Vulnerability of Municipal Transportation Assets to Sea Level Rise and Storm Surge

Technical Paper 167
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Rhode Island Statewide Planning Program
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Executive Summary

Sea level rise and the gradual increase in high tides have been occurring for decades. International, national, and Rhode Island-based experts agree that the rate of sea level rise will increase by the end of the century. Sea level rise presents a major challenge to Rhode Island's transportation infrastructure, both via daily tidal flooding of coastal assets and making storm surge events more severe. The latest estimates of the scientific community are that Rhode Island could experience up to 7 feet of sea level rise by the end of the century. During that same time period Rhode Island can expect at least one 100-year storm surge event, an event whose severity will potentially be magnifies by sea level rise.

This analysis follows up on a similar, prior technical paper entitled "Technical Paper 162: Vulnerability of Transportation Assets to Sea Level Rise." The prior paper piloted a methodology for analyzing sea level rise vulnerability by focusing on assets under state jurisdiction. This paper (Technical Paper 167: Vulnerability of Municipal Transportation Assets to Sea Level Rise and Storm Surge), seeks to follow up on those prior efforts by utilizing additional data, including storm surge modeling, and focuses on municipal assets in order to help the cities and towns of Rhode Island prepare for sea level rise and storm surge in their local planning efforts.

The analysis identifies the transportation assets at risk under one, three, five and seven feet of sea level rise, and analyzes how these sea level rise scenarios would interact with a 100-year storm surge event. This analysis does not include erosion, riverine flooding, precipitation, and is based on current conditions. For the purposes of this paper, "transportation infrastructure" may include all state or municipally owned roads and bridges in Rhode Island. Using a GIS-based methodology, the analysis shows that all 21 coastal Rhode Island communities will experience impacts to their transportation infrastructure due to sea level rise.

Figure 1: Scenarios Included in Analysis

Sea Level Rise	Storm Surge
	100-Year Storm Event
1 FT SLR	100-Year Storm Event + 1 FT SLR
3 FT SLR	100-Year Storm Event + 3 FT SLR
5 FT SLR	100-Year Storm Event + 5 FT SLR
7 FT SLR	100-Year Storm Event + 7 FT SLR

The analysis shows that in Rhode Island 1.9 miles of roadway are expected to flood at high tide under one foot of sea level rise, 34 miles of roadway at three feet of sea level rise, 102 miles of roadway at five feet of sea level rise, and up to 175 miles of roadway at seven feet of sea level rise.[1] Additionally, 81 bridges may be affected by the projected sea level rise. Under current conditions, a 100-year storm surge event would flood up to 337 miles of roadway. With one foot of sea level rise a similar event would flood 373 miles of roadway, three feet of sea level rise would see 436 miles flooded, five feet would cause 505 miles to flood, and seven feet would see 573 miles flood in the event of a 100-year storm event. 163 bridges would potentially be affected under these combined sea level rise and 100-year storm event conditions. [1]

The vulnerability assessment portion of this analysis found that, while the most vulnerable individual transportation assets are located in Rhode Island's East Bay region, all coastal cities and towns will face serious challenges in coping with the effects of sea level rise and storm surge regardless of their geographic location. Though the transportation assets impacted may only be of local significance, the cumulative impact could be serious, particularly for the municipal governments responsible.

Integral to the goals of this project is the presentation of data in a manner that is accessible and understandable for individuals serving in a wide variety of municipal government roles, from those with long experience relating to coastal

[1] These figures are cumulative, and based on current conditions. They do not account for coastal erosion and other factors that will likely increase the exposure of transportation assets to sea level rise. Please see "Overview of challenge presented by coastal flooding to transportation assets" and "Limitations" sections for a complete accounting of the limitations of this study.

flooding, to those only learning about them for the first time. To this end Technical Paper 167 is accompanied by a robust online presence, described in the text box below. In addition to a general background and information regarding the project, this online presence can help guide a reader to appropriate supplemental materials. For example, a reader approaching the subjects in this paper for the first time may wish to start with the easy introduction provided in the municipal fact sheets. This paper is intended for those seeking to move beyond the introduction to a more detailed understanding of this analysis, and those preparing to conduct an analysis of their own. For those prepared to move into their own analysis, the data generated by this Technical Paper is provided online in The Digital Appendix, which allows users to find the data most directly relevant to their interests.

Additional Online Materials for Technical Paper 167

http://www.planning.ri.gov/geodeminfo/data/mun-slr.php: Main Project Web Page

http://www.planning.ri.gov/geodeminfo/data/mun-slr-fs.php: Location of municipal factsheets, a great resource for prompting discussion with people who are new to the topic

http://www.planning.ri.gov/geodeminfo/data/append.php: The Digital Appendix, which contains all the supplemental materials that would not fit in Technical Paper 167. Readers interested in learning more can customize the materials they gather in reference to their specific interests.

Project Objectives

This analysis follows up on the results of "Technical Paper 164: Vulnerability of Transportation Assets to Sea Level Rise," which piloted the combination of a GIS-based exposure analysis with a vulnerability analysis to assess the impacts of sea level rise on the transportation system. This Technical Paper follows up on those efforts and provides added information regarding seal level rise and storm surge to the municipalities.

The analysis aims to communicate the estimated geographic extent of sea level rise in relation to transportation infrastructure, and to provide municipal and state level transportation stakeholders with an overview of assets most vulnerable to sea level rise. The specific objectives of the project include:

- Provide an overview for state and municipal staff, as well as members of the public, on the exposure of Rhode Island's transportation assets to coastal inundation and storm surge.
- Provide RIDOT, municipal planning and public works departments, and other transportation stakeholders, estimates of the exposure of specific roads under different sea level rise and storm surge scenarios.
- Develop and expand upon the vulnerability and risk method for ranking adaptation priorities.
- Identify the transportation assets considered most vulnerable in each city or town.
- Provide planners and public officials with a sketch of the next steps available to their municipality or agency.

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Introduction

Rhode Island, as a coastal state, has a long history of major and minor flooding events during which water inundates, or covers, land area that is currently, on average, dry. Statewide Planning analyzed the impacts of two types of flooding events on transportation infrastructure through this project: sea level rise and storm surge. Sea level rise (SLR), is the term for the effectively permanent inundation of dry land due to the rise in the average water level of the oceans. Storm surge is the term for a short-term inundation event which occurs when large storms move large masses of water onto previously dry areas. Once the storm dissipates, the water returns to its normal level.

Sea level rise and storm surge are fundamentally different processes. A change in sea level can occur over very long periods, and is effectively permanent, while storm surge is a temporary event, which covers the dry land with water for several days but ultimately leaves it dry again. These fundamentally different processes are included in this paper because they are interrelated based on their impacts on coastal infrastructure and policy. Both processes present the potential for serious damage to the coastal communities of Rhode Island, and the risks the two types of hazard present will be manifesting over the same time frame, roughly the next century.

Index of Terms

Though it is the goal of this document to be accessible to those without a background in climate science, some technical terms are unavoidable. It is hoped that this short index of terms will help the lay person better access the information contained in the rest of the text.

Exposure – The extent of an asset projected to be exposed to inundation during sea level rise or storm surge conditions. The asset might only be inundated once in the case of an asset exposed to storm surge, or it might be permanently under water in certain sea level rise conditions.

Freeboard – The space between the bottom of a bridge's structure and the surface of the water underneath the bridge. Strictly speaking, bridges that are not over a body of water are not considered to have a freeboard, but for the purposes of the analysis the bridge's height over land was considered to be a freeboard measurement.

