and Atmospheric Administration (NOAA) defines the flood thresholds based on the surrounding topography and the potential consequences of high water levels. A minor flood is defined 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.

Sweet *et al*. (2017, 2018) analyzed for trends in minor flooding 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.

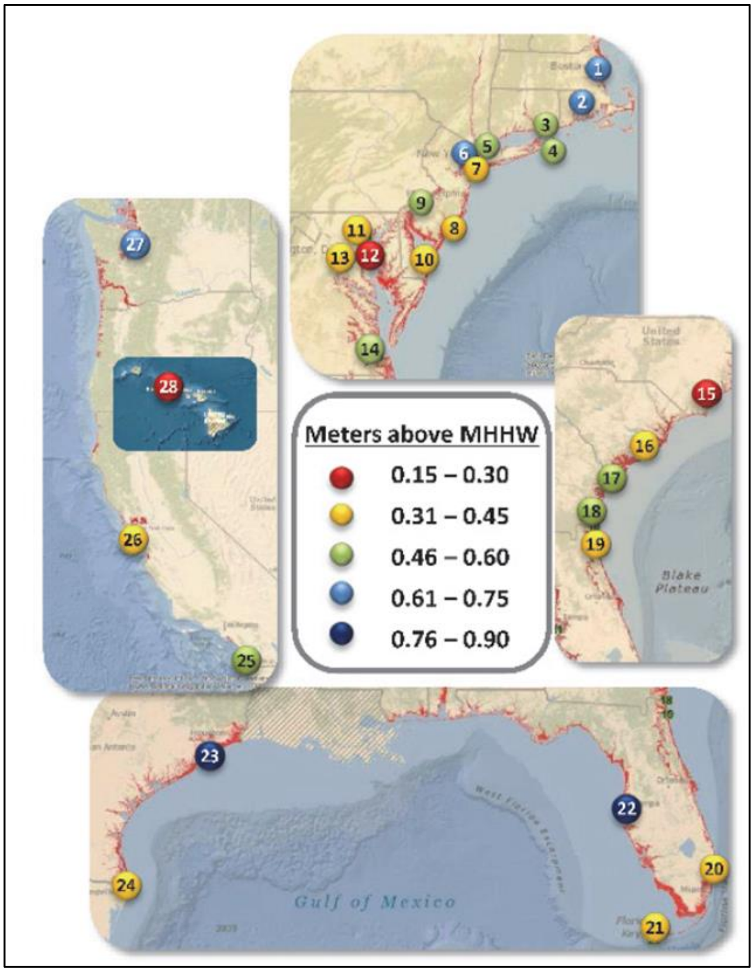

Figure 4. High tide gauge locations (from Sweet *et al*. 2017).

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 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.