Inundation – The coverage of a previously dry asset with water. This coverage can be permanent, temporary, or recurring.

Mean Higher High Water (MHHW) - There are two high tides in each day, and one of those two is always higher than the other. The higher of the two high tide lines is called "Higher High Water." The National Oceanic Observatory Administration defines the MHHW as the average of the Higher High Water readings in a location over a 19 year period Return Period.

Return Period – The return period of a storm is a shorthand way for experts and policy makers to standardize and discuss the strength of a theoretical storm event. It is also an expression of the characteristics of that theoretical storm, and an educated guess as to how often such a storm could occur.

Severe storms, such as those that cause surge, can be described as high risk, low probability events: If a storm were to occur the damage could be catastrophic to those affected, but the likelihood that a storm will actually occur in any specific year, in any specific place, is very low. We do know that these storms can happen because they have happened before, but we lack the knowledge to predict precisely when they will happen. This picture changes, however, if you take more locations or years into account. For example, Rhode Island is unlikely to be hit by a severe storm this year, but based on historic experience it is very likely that somewhere in the east coast of the United States will be hit by a severe storm this year. A similar statistical affect can be achieved by expanding the time frame instead of the geography. So, rather than looking at all of the eastern seaboard for one year, one can look at a specific place for 100 years.

Using this technique, climate scientists are able to determine both the risk of a severe storm in a specific place in any given year, and also the number of years over which the arrival of such a storm becomes a near certainty. In the case of the storms being discussed in this analysis, the risk is actually 1% in any given year, but that risk rises to nearly 100% in a 100 year period. So just like it is very likely that there will be a severe storm somewhere in the United States this year, it is also very likely that there will be a similarly severe storm in Rhode Island sometime in the next 100 years. This is called that theoretical storm's "return period."

The concept of a return period allows scientists to talk about storms based on an understood quantity, the severity of their impact, as opposed to weather data like wind speed and direction that might vary based on whether a storm is a hurricane or a nor'easter. Because many different types of severe weather can cause damage, it is useful not to restrict focus to just one type of storm.

The danger of the use of the concept of return period is the perception by many that the return period is a kind of mechanical process, that it is literally expected that there will be a storm of that intensity every 100 years, to the day. This is no more likely than a coin toss resulting in heads immediately following tails, one after the other, through numerous tosses. Though there is a 50% chance of each side of the coin presenting on average, each individual toss has a 50/50 chance of presenting one or the other regardless of whether heads or tails presented in the previous toss. Similarly, regardless of how recently or how long ago a storm event occurred, there will always be a 1% chance of a 100-year storm event.

Sea Level Rise – The change in the average sea level over time. This can occur for any number of reasons, but recent research shows that the rate of change is accelerating. This change means that in the future, on a normal, storm-free day, the surface of the ocean will be at a higher point on the shore line than it would have been in the past. Phenomenon related to the normal functioning of the ocean and related waters, such as tidal action, will also be higher. Though the extent often depends on the specific location involved, in general the low water mark and the high water mark in a given location can be expected to move upwards over time relative to their current locations.

Strom Surge – Storm surge occurs when the low atmospheric pressures created by large storms pulls up a bubble of water above the height it would usually be expected. When the storm moves over the land this bubble is dragged along with it, forcing water to move from a starting point at sea level up into the topography of the surrounding landscape. How much water is forced onto the land is a function of the amount of low pressure the storm has created, which is in turn a measure of the strength of the storm. How far the water moves inland is an interaction between the amount of water being carried by the storm, the type of topography in a given area, and the height of sea level at the time. So, the storm surge from a very strong storm that arrives at low tide in an area with very steep topography might move less far inland than a weaker storm that arrived at high tide in a place with shallow topography.

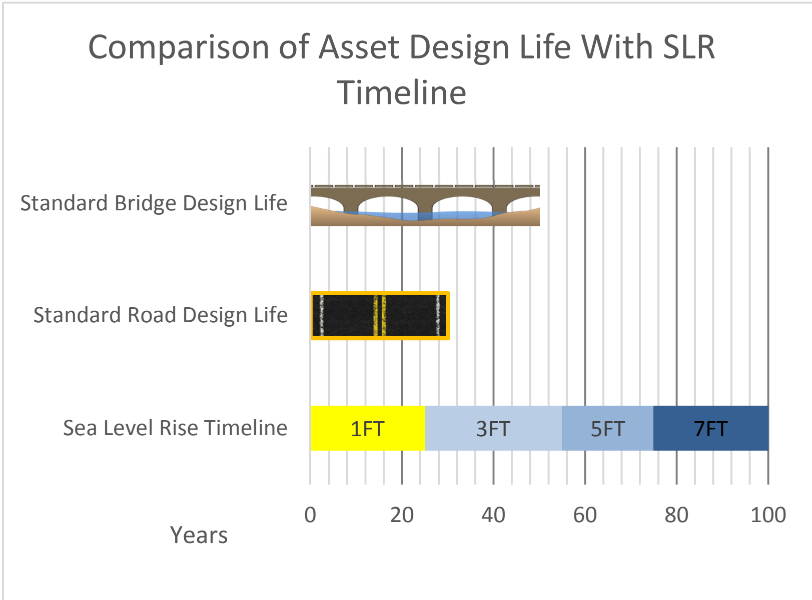
Tidal Spread – The difference between the higher of the two daily high water lines and the lower of the two daily low water lines.

Vulnerability – When used in the context of disaster preparedness, vulnerability is a concept that discusses the extent to which changes could harm or affect a system, or community. Though potentially a broad term that can apply to emotional as well as physical factors, in the context of the analysis presented in this technical paper vulnerability is applied to the physical capacity of the transportation system to service the needs of the various communities and populations in Rhode Island. Though discussing a physical infrastructure, some of the ways this infrastructure is used are not quantifiable, and so vulnerability should be understood as a relative measurement.

Relevance and Risk

Although the risks Rhode Island faces due to sea level rise and storm surge are expected to arrive by the end of the century, this does not mean that the state has 100 years to address the issue. The risks are in some ways immediate, while also increasing gradually over the next century. The way this risk should be understood requires taking into account the different natures of the two threats faced: sea level rise and storm surge.

Figure 2: Sea Level Rise and Asset Design Life



Sea Level Rise

Sea level rise is expected to occur gradually over the course of the next century with one foot of sea level rise expected within the next 25 years. This may seem a distant threat, but it seems less abstract when the design life of transportation assets are taken into account. As the design life of the standard roadway is around 30 years, and the life of a standard bridge is around 50 years, many of the roads and bridges built today will be around when sea level rise has become a present reality. In an environment with limited transportation infrastructure funding, it would be unwise to spend resources on assets that will not be useful for their entire design life. Wise planning today, that takes sea level rise into account, can help ensure that the transportation assets being built now will give our communities the expected return on investment.

Storm Surge

The risks associated with storm surge are different than the risks posed by sea level rise. Rather than presenting a steadily advancing risk, a 100-year storm event has a 1% risk of occurring in any given year. What will change during this period is the implication of what a 100-year storm surge event will mean to those living in Rhode Island's coastal communities.

For the purposes of this analysis, the main interaction of interest between sea level rise and storm surge is in what one might call the starting point of the storm surge. In the same way that a wave will travel to a point farther up the beach at high tide than at low tide, storm surges will tend to travel farther inland in a more advanced sea level rise scenario than under current conditions. The energy in the wave or storm surge may be the same, but if the starting point is higher, the wave or surge reaches a higher point. Since sea level rise will be changing the water level over a one hundred year period, and since a 100-year storm event can occur at any time within the next century, this analysis will examine the exposure and vulnerability to transportation assets that would occur if a 100-year storm surge event occurred during each of the sea level rise scenarios.

The described risks are not academic. Beyond the real world implications of a storm, Executive Order on Floodplain Management 11988[2] (issued in 1977) requires that all projects built with federal funding, including transportation projects built via the State Transportation Improvement Program (STIP) process, be built as much as possible to avoid the 100 year flood plain. The Executive Order on Flood Risk Management Standards 13690,[3] though it has yet to be implemented, has the potential to require all future projects in flood plains be elevated above the water line of the 100-year storm event. This effort will be complicated by the fact that the historic assumptions used to calculate the severity of a 100-year storm have become subject to change.

The risks associated with storm surge, which will be gradually magnified by sea level rise, can be expected to manifest over the course of the next century in a way that will affect assets under construction today. The immediate risk is low, but the risk grows over the medium and long-term, and the severity of the impact over that time period will increase as a result of sea level rise. By taking these issues into account the state and municipalities can better plan for current and future transportation infrastructure investments.

Overview of STORMTOOLS Data

The analysis presented in this paper is based on data prepared by the Coastal Resources Management Council (CRMC) in collaboration with the University of Rhode Island (URI) and published under the name STORMTOOLS. STORMTOOLS is intended as a way to make the data outputs of a complex set of modeling processes freely available to all Rhode Islanders, and consists of a series of maps and data sets depicting the SLR and storm surge that can be expected over the next century. The data is available online via the STORMTOOLS website[4] as well as via RIGIS.[5] This section will provide an introduction into the way the models used in STORMTOOLS function to give the reader an idea of what the data illustrates.

Sea Level Rise

The sea level rise data presented in this analysis were the result of a process that took broad predictions about sea level rise, produced by a variety of national and international agencies, and adjusted them to create forecasts relating to local conditions in Rhode Island. This process led to the creation of sea level rise scenarios by the STORMTOOLS team, which were projected into GIS. The Statewide Planning Program then placed this data in a mapped context and used it for the analysis portion of this project.

The scenarios used in this analysis, and in STORMTOOLS, were one, three, five, and seven feet of sea level rise. This is in line with policies established by other Rhode Island state agencies, notably the Coastal Resources Management Council (CRMC), and in line with the updated comprehensive plan guidelines, enacted by the Rhode Island State Legislature in January 2016. These laws and policies also reflect scientific work produced by the NOAA and the Army Corps of Engineers. Each of these four scenarios has a timeframe during which the scenario is expected to occur according to recent climate projections for the United States and Rhode Island. The CRMC adopted this timeline in the State of Rhode Island Coastal Resources Management Plan, and as such this timeline will be used in this paper as the accepted timeline for discussion purposes.

Decision makers may, however, want to look into the specifics that informed these assumptions, and make decisions based on how risk-averse (or conservative) decision-makers wish to be in their approaches to maintaining coastal

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[2] https://www.fema.gov/executive-order-11988-floodplain-management

[3] https://www.whitehouse.gov/the-press-office/2015/01/30/executive-order-establishing-federal-flood-risk-management-standard-and-

[4] http://www.beachsamp.org/resources/stormtools/

[5] http://www.rigis.org/

transportation infrastructure. While considering the probable timeframes for each scenario, it is helpful to compare timeframes to the design life of new transportation infrastructure, routine maintenance and upgrades, and the actual age of existing transportation infrastructure in the state.

To determine the geographic areas projected to be inundated under sea level rise conditions, the STORMTOOLS team used geographic information systems (GIS) and a method known as a "modified bathtub" model. The "bathtub" model projects sea level rise by modeling a vertical increase in the current water level over the existing terrain, much like filling a bathtub. This is done in GIS using data called a digital elevation model, or DEM, essentially a three-dimensional model of the terrain in Rhode Island created using data gathered in 2011 with light detection and ranging (LiDAR)[6] equipment attached to aircraft. To show the inundation from sea level rise, one groups all elevations in the DEM that are, for example, between sea level and one foot above sea level. For the three feet of sea level rise scenario, one would gather all the elevations between one foot above sea level and three feet above sea level.

A difficulty with this model used by the STORMTOOLS team is that "sea level" can be a difficult concept to pin down with the necessary specificity. Sea level is not static: there is constant wave motion, and tides rise and fall. For the purposes of this analysis, "sea level" was defined as Mean Higher High Water, a measure of high tide defined by NOAA. This also does not completely resolve the issue, because sea levels are not uniform across the planet's surface. Relative to the center of the earth, the water level at Newport is a different elevation from the water level at Providence. Using the bathtub model without accounting for this issue could result in underreporting water levels at Providence, or over reporting them at Newport. To account for this, the model must be "modified." The STORMTOOLS team handed off their DEM to researchers at NOAA, who used the DEM to run VDatum, a program that adjusts the elevation values in the DEM so they are relative to mean MHHW, rather than the center of the planet, thus accounting for variability in the tidal activity in Rhode Island's Narragansett Bay.[7] With the modified DEM, the STORMTOOLS team was able to run the modified bathtub model as described previously: sea level rise inundation zones were determined by capturing all areas with elevation less than or equal to the amount of sea level rise under a given scenario. The end result is a series of GIS layers representing the elevation zones inundated in the different sea level rise scenarios.

Storm Surge

The STORMTOOLS team also produced the 100-year storm surge data presented in this analysis. Unlike sea level rise, storm surge can be a highly localized phenomenon based on the interaction between the storm surge and the topography of a specific area. The STORMTOOLS team first modeled a 100-year storm surge event, and then added sea level rise inundation. In modeling the 100-year storm event the STORMTOOLS team had the advantage of a number of well understood, off the shelf tools for modeling different aspects of storm surge, as well as high quality national and local data sets. Notably, the DEM mentioned in the previous section, NOAA's Sea, Lake and Overland Surges from Hurricanes (SLOSH) model, and the data points from the Army Corps of Engineer's North Atlantic Coast Comprehensive Study representing the bathymetric topography in the areas running up to the current water line. These data sets, in combination with other available data and modeling tools, allowed the STORMTOOLS team to first understand the forces behind storm surge, and then model how the energy contained in the water of a storm surge event would move up into the topography of the coastal region. This was done in a GIS environment. Once the final water levels

Figure 3: Included Analysis Scenarios

Sea Level Rise	Storm Surge
	100 Year Storm Event
1 FT SLR	100 Year Storm Event + 1 FT SLR
3 FT SLR	100 Year Storm Event + 3 FT SLR
5 FT SLR	100 Year Storm Event + 5 FT SLR
7 FT SLR	100 Year Storm Event + 7 FT SLR

[6] LiDAR uses lasers in a manner similar to the way radar uses radio waves: to detect distances. By fitting two sensors on an aircraft and measuring distances to the ground, LiDAR detectors create a picture of the ground, and can "see" through things like leaf cover and structures. The raw data requires significant processing to be usable as a DEM.
[7] VDatum does not account for localized tidal differences in smaller inlets.

were determined, one, three, five, and seven feet of sea level rise were added to the top of the surge water level to depict how the impact of storm surge would be different under the different sea level rise scenarios.