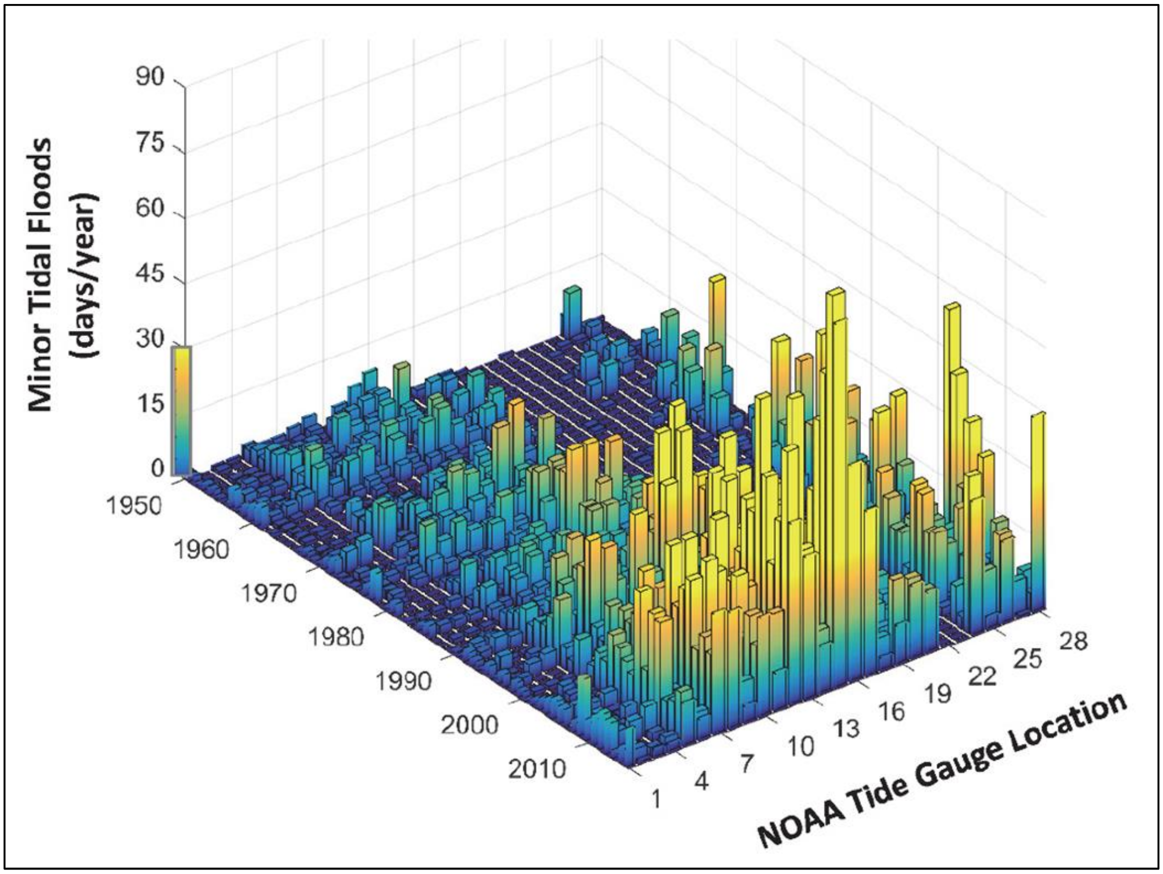

Figure 5. Tally of minor high tide flooding at selected gauges (from Sweet *et al*. 2017).

The analysis of Sweet *et al*. (2018) for projected conditions at coastal regions throughout the U.S. is summarized in Table 1. Two future scenarios (Intermediate Low and Intermediate) are shown 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 time period. These flooding events include minor, moderate, and major events as previously defined. For example, using the Intermediate Low scenario, Sweet *et al*. (2018) estimates 44 annual flood events at locations in the NE Atlantic region on average with a standard deviation on that estimate of 11 events per year from 2041 to 2050. They estimate further increases in the subsequent time period of 234 annual flood events with a standard deviation of 56.

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 very 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%

2. Workshops

High tide (sunny day, nuisance) flooding is causing problems today and is projected to worsen as described in the previous section. The workshops conducted as part of this study were focused on sharing experiences of participants in emerging issues related to SLR and responses to those issues that have been made to date. The objective was to also begin to focus efforts on what can most effectively be accomplished to mitigate these effects in the future.

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)

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. The lists of participants at each workshop are provided in Appendix B.

The workshop agenda varied from location to location, but included the following activities:

- Welcome and introductions (host agency and Brian Beucler, FHWA).
- Presentation of the issue and outline for the meeting (Roger Kilgore, workshop facilitator).
- Guided discussion in the morning including presentations from a selection of participants.
- Breakout sessions in the afternoon regarding highest priorities and need.
- Recap and final comments.

This report summarizes the discussions and findings of the workshops and synthesizes the results into a series of recommendations.

2.1. Presentations

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

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

2.2. Discussion Questions

The workshops featured a series of guided discussions following a list of discussion questions. The first set of discussion questions pertained to the identification of potential consequences of SLR experienced or anticipated by the participants. The culmination of these discussions is provided in list form in Appendix A. The discussion questions were:

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

These discussions were followed with an examination of the institutional and regulatory context within which the participants work to address the emerging consequences of SLR. This discussion was prefaced by a listing of some of the statutory and regulatory frameworks relevant to transportation design, construction, and maintenance including:

1. Moving Ahead for Progress in the 21st Century (MAP 21) (2012).
2. Fixing America's Surface Transportation (FAST) Act (2015).
3. FHWA Order 5520 (2014) "Transportation System Preparedness and Resilience to Climate Change and Extreme Weather Events."
4. FEMA regulations and criteria.
5. U.S. Army Corps of Engineers 404 permit process.
6. Jurisdictional/environmental/environmental justice constraints on maintenance and other solutions.