It is worth noting here a minor difference in the way sea level rise and storm surge were examined in this analysis. Because storm surge is outside of the normal experience of most people, it was felt to be important to include a scenario depicting storm surge under current conditions. A similar "current conditions" scenario was not felt to be important for sea level rise.

Limitations

Although the data produced by the STORMTOOLS team and utilized in this paper are high quality, scientifically defensible products, it should be noted that the data and conclusions presented in this analysis are the best possible results given the tools currently available. A number of variables were omitted from the modeling that will undoubtedly affect the inundation in any given location. Most broadly, some of the assumptions used to create STORMTOOLS are based on national models that may not be correct for Rhode Island. Recent research has suggested that in the northeastern United States sea level rise may be occurring more rapidly due to land subsidence and changes in the ocean circulation. Therefore Rhode Island may see its high tide line advance faster than the rest of the nation, and in advance of the milestones projected nationally for sea level rise. Research on this aspect of sea level rise is still ongoing.

The analysis did not include a number of variables that affect the impacts of sea level rise and storm surges, including erosion, changes in precipitation, changes in storm severity, and riverine flooding. For communities facing sea level rise, erosion due to wave action is very likely to magnify the impacts of the inundation. Though CRMC has done some important work in forecasting this process, these conclusions have not yet been combined with the sea level rise work presented in STORMTOOLS. Similarly changes in precipitation may change way the geography in Rhode Island reacts to sea level rise and storm surge, but research on this topic is still in an early stage.

One issue particularly important for understanding storm surge is the changing definition of the return period. It is recognized that the past assumptions were combined to create the current definition of a "100-year storm event" are in flux as the current climate changes. Storms of this level of severity are likely to become increasingly common, meaning that they will eventually pose more than a 1% risk in a given year. Addressing this aspect of the changing climate is an important task for Rhode Island but falls outside of the scope of this analysis.

Riverine flooding is likely to interact with all of the above factors. While riverine flooding is of key importance to many communities in Rhode Island, the data and modeling requirements of this variable have proved much more difficult to overcome. The STORMTOOLS team has undertaken a small pilot project to examine these issues, but it is likely to be several years before this information will be incorporated into a generalizable picture of the state as a whole.

Beyond the recognizably unaddressed variables, some aspects of sea level rise and storm surge will always remain beyond the scope of a computerized model. These results represent a statistical product based on current conditions. Over the 100-year time frame of this analysis it is inevitable that the natural and built environments will continue to change in ways that make it difficult to predict precisely what the actual impact of a storm event on transportation infrastructure will be. This analysis is not a substitution for a detailed examination of the facilities in question by those with local knowledge and specific skills related to the construction and maintenance of the assets.

Analysis Methodology

Using the STORMTOOLS data, RISPP staff analyzed the exposure and vulnerability of municipal transportation assets to sea level rise and storm surge. They gathered data on roads and bridges, determined the exposure of those assets using a GIS based methodology, and then assessed the vulnerability of the exposed assets. Because the goal of the analysis was to provide the cities and towns of Rhode Island with information in an easily communicated format, assets that had been included in "Technical Paper 164: Vulnerability of Transportation Assets to Sea Level Rise" were omitted from this analysis. Some of the assets, such as airports and rail tracks, had very small exposures in a fairly small number of municipalities, thus making their importance only of interest to one or two municipalities. Other assets, such as ports, are exceedingly difficult to quantify in a systematic way. Transit and bicycle assets, while widespread through the state and with exposures that were easily included, operate mostly on or near roadways, and so their analysis could be wrapped into the roadway analysis for the sake of clarity.

Transportation Asset Data

Because Statewide Planning focused its analysis on Rhode Island's roads and bridges, much of the data utilized was provided by RIDOT. This data consists of road and bridge GIS data. RIDOT also produces GIS layers depicting statewide bike routes and evacuation routes, both important things to consider in examining the vulnerability of road and bridge assets. The Rhode Island Public Transit Authority (RIPTA) provided GIS data depicting the current state of their bus route network, while STORMTOOLS provided data pertaining to the sea level rise and storm surge scenarios that form the core data piece of this analysis.

Figure 4: Source Layers and Codes

Data Layer	Source Agency	Public Location	Scenario Set Used
Roads	RIDOT	RIGIS	SLRRoads, SurgeRoads
Bus Routes	RIPTA	RIGIS	All
Bike Routes	RIDOT	RIGIS	All
Evacuation Routes	RIDOT	RIGIS	All
Rhode Island Bridges Over 25 Feet	RIDOT	RIGIS*	SLRBridges SurgeBridges
Rhode Island Mean Higher High Water	STORMTOOLS	RIGIS	All
SLR 1 Ft, Vector and Raster	STORMTOOLS	RIGIS	SLRRoads, SLRBridges
SLR 2 Ft, Vector and Raster	STORMTOOLS	RIGIS	SLRRoads, SLRBridges
SLR 3 Ft, Vector and Raster	STORMTOOLS	RIGIS	SLRRoads, SLRBridges
SLR 5 Ft, Vector and Raster	STORMTOOLS	RIGIS	SLRRoads, SLRBridges
SLR 7 Ft, Vector and Raster	STORMTOOLS	RIGIS	SLRRoads, SLRBridges
100-Year Storm Surge Event, Vector and Raster	STORMTOOLS	RIGIS	SurgeRoads, SurgeBridges
100-Year Storm Surge Event + SLR 1 Ft, Vector and Raster	STORMTOOLS	RIGIS	SurgeRoads, SurgeBridges
100-Year Storm Surge Event + SLR 2 Ft, Vector and Raster	STORMTOOLS	RIGIS	SurgeRoads, SurgeBridges
100-Year Storm Surge Event + SLR 3 Ft, Vector and Raster	STORMTOOLS	RIGIS	SurgeRoads, SurgeBridges
100-Year Storm Surge Event + SLR 5 Ft, Vector and Raster	STORMTOOLS	RIGIS	SurgeRoads, SurgeBridges
100-Year Storm Surge Event + SLR 7 Ft, Vector and Raster	STORMTOOLS	RIGIS	SurgeRoads, SurgeBridges

Determining the Exposure of Transportation Assets to Sea Level Rise

The "exposure" phase of the analysis began with a GIS intersect that projected the exposure to sea level rise and storm surge of roads, bridges, RIPTA routes and bicycle infrastructure, in each storm surge and sea level rise scenario. Road segments that were exposed to sea level rise or storm surge, and also carry RIPTA routes or bicycle infrastructure, were marked for the vulnerability analysis portion of the project. Bridges were analyzed based on characteristics, such as height above the water and the vulnerability of their access roads, which were likely to render the bridge inoperative.

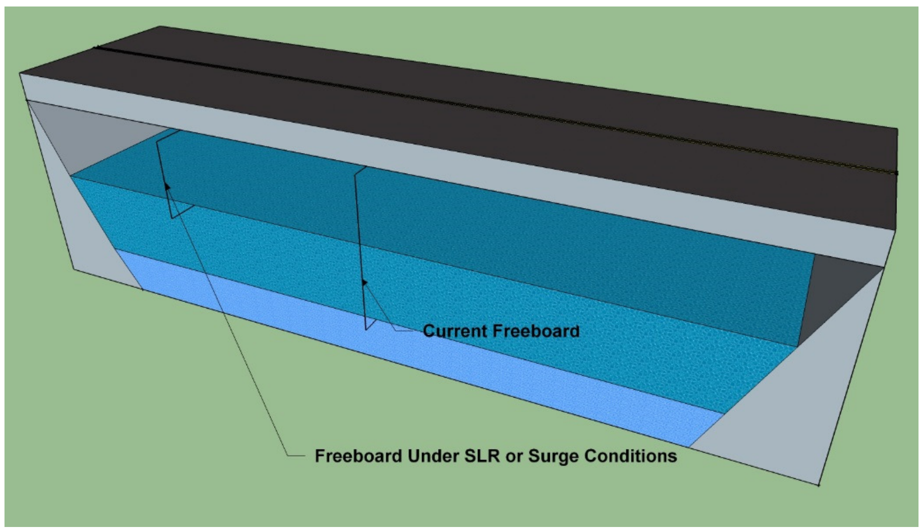
Roads

Statewide Planning used the “intersect” function in GIS to examine where the inundation in the different sea level rise scenarios was likely to impact the road network. When the road network and the different sea level rise scenarios are input into the tool, the computer returns only those roadways where the zone of probable inundation covered the roadways. The information attached to these returned roadways was also altered so that the initial level of inundation was attached to each segment. As a result, a GIS user could examine the returned roadway segments and see how many linear feet of roadway are expected to first be inundated under the one foot, three feet, five feet, and seven foot inundation scenarios. The returned roads that spatially intersected the bus, bike, and evacuation route layers were then selected, and the segments were marked in the GIS environment. The end result was a GIS layer where each road segment was marked for the first water level scenario in which it was forecast to be inundated under sea level rise, and where it was noted whether or not each segment was an evacuation route or carries intermodal traffic. Statewide Planning used the same process to identify the roadway segments exposed to the 100-year storm surge scenarios.

Bridges

The interaction of a bridge with water is more complex than that of a roadway. For a bridge the key characteristics to understand are the height of the freeboard and the accessibility of the bridge landings. An element of difficulty was added to this process by the tidal nature of many of the waterways in Rhode Island. Though RIDOT bridge inspection datasheets were manually incorporated into the GIS by RISPP staff, it was not possible to tell when in the tidal cycle the RIDOT inspectors had measured the freeboard, or even if the waterway in question was tidal in nature. This added a level of uncertainty to the data that needed to be accounted for. Some bridges were identified as a concern both due to freeboard height and accessibility, some for only one or the other. As with roads, bridges that carried intermodal facilities and evacuation routes were marked for scoring in the vulnerability assessment.

Figure 5: An illustration of a bridge within a SLR area but not subject to freeboard concerns.

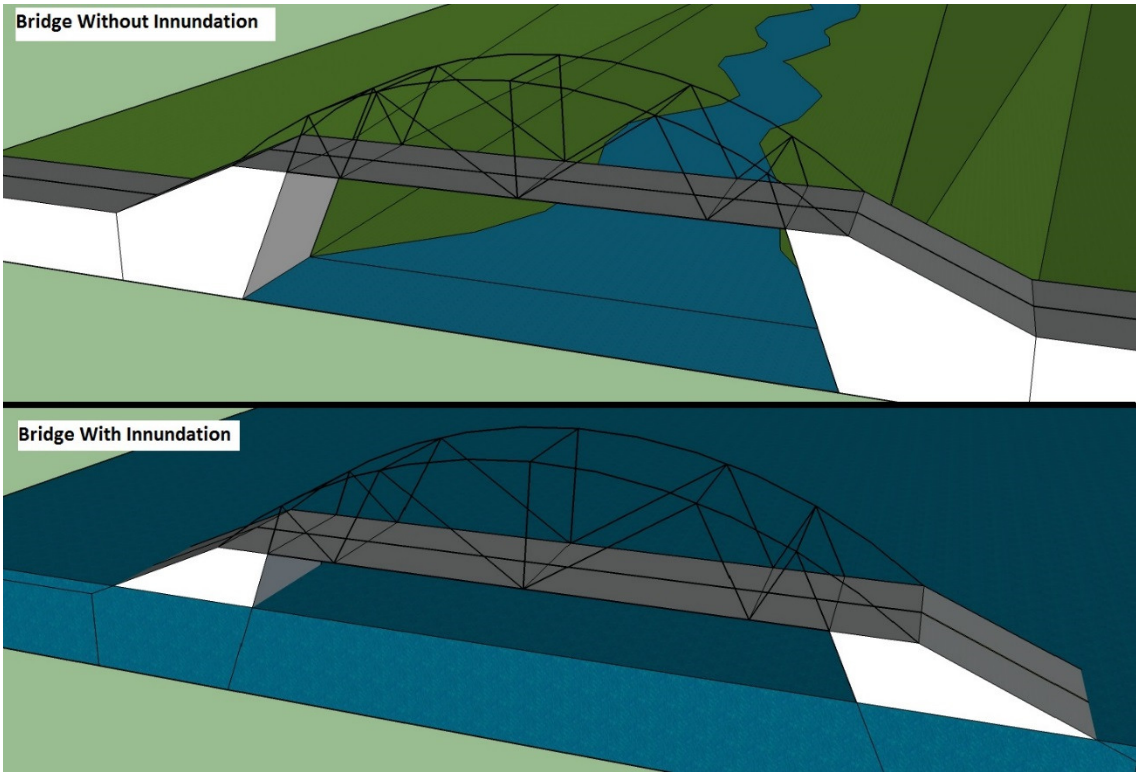


Freeboard

Practically speaking, sea level rise and storm surge can be expected to have little impact on a bridge if the freeboard, or height above the water, is large enough. If the water level does not interact with the bottom of the bridge, the bridge will probably not sustain damage from the changed conditions, and will continue to function as a bridge. As a result, the fact that a bridge is within an area projected to undergo sea level rise does not necessarily imply that the bridge will be impacted. As a result, determining the freeboard exposure of a bridge required more than the use of the intersect tool.

Bridges were initially identified using the intersect tool. The identified bridges were then marked as being a "Bridge Of Concern" if the freeboard data (from RIDOT) was less than the water height (from the STORMTOOLS raster layer) under the seven foot sea level rise and storm surge scenarios. Unlike roads, bridges were not broken out by scenario beyond the highest sea level rise and storm surge scenarios due to concerns that this would overstate the precision of the analysis. As an added level of precaution, it was assumed that all bridge freeboards were taken at a very low tide. Given an average tidal spread at the Newport tidal gauge of 42 inches, all bridges whose freeboards were within 42 inches of the highest sea level rise or storm surge scenarios was also marked as a bridge of concern. This analysis was unable to locate the freeboard height for several bridges within the sea level rise or storm surge zones and these were marked as being of concern.

Figure 6: Illustration of how inundation can create accessibility issues



Landing Accessibility

Notwithstanding the importance of freeboard, a structurally sound bridge can still be rendered useless if it is isolated from the rest of the road system at either end, even if the isolation occurs beyond the ends of the bridge proper. For example, an exceptionally tall bridge which would be otherwise unaffected by rising water might be rendered useless by flooding at either of the "landings" of the bridge. To determine the accessibility of the bridges, staff reviewed the road networks that connect each bridge under seven feet of sea level rise and storm surge scenarios. This could not be done automatically due to the nature of the data created by STORMTOOLS. Since freeboard was not involved in this measurement there was no need to apply a tidal spread. If the facility that the bridge carries would be cut off by inundation on one or both landings, it was considered a concern due to accessibility issues.