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

1. Which of these statutes or regulations have you experienced as barriers and what have you experienced that is not on the list?
2. Which of these statutes or regulations have facilitated a response to SLR?
3. Is lack of leadership an institutional barrier for responding to the challenges of SLR?
4. Who is not here (local, state, federal agencies, business, etc.) that should be?
5. Is there an appropriate balance between long-term and short-term decision making in your organization or among collaborating organizations?

After the open discussion periods, the participants were divided into three breakout groups for more detailed discussion to identify the most pressing needs and the most useful tools or strategies for addressing those needs. The breakout groups were asked to address the following questions and then report back to the rest of the workshop participants:

1. Which potential consequences of SLR would you rank as the most important to you? Why?
2. Which responses to those consequences have you found to be most effective? Least effective?
3. What areas of research would you identify as “low hanging fruit” for addressing the emerging issues associated with SLR?
4. What areas of guidance (programmatic or technical) from appropriate local, state, or federal authorities would be most helpful?

To facilitate a productive discussion, a common set of definitions was presented from FHWA Order 5520:

- **Preparedness**. Preparedness means actions taken to plan, organize, equip, train, and exercise to build, apply, and sustain the capabilities necessary to prevent, protect against, ameliorate the effects of, respond to, and recover from climate change related damages to life, health, property, livelihoods, ecosystems, and national security.
- **Resilience**. Resilience or resiliency is the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions.
- **Adaptation**. Adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects.

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 section summarizes the results of the discussions and findings from the workshop.

3. Findings

The workshop participants were highly engaged because they generally recognized the effects of SLR that are now occurring and that there is a reasonable expectation that the effects will intensify. Furthermore, participants recognized that many organizations responsible for or influencing the development of the transportation infrastructure are unprepared even though many are recognizing the need and are working diligently to prepare.

Much of the discussion at the four workshops exhibited common themes, though there were regional differences. These common themes, regional themes, current responses, and identified needs are described in the following sections.

3.1. Common Themes

Sea level rise is affecting all coastal regions of the U.S. and common themes emerged from the workshops:

- Communities are recognizing the short-term changes, but are slow to react because the changes are incremental now, but 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[3] is a common strategy (already implemented or in planning) to keep out high tides. However, participants identified several issues with this strategy including inadequate right of way, the danger of roads serving as water barriers[4], 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 SLR estimates, may be beneficial in responding to the emerging issues related to SLR.
- Roadways are often viewed by politicians and the general 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,[5] but few see the larger context and each sees the emerging issues related to SLR in different ways, depending on their agency's missions.
- Few state DOTs have staff dedicated to – or at least highly tuned toward -adapting to SLR, specifically, and climate change more generally.
- Finding adequate funding for SLR adaptation continues to be a challenge, leaving State DOTs to rely on flood emergencies to fund adaptation, when feasible.
- Most regions have conducted vulnerability assessments/studies of some sort, but few efforts to actually implement adaptation strategies have been made, largely because of resource limits.

While there were regional variations in the attention paid to each of these themes, these were identified as common challenges to responding to changing sea levels and the resulting consequences. These themes also provided direction/insight into the identification of useful responses to the challenges.

---

[3] Raising bridges was also mentioned, but raising roads to keep them dry and as a water barrier was mentioned much more often.

[4] FHWA discourages the use of road embankments as water barriers or levees. (Many participants referred to the potential use of road embankments as levees.)

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

3.2. Regional Themes

Some issues were unique to a particular coastal region or regions and this depended in part on the coastal processes dominant in that area. These themes also depended on the relationship between the coast and the proximity of the transportation infrastructure.

Mid Atlantic (Maryland) Workshop. Extensive areas of low-lying land, e.g. Dorchester County (Maryland) will be underwater by mid-century raising issues regarding the effects on well-established ways of life. The need for abandonment of certain areas and roads seems clear, but there is little political will to face this reality. Septic systems are failing because of rising groundwater and access for emergency services is impaired by more frequent flooding.

The Maryland State Highway Administration is currently designing for 2 feet of SLR by 2050 as a consistent approach to considering the future across projects. There have also been many efforts to communicate the coming changes in the Mid-Atlantic area including a documentary film “High Tide in Dorchester” to communicate the immediacy of the issue.

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

FDOT districts have some flexibility to modify roadway and bridge designs to accommodate SLR, but there is no consistent basis for those modifications. In general, FDOT bridge clearances are not presently designed for SLR.