Providence Hurricane Barrier

It is assumed for the purposes of this project that the Providence hurricane barrier will function to protect the city against a storm surge event, and so bridges and roads located on the inside of the barrier were removed from the storm surge evaluation. The current barrier cannot be relied upon to protect the city from sea level rise as this is not its designed function. As a result roads and bridges vulnerable to sea level rise behind the barrier remained in the analysis.

Vulnerability Assessment

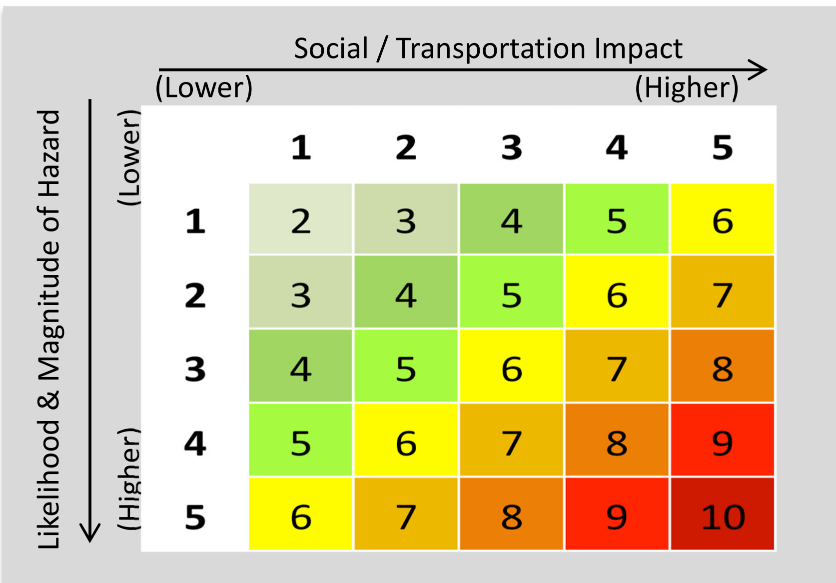
The vulnerability assessment was an exercise to determine the *relative* vulnerability of transportation assets and prioritize the assets deemed most vulnerable based on a set of criteria. To conduct the vulnerability assessment, a basic index of vulnerability was developed for each asset category. The vulnerability assessment creates a composite vulnerability score for each individual affected asset. The vulnerability index was designed specifically for each different asset type, and provides a *relative, not absolute*, ranking of vulnerability.

The vulnerability index used in this analysis worked with a concept of vulnerability that included both the characteristics of the physical hazard (e.g. length or area flooded, how soon the asset will flood, the elevation of the infrastructure) and the importance of the asset to society, or in this case, to the transportation system (e.g. use level of the asset, capacity, and existence of alternatives). The concept of vulnerability is summarized by the following equation:

Vulnerability = Likelihood and magnitude of hazard + Social / transportation impact of the hazard occurring

The hazard and system impact scores and weights were balanced such that the hazard and system scores each represent half of the highest possible final vulnerability score. The highest score a road could receive would be 10, the lowest would be 0, with 5 possible points coming from the hazard and system scores. Within these broader guidelines, numeric and weights were created based on the asset class being studied and the scenario type in question.

Figure 7: A Visual Interpretation of Vulnerability



The vulnerability rankings differentiate among assets to support the prioritization of assets for further study and action. Therefore the index was designed to produce results that would spread across a range of values. Low vulnerability index values should not be interpreted as low vulnerability, but rather, *lower* vulnerability than other assets. It should be noted that the data used in this assessment is not an exhaustive list. Municipal planners, who may have more data, could certainly expand on this methodology. A detailed description of the method used in the composition of the index is available in Appendix 4.

Roadway Vulnerability Assessment

For simplicity of presentation, RISPP scored the roadways in each municipality as a whole, rather than by each individual segment. It should be understood that the different segments in a road do not necessarily have the same characteristics, even within a given municipality. In order to group the segments in this way, the roads were initially scored at the segment level, and then these segment scores were averaged based on the percentage of the full road length each segment represented. So if a ten mile long road contained four segments, one that was five miles long, one that was three miles long, and two segments of a mile each, the scores assigned to the short segments would each be 10% of the final road score, the three mile long road would be 30% of the final score, while the five mile long segment would be 50% of the final score. These scores only relate to that portion of a roadway in a given municipality that are exposed to inundation.

Hazard

The hazard component of the score comprises those characteristics that determine how severely the asset will be affected and how soon, based on the scenario timeline discussed earlier. The roadways were analyzed based on the centerline length of possible road inundation in each scenario. Shorter segments received a lower numeric score than longer ones, and segments that are forecasted to be inundated earlier receive higher scores than those that are forecasted to be inundated later. For example, a road that will possibly see 75 feet of inundation at one foot of sea level rise will get a higher score than a road that will possibly see the same inundation at 7 feet of inundation. Similarly a road expected to have 50 feet of inundation at 3 feet of sea level rise will see a lower score than a road expected to see 200 feet of inundation at 3 feet of sea level rise.

The same general process was used for both storm surge and sea level rise scenario sets, except that some of the specific weights and numeric assignments used for the vulnerability assessment. Because the weights are intended to create a relative vulnerability score, it was important to adjust the scoring system to reflect the much larger impacts that can be expected from storm surge. Because storm surge is likely to go so much further inland than sea level rise, weights used to determine how likely a road segment is to be threatened had to be adjusted to avoid having all affected roads being flagged as highly vulnerable. The weights can be reviewed in Appendix 4.

System Impact

Determining the system impact of sea level rise or storm surge is a way of indicating how severely the transportation system as a whole would be affected if a given asset were lost. For example, the loss of a very busy road with a bus route, bike lanes, and which serves as an evacuation route would greatly affect the lives of a large number of people, but the loss of an infrequently accessed cul-de-sac would only seriously affect a small number of immediate residents.

In the analysis, RISPP used a roadway's functional classification as an indicator of its importance to the transportation system. The functional classification system ranks roads based on their use, access, design, and many other factors. For the purposes of the vulnerability analysis, roads with higher functional classifications were assigned higher numeric scores than those with lower ones. For example, a principal arterial was assigned a higher numeric rank than a major collector. Rhode Island's functional classification system is described in the 2014 Technical Paper 165: The State of Rhode Island Functional Classification System, and the data provided by RIDOT included the functional classification of every road in the state. Similarly, RIDOT maintains a database depicting whether or not a road has been selected as an evacuation route, and such roads were given a higher score than those without an emergency management function.

As was discussed in the section entitled "Analysis Methodology," the inclusion of public transit and bicycle infrastructure was a way to simplify presentation. Though vital transportation systems in their own right, much of the bicycle and bus infrastructure utilize on-road segments. Such segments were given a higher score. The entire system impact methodology was the same for sea level rise and storm surge scenario sets.

Bridge Vulnerability Assessment

The bridge assessment required taking into account a large number of physical and social properties. Unlike the roads assessment, which focused on the imminence and severity of the impact in determining the vulnerability score, the bridge assessment focused on variables that would increase the likelihood of the bridge being impacted. As was discussed in the exposure analysis section on bridges, this was done both because of the intrinsic complexity of bridges and because of uncertainties in the data available.

Hazard

Bridges where freeboard was thought to be directly exposed to water action were given a high score, as were bridges with potentially isolated landings. Bridges that were not shown to be directly inundated, but where the freeboard was considered to be within the tidal spread, were given scores that decreased as the height of the freeboard increased.