Pacific (Washington) Workshop. A major concern is that existing roads and bridges block natural sediment and woody debris paths to the ocean. While this problem exists under current conditions, SLR, glacial retreat, and potential changes to precipitation patterns may be compounding these blockage issues. Rivers and streams are depositing sediments in tidal areas from eroding unconsolidated materials exposed due to glacial retreat; increased flow (transport capacity) due to changes in the proportions of the watersheds that are dominated by either snow or rain processes and must overcome increasingly high tailwater elevations at the coast. Culvert maintenance was also cited as a major problem for WSDOT that is only expected to worsen with SLR.

The City of Olympia has prepared strategies for adapting to SLR in its low-lying urban areas. Establishing long-term governance and financial mechanisms will be essential for implementation.

North Atlantic (Massachusetts) Workshop. 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, navigational hazards previously visible are being submerged and becoming problematic.

3.3. Current Responses

The workshop participants shared some of the responses to the emerging issues of SLR 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.
- Engineering solutions.

Regulatory and institutional responses are those where changes to the context in which the transportation (or other 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.

Numerous operational responses were identified by participants. These include road closures, road abandonment, as well as enhancing current practices in slope stabilization, stormwater controls, and roadside vegetation management. Most of these responses have been used for reasons other than climate change, but have been adapted for climate change.

Finally, as SLR 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.

Many of the responses described by participants, as well as others are summarized in list of possible responses in Appendix A.

3.4. Identified Needs

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

- Science guidance and research
- Engineering and technical guidance
- Social science and economics tools
- 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.

3.4.1 Science Guidance and Research

Several needs for addressing the effects of SLR were identified that fall in the category of science guidance and research. Defining local projections of SLR which should be used for design was the most common science guidance need. Participants observed that there is a wide range of projections for SLR by mid or late century, but no common authoritative guidance. 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 2100 as the appropriate time horizon for evaluating SLR, but does not have a quantitative design value.

Most workshop participants believed, with some exceptions, that national quantitative SLR design standards would stimulate appropriate design and adaptation work targeted to achieving such standards that would increase the resilience of our transportation infrastructure. They further emphasized that the standards should be mandatory rather than suggestions and fully backed with the credibility and authority of a federal and/or national entity (e.g. FHWA, AASHTO, NCHRP).[6] Regional standards would be better than the current patchwork of guidance and suggestions, but not as effective as national standards.

A second area of science-based guidance and research is the projection of groundwater rise rates and saltwater intrusion. Tools, such as groundwater models or regional studies, were mentioned as being helpful in anticipating the effects on the operations and maintenance of various components of the transportation infrastructure.

A third area is characterized here as focused applied research related to effects of a changing environment on transportation systems. These include 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.
- SLR and GW level increases on foundation design.
- SLR and GW level increases on seismic impacts.

[6] NCHRP project 15-61 is currently evaluating development of quantitative SLR design recommendations.

A fourth science-based area expressed frequently by participants pertains to the ecological and/or geomorphological responses of natural systems to SLR. The relative importance of each of these varies by coastal region, but the list includes a wide range of topics:

- Identification of the effects of climate change (flooding changes and SLR) on the transport of woody debris and sediment movement especially at the freshwater – coastal interface.
- Identification of how shoreline changes resulting from SLR 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 SLR on coastal scour and shoreline erosion processes.
- Identification of the effects of SLR on saltwater and freshwater fish habitats.

Participants noted that there may already be actionable research in some of these areas of which they are simply unaware. In such cases, the need expressed by the participants was for literature reviews and syntheses of these topics to be undertaken to identify what is already known and on what future research might focus.

3.4.2 Engineering and Technical Guidance

Workshop participants identified specific guidance needs in the engineering and other technical areas. In many cases, these areas reflected the need for design guidance.

One of the most common engineering needs was for guidance on 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 was a need for technical strategies for raising roads incrementally as sea levels rise.

A second engineering need related to the effects of SLR 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. There was 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 – tides, storm surge, and rainfall. This topic was referred to as “compound flooding” and “coincident frequency analysis” during these discussions. Participants noted that some research has been completed in this area (e.g. Kilgore *et al*. 2013), but more work is needed. Guidance for estimating projected precipitation from coastal storm events was also mentioned as a needed tool to better estimate stream flooding.[7]

Participants further identified guidance on the design of the interface between stormwater/storm drains and the tidal environment. With SLR, there is a need to adjust the tailwater design

[7] Part of NCHRP 15-61 is directed to providing guidance on estimating projected precipitation.

assumptions at the outlets of storm drains to insure continued drainage. There is also a need to consider design guidelines for tide gates, backflow controls, pump stations, and auxiliary power.[8]

Other engineering guidance areas described as needs include:

- 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).

3.4.3 Social Science and Economics Tools

Many of the needs expressed by the workshop participants were not related directly to science or engineering. The following needs were discussed at multiple workshops:

- Communications tools to introduce unwelcome changes, e.g. SLR, in a positive way that expresses hope and inspires constructive responses.
- Communications tools to expand awareness of the current experiences of SLR and potential changes yet to be experienced.
- Training for regional, state, and local personnel responsible for adaptation covering how to recognize coming changes and how to prepare.
- 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.

3.4.4 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. The participants frequently cited examples where 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 SLR complicates the recognition of the fundamental issues and challenges for the development of effective response strategies to SLR.

Not surprisingly, a major need was identified for additional financial and personnel resources. Such resources could be used for more comprehensive asset management systems, monitoring

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

programs, and investments in more resilient infrastructure. Such resources, participants noted, would have benefits throughout their organization beyond a more effective response to SLR.

Better intra- and inter-agency communication was frequently cited as a need. This ranged from abolishing – or at least perforating – the decision-making silos that exist within many agencies and between agencies. Broader participation in the discussion about responses to SLR was also raised as a means 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 SLR(e.g. utilities and water/wastewater providers) may provide a better understanding of the overall effects of SLR and potentially enable identification of more robust solutions. Outreach to tribes may also contribute to better solutions.

Also related to communications is 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.

Sharing of information and data was cited as a need. Setting up interagency data sharing of SLR projections, monitoring information, adaptation cases studies, design approaches, and other information were discussed.

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 SLR.

4. Recommendations

The benefits of this series of four workshops were the confirmation of the emerging issues related to SLR 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 previously in Section 3.1 inform the selection of appropriate next steps. Those themes include: 1) a recognition of historical SLR 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 SLR estimates, 4) the lack of staffing dedicated to – or at least informed about – responding to SLR, 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 recommendations are offered (grouped by needs areas):

1. Scientific guidance and research.
    a. National technical reference materials addressing quantitative SLR estimates should be developed as a tool for state and local communities to use for adaptation designs. The reference materials should be adaptable to local and regional differences in relative sea level rise.
    b. Synthesis studies, including literature reviews, should be conducted on the identified scientific research needs. AASHTO and/or 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.
2. Engineering and technical guidance.
    a. National technical reference materials should be developed on the use of raised roadways to limit inundation caused by flooding including that caused by SLR.
    b. National technical reference materials should be developed for estimating joint probabilities for high tides, storm surges, and rainfall.
    c. FHWA and/or AASHTO should assist coastal states in prioritizing and implementing the remaining identified guidance needs.
3. Social science and economics tools.
    a. FHWA websites on resilience and adaptation have been useful to many practitioners. FHWA should consider expanding the site to include non-federal lessons learned and/or studies related to adapting to sea-level rise that promote good practice. FHWA should also consider encouraging state and regional organizations to create or enhance web-based clearinghouses of lessons learned and case studies.
    b. FHWA should update NHI training course 135082 “Highways in the Coastal Environment” to include lessons on adaptation and more broadly promote the course. In addition, new NHI courses and materials covering the broader topic of “Resilient Highways” could also be developed.
4. Institutional and coordination strategies.
    a. To improve federal interagency coordination, the White House should convene a collaboration of federal agencies to discuss joint action on SLR issues.
    b. To improve state interagency coordination, each state should convene a collaboration of state agencies to discuss joint action on SLR issues.

Implementation of any of these recommendations will require political and technical leadership at local, state, and national levels. While implementation of some recommendations may seem remote, a key to achieving them is first to identify the goal.

References

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

Jacobs, J.M., L.R. Cattaneo, and W. Sweet 2018. “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.

Kilgore, R. T., D. B. Thompson, and D. T. Ford, “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 March 2013.

Sweet, W. V., J. J. Marra, and G. Dusek 2017. *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-content/sotc/national/2017/may/2016_StateofHighTideFlooding.pdf

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*, National Oceanic and Atmospheric Administration, Technical Report NOS CO-OPS 086.