Because the impact of tide upon the recorded freeboard heights is not known, this graduated scoring system allowed RISPP staff to capture the risk that the freeboard measurements had been taken at low tide.[8] The lower the freeboard within the tidal spread, the more likely that tidal action could cause interaction between inundation and the bridge, and so such bridges were assigned a higher score. Conversely, a higher freeboard is less likely to have a problematic interaction with inundation, and so was assigned a lower score. As part of this process, bridges located over major tidal waters were assumed to be at more risk from tidal action than those over riverine waterways or land. Even if riverine areas are subject to tidal action for some part of the day, the fact that they are non-tidal at other parts of the day will serve to narrow the tidal spread and reduce the risk to the bridge. Bridges over dry land are not threatened by tidal action at all. Because all bridges were given a tidal spread assessment, bridges over major tidal waters were assigned higher scores, bridges over riverine water were assigned no score, and bridges over land were assigned a slightly negative score.

System Impact

Because many of the concerns that determined the functional classification, such as accessibility, were irrelevant to bridges, system impact in this case used Annual Average Daily Travel (AADT) instead of functional classification. This is a measure of how many car trips over the asset take place on an average day, based on a year's worth of data. Bridges were assigned high, medium, or low scores based on how much use the bridge experiences. Also included in the system impact was the presence of intermodal facilities, such as bus or bike routes, and the inclusion of the bridge in an evacuation route. As with roads, bridges were assigned extra score for carrying intermodal facilities and evacuation routes.

Limitations

The methods described above have the advantage of being somewhat mathematical: values were assigned to characteristics, the presence or absence of the characteristic in the asset was determined based on existing data, and a weighted average was used to determine the final score. This methodology was used to avoid bias in determining vulnerability. However, the assignment of values and weights was ultimately based on the professional judgement of the RISPP staff. The values used were repeatedly tweaked so that the end results produced logical and balanced outcomes, but there is no "scientific" basis for these results beyond the desire to properly represent the variables portrayed in an appropriately relative way.

As mentioned previously, the exposure and vulnerability stages of this study did not take into account projections of erosion, precipitation or any number of other variables that were beyond the scope of this project. High tide and subsequent sea level rise scenarios may be higher in inlets. For all assets projected to be inundated, further study is recommended.

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[8] See bridges section of exposure analysis

Figure 8: Statewide SLR Road Exposure Summary by Functional Classification

Functional Classification	1Ft SLR	3Ft SLR	5Ft SLR	7Ft SLR	Total
Interstate (Linear Miles)	0.09	0.04	0.11	0.24	0.49
Interstate (% of Total)	4.86%	0.14%	0.19%	0.36%	0.31%
Other Freeways and Expressways (Linear Miles)	0.12	0.12	1.21	1.25	2.71
Other Freeways and Expressways (% of Total)	6.52%	0.44%	2.03%	1.85%	1.73%
Other Principal Arterial (Linear Miles)	0.07	0.70	4.14	5.82	10.73
Other Principal Arterial (% of Total)	3.48%	2.57%	6.95%	8.61%	6.86%
Minor Arterial (Linear Miles)	0.15	1.79	3.85	4.98	10.78
Minor Arterial (% of Total)	7.73%	6.56%	6.47%	7.37%	6.89%
Major Collector (Linear Miles)	0.13	4.43	6.16	8.94	19.66
Major Collector (% of Total)	6.99%	16.18%	10.34%	13.21%	12.56%
Minor Collector (Linear Miles)	0.00	0.78	1.31	1.05	3.14
Minor Collector (% of Total)	0.00%	2.84%	2.21%	1.55%	2.01%
Local (Linear Miles)	1.34	19.50	42.76	45.37	108.96
Local (% of Total)	70.42%	71.27%	71.81%	67.06%	69.64%
Grand Total (Linear Miles)	1.90	27.37	59.54	67.65	156.46

Figure 9: Statewide Roads Exposed to 100-Year Storm Surge Event Plus SLR by Functional Classification

Functional Classification	No SLR	Plus 1Ft SLR	Plus 3Ft SLR	Plus 5Ft SLR	Plus 7Ft SLR	Grand Total
Interstate (Linear Miles)	1.50	0.16	0.21	0.17	0.45	2.49
Interstate (% of Total)	0.45%	0.45%	0.33%	0.24%	0.65%	0.43%
Freeways and Expressways (Linear Miles)	2.11	0.92	0.95	1.59	0.99	6.56
Freeways and Expressways (% of Total)	0.63%	2.54%	1.51%	2.30%	1.44%	1.14%
Principal Arterial (Linear Miles)	17.76	2.50	2.73	2.86	2.66	28.50
Principal Arterial (% of Total)	5.27%	6.88%	4.35%	4.15%	3.87%	4.97%
Minor Arterial (Linear Miles)	21.57	2.27	3.90	3.20	4.04	34.98
Minor Arterial (% of Total)	6.40%	6.25%	6.21%	4.64%	5.89%	6.10%
Major Collector (Linear Miles)	34.00	4.26	6.19	7.29	8.06	59.80
Major Collector (% of Total)	10.09%	11.72%	9.85%	10.58%	11.76%	10.43%
Minor Collector (Linear Miles)	29.00	1.89	3.44	3.37	2.26	39.95
Minor Collector (% of Total)	8.61%	5.20%	5.47%	4.89%	3.30%	6.97%
Local (Linear Miles)	230.94	24.34	45.39	50.42	50.10	401.19
Local (% of Total)	68.55%	66.96%	72.28%	73.19%	73.09%	69.96%
Grand Total (Linear Miles)	336.88	36.35	62.80	68.89	68.55	573.47

Findings: Exposure and Vulnerability

There are many ways to examine this data. Exposure statistics are a good first step in an analysis that simply compiles the amount of any given asset in a given geographic area that could be exposed to inundation. The vulnerability assessment adds important value to an analysis by factoring in issues such as risk and systemic value. The vulnerability assessment provides a way to interpret the data and to begin forming a policy. From a statewide perspective, vulnerability can be subdivided between vulnerability that is ranked by asset and vulnerability that is summarized by municipality. The former method is useful for determining the individual assets in the state that are most vulnerable; useful information for state planners and the affected municipalities. The latter method sums the vulnerability scores of all the exposed assets in each municipality, allowing the user to see which municipalities are most vulnerable overall. This method is potentially more useful for municipal decision makers trying to grapple with the scale of the problem.

Figure 10: Statewide Bridges Exposed to Sea Level Rise by Hazard Type

Issue Type	No Freeboard Concern	Possible Freeboard Concern	Grand Total
No Accessibility Concern		31	31
Accessibility Concern	19	98	117
Grand Total	19	129	148

Figure 11: Statewide Bridges Exposed to 100-Year Storm Plus SLR by Hazard Type

Issue Type	No Freeboard Concern	Potential Freeboard Concern	Grand Total
No Accessibility Concern		22	22
Accessibility Concern	9	59	68
Grand Total	9	81	90

While all views of the data are valuable, some of the key takeaways from the data show that it is the local decision makers that have the most to gain from incorporating this data into policy decisions at an early date. From a systemic perspective, the Rhode Island transportation network has evolved in such a way that the truly critical assets are mostly located away from the coast. Nonetheless many miles of smaller roads and bridges will be affected by sea level rise and storm surge. Approximately 70% of these exposed roads and bridges are local facilities (regardless of sea level rise or storm surge scenario), which are ineligible for federal aid funding. These results, and the current fiscal environment, suggests that the majority of the burden of both sea level rise and storm surge will fall on local budgets.