Appendix A. Emerging Consequences and Reponses

Potential Consequences (loss of function/increased maintenance)

1. Roads
   a. Roadbed saturation causing pavement degradation, sinkholes, and service life reduction
   b. Rutting asphalt causing hydroplaning issues
   c. Increased frequency of embankment overtopping
   d. Increased frequency of temporary road closures
   e. Reduction in visits for businesses
2. Bridges
   a. Navigational clearances compromised
   b. Loss of freeboard
   c. Altered risk of wave loading that is sensitive to sea level and bridge height
   d. Increased deterioration of undersides of decks and damage to (fixed) under-bridge utilities because of saltwater exposure
   e. Increased risk to mechanical/electrical systems because of saltwater exposure
3. Tunnels
   a. Increased frequency of flooding
   b. Increased potential for infiltration
   c. Increased risk to mechanical/electrical systems because of saltwater exposure
4. Culverts
   a. Pipe floatation/settlement
   b. Tidal erosion of end treatments or support
   c. Infiltration/exfiltration
   d. Sedimentation
5. Stormwater Quantity Management
   a. Pipe floatation
   b. Infiltration into the storm drain system
   c. High tailwater
      i. Storm drain backflows
      ii. Increased frequency of flooding during rainstorms
      iii. Increased sunny day flooding
      iv. Decreased velocities and increased sediment deposition

d. Storage losses in dry/wet ponds resulting from rising groundwater
e. Interference of backflow prevention or tide gates by barnacles
f. Saltwater damage to pipes, junctions, and inlets

6. Stormwater Quality Management
    a. Reduced infiltration capacity because of high groundwater affecting stormwater infiltration facilities and septic systems
    b. Storage losses in water quality ponds resulting from rising groundwater
    c. Saltwater intrusion interfering with biological processes
    d. Shortcutting loading of fertilizers and herbicides to receiving waters
    e. Increased frequency of combined sewer overflows
    f. Increased frequency of high tailwater preventing releases of combined sewer overflows and the associated health issues
    g. Loss of coastal wetlands
7. Other
    a. Seawalls
        i. Piping behind seawalls in porous soils
        ii. Boat wakes more frequently overtopping seawalls
    b. Increased maintenance costs to keep roads functioning. When to draw the line? Who decides?
    c. Ecological effects on coastal ecosystems, e.g. saltwater marshes
    d. Widening of FEMA (or locally regulated) floodplains, rising Base Flood elevations
    e. Extension of tidal influenced zone upstream
    f. More vulnerability during storms, smaller storms more damaging, further inland, breaching barrier islands
    g. Loss of beaches
    h. Deterioration of concrete, metals, and other materials increasingly exposed to saltwater
    i. Groundwater supply contamination
    j. Changes to liquefaction of underlying soils during seismic events
    k. Effects on septic systems

Potential Responses

1. Roads
    a. Temporary road closures

b. Permanent road closure
c. Raising roads
    i. May cause increased damage to roadbeds during storms
    ii. May cause unintended flooding consequences upstream
d. Relocate roads
e. Reclassify functional class of roads
f. Rerouting of emergency vehicles, school busses, transit
g. Parking restrictions to avoid flooded cars
h. Sealing/armoring of embankments
i. Seawalls
j. Use of non-metallic MSE wall straps

2. Bridges
    a. Temporary or permanent closures
3. Tunnels
    a. Temporary or permanent closures
    b. Increased flood proofing
4. Culverts
    a. Watertight joints to prevent infiltration/exfiltration
5. Stormwater Quantity Management
    a. Watertight joints to prevent infiltration/exfiltration
    b. Installation of pumping systems and check valves
    c. Installation of tide gates/valves
    d. Adding offline storage volume (or larger diameter culverts), allowing for surcharge
    e. Making watershed modifications/storage upstream/flow reduction through low impact development strategies
6. Stormwater Quality Management
    a. Modify vegetation to include salt tolerant plants and other bio-habitat changes
    b. Inject stormwater underground
    c. Apply stormwater to irrigate maintenance yards/golf courses/ROW
    d. Reduce use of fertilizers and herbicides to establish and maintain roadside vegetation
    e. Relocate wetlands to higher ground

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

Appendix B. Workshop Attendees

Table 2. 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	MDOT SHA
Douglass	Scott	President, South Coast Engineers	SCE
Gilliam	LaTonya	Engineer	DelDOT
Goettler	Gina	Transportation Engineer (Hydraulics)	MDOT SHA
Graff	Robert	Manager, Office of Energy and Climate Change Initiatives	DVRPC
Habic	Elizabeth	Climate Risk and Resiliency Program Manager	MDOT SHA
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	NC
Liang	Joy	Environmental Specialist	FHWA
Lupes	Becky	Air Quality Specialist	FHWA
Mattejat	Peter	Environmental Manager	MDOT MDTA
McDaniel	Andrew	Manager, Highway Stormwater Program	NC
Michalski	Michael	District Operations Engineer	MDOT SHA
Neighorn	Jim	Hydraulic Engineer	FHWA
Pujara	Karuna	Deputy Director	MDOT SHA
Seiger	William (Bill)	Division Chief, Waterway Construction	MDE
Singleton	Eileen	Principal Transportation Engineer	Balt Metro Council
Sisson	Steve	Sussex County Review Coordinator	DelDOT
White	Ryan	Director of Public Works	Dorchester County, MD
Yurek	Russ	Director	MDOT SHA

Table 3. 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	FDOT
Claridge	Kevin	Director of the Florida Coastal Office	FDEP
Danchuk	Samantha	Assistant Director	Broward County, FL
Dominguez	Mario	Assistant District 6 Drainage Engineer	FDOT
Douglass	Scott	President, South Coast Engineers	SCE
Earp	Katey	Drainage Design Engineer	FDOT
Gray	Whitney	Administrator, Florida Resilient Coastlines	FDEP
Jenkins	Rick	Drainage Design Engineer	FDOT
Kafalenos	Robert	Air Quality Specialist	FHWA
Knight	Chase	Composite Materials Research Specialist	FDOT
Konyha	Kenneth	Principal Hydrologic Modeler	SFWMD
Maamar-Tayeb	Abderrahmane	Transportation Engineer	TXDOT
Nolan	Steve	State Structures	FDOT
Nurmi	Cynthia	Hydraulic Engineer	FHWA
Obeysekera	Jayantha	Chief Engineer	SFWMD
Poole	James	District 4 Drainage Engineer	FDOT
Ribbeck	Carlos	Consultant for District 6 Drainage Department	FDOT Consultant
Salazar	Ricardo	District 6 Drainage Engineer	FDOT
Spirio	Carl	State Drainage Engineer	FDOT
Tachiev	Georgio	Consultant for District 6 Drainage Department	FDOT Consultant

Table 4. Workshop attendees in Olympia Washington.

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

Table 5. Workshop attendees in Boston Massachusetts.

Last Name	First Name	Title	Affiliation
Arpino	Michael		FHWA (MA Division)
Bartha	Stephen	Tunnel/Structural Engineer	FHWA
Belanger	David	District Operation/Maintenance Engineer, District 6	MassDOT
Beucler	Brian	Senior Hydraulics Engineer	FHWA
Collette	Peter	Maintenance Engineer, District 4	MassDOT
Crean	Teresa	Coastal Community Planner	Univ. of RI Coastal Resource Center
Douglass	Scott	President, South Coast Engineers	SCE
Dvelis	Jason	Environmental Protection Specialist	FHWA
Fouad	Hanan	Hydraulic Engineer	MassDOT
Griffin	Mark	District Inspection Engineer/D6 Bridge & Tunnel Inspector, District 6	MassDOT
Hebson	Charlie	Chief Hydrologist	Maine DOT
Hogan	Mike	Transportation Supervising Engineer - Hydraulics & Drainage	CT DOT
Howard	Kirsten	Coastal Resilience Coordinator	New Hampshire Coastal Program
Jacobs	Jennifer	Professor, Dept. of Civil and Environmental Engineering	Univ of NH
Knisel	Julia	Coastal Shoreline and Floodplain Manager	MA Office of Coastal Zone Management
LaBranche	Julie	Senior Planner	Rockingham Co. NH Planning Commission
Lupes	Becky	Air Quality Specialist	FHWA
Mallette	Timothy	Hydraulic Engineer	NHDOT
McCullough	Rick	Director of Environmental Engineering, District 6	MassDOT
Mecray	Ellen	Regional Climate Services Director, Eastern Region	NOAA
Miller	Norm	District Drainage Engineer - Maintenance Division	CT DOT
Miller	Steven	Supervisor, Environmental Management and Sustainability	MassDOT
Paris	Timothy	Project Development Section	MassDOT
Vieira	Daniel	Assistant District 5 Maintenance Engineer	MassDOT

Appendix C. Participant Presentations

The following presentations are provided in a separate pdf document:

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