ROADS

Key Finding- Exposure

Assuming sea level rise and storm surge occur as predicted, the analysis shows that every coastal city or town in Rhode Island faces the potential of seeing some road assets exposed to inundation impacts. Many of these impacts reach far inland, up tidal rivers and streams that might not seem obvious sources of vulnerability. In total 175 miles of road centerline will potentially be exposed to sea level rise, and 573 miles to storm surge. Statewide, 70% of these miles will be in the form of local roads.

Key Finding- Vulnerability

When the road system is ranked, the top ten roads most critically vulnerable to sea level rise and storm surge are generally found on Aquidneck Island, Jamestown, or in the East Bay. This situation has been caused by a mixture of geography and land use practice. The islands of Jamestown and Aquidneck are vulnerable geographically due to being relatively low-lying areas completely surrounded by water. The East Bay communities have become vulnerable due to their orientation towards Providence and Fall River, as well as the closeness of the Massachusetts border. Though there are important cross border transportation facilities, many of these are new. Older facilities tended to be squeezed between the border and the bay, a tendency that combined with the nautical origins of these communities and the local importance of Providence and Fall River cause much of the area's development to remain close to the coast. As a result, though the East Bay is highly vulnerable to inundation in general, its transportation infrastructure in particular remains much closer to vulnerable areas than is the case elsewhere in Rhode Island. These are the roads where the longest sections of critical roadway could be inundated earliest.

Figure 12: Linear Feet of Road Exposed to SLR by SLR Scenario

City or Town	1Ft SLR	3Ft SLR	5Ft SLR	7Ft SLR	Total Miles
BARRINGTON	0.01	1.26	5.22	7.94	14.44
BRISTOL	0.01	1.03	3.14	2.40	6.59
CHARLESTOWN	0.23	3.23	4.03	5.05	12.54
CRANSTON	0.00	0.01	0.26	0.24	0.51
EAST GREENWICH	0.00	0.07	0.20	0.19	0.46
EAST PROVIDENCE	0.01	0.05	0.65	0.88	1.59
JAMESTOWN	0.00	0.56	1.27	1.35	3.18
LITTLE COMPTON	0.00	0.71	0.64	0.49	1.83
MIDDLETOWN	0.00	0.60	1.50	0.66	2.75
NARRAGANSETT	0.17	3.92	6.12	5.58	15.80
NEW SHOREHAM	0.10	0.51	1.24	1.72	3.57
NEWPORT	0.26	1.91	6.78	8.04	16.99
NORTH KINGSTOWN	0.02	1.00	3.39	3.55	7.95
PAWTUCKET	0.00	0.01	0.01	0.02	0.05
PORTSMOUTH	0.00	1.61	2.68	2.85	7.14
PROVIDENCE	0.30	0.11	1.88	6.67	8.96
SOUTH KINGSTOWN	0.31	1.81	3.99	3.70	9.81
TIVERTON	0.12	1.01	2.03	1.63	4.80
WARREN	0.05	0.95	2.88	2.19	6.08
WARWICK	0.18	2.46	6.17	7.59	16.39
WESTERLY	0.13	4.31	5.32	4.87	14.63
Grand Total	1.90	31.73	68.26	73.82	175.71

Figure 13: Linear Feet of Roads Inundated by a 100-Year Storm Surge Plus SLR

City or Town	No SLR	1Ft SLR	3Ft SLR	5Ft SLR	7Ft SLR	Total Miles
BARRINGTON	53.91	5.08	5.93	4.82	3.85	73.58
BRISTOL	13.12	0.71	1.64	1.67	2.07	19.21
CHARLESTOWN	18.61	1.63	2.94	3.00	3.56	29.74
CRANSTON	2.73	0.34	0.94	1.44	2.36	7.81
EAST GREENWICH	0.78	0.08	0.17	0.08	0.10	1.21
EAST PROVIDENCE	9.01	2.92	5.45	8.33	7.70	33.41
JAMESTOWN	6.92	0.97	1.28	1.27	1.29	11.72
LITTLE COMPTON	3.90	0.68	1.34	1.04	1.23	8.19
MIDDLETOWN	4.80	0.62	1.33	1.29	1.17	9.20
NARRAGANSETT	24.64	3.39	5.54	5.52	4.95	44.03
NEW SHOREHAM	4.65	0.42	0.71	0.62	0.86	7.25
NEWPORT	26.53	2.47	4.13	4.12	4.22	41.47
NORTH KINGSTOWN	21.01	2.04	5.27	8.55	9.08	45.94
PAWTUCKET	0.51	0.03	0.11	0.18	0.20	1.03
PORTSMOUTH	22.64	2.80	4.29	3.85	3.44	37.01
PROVIDENCE	8.90	0.47	0.73	0.73	0.91	11.74
SOUTH KINGSTOWN	15.75	1.82	2.86	2.78	3.52	26.74
TIVERTON	8.74	0.66	1.28	1.23	1.02	12.94
WARREN	15.11	1.42	2.37	2.08	2.19	23.17
WARWICK	51.75	5.87	10.76	12.97	11.94	93.29
WESTERLY	22.87	1.94	3.74	3.32	2.88	34.75
Grand Total	336.88	36.35	62.80	68.89	68.53	573.46

Figure 14: Top 10 Roads Vulnerable to Sea Level Rise in Rhode Island

Rank	Municipality	Road Name	Linear Feet Affected By:				Total	Hazard Score	Functional Classification	Evacuation Route	Intermodal Facility	System Score	Vulnerability Score
			1Ft SLR	3Ft SLR	5Ft SLR	7Ft SLR							
1	BRISTOL	HOPE ST		315	1,762	440	2,517	4.20	Principal Art.	Yes	Yes	4.40	8.60
2	NEWPORT	MEMORIAL BLVD				5,426	5,426	4.97	Principal Art.	No	Yes	3.38	8.35
3	BARRINGTON	WAMPANOAG TRL			5,839	6,210	12,049	4.57	Major Col.	No	Yes	3.70	8.27
4	JAMESTOWN	CONANICUS AVE			1,558	389	1,946	4.30	Minor Art.	Yes	Yes	3.66	7.96
5	BARRINGTON	COUNTY RD N				1,253	1,253	3.50	Principal Art.	Yes	Yes	4.40	7.90
6	JAMESTOWN	NORTH RD		1,257	328	207	1,791	3.96	Principal Art.	Yes	Yes	3.80	7.76
7	BARRINGTON	COUNTY RD	14	140	2,655	1,096	3,904	3.60	Principal Art.	No	Yes	4.10	7.71
8	NARRAGANSETT	BEACH ST			5,440	1,123	6,564	4.36	Minor Art.	No	Yes	3.29	7.65
9	WARREN	MAIN ST	13	343	521	154	1,031	3.18	Minor Art.	Yes	Yes	4.40	7.58
10	TIVERTON	STATE HWY 24 S	308	217	138	20	683	3.72	Principal Art.	No	Yes	3.70	7.42

Figure 15: Top 10 Roads Vulnerable to a 100-Year Storm Surge Plus SLR

Rank	Municipality	Road Name	Linear Feet Affected By 100-Yr Surge Plus:						Hazard Score	Evacuation Route	Intermodal Facility	Functional Classification	System Score	Vulnerability Score
			0Ft SLR	1Ft SLR	3Ft SLR	5Ft SLR	7Ft SLR	Total						
1	BARRINGTON	COUNTY RD N	2,875					2,875	5.00	Yes	Yes	Principal Art.	4.40	9.40
2	NORTH KINGSTOWN	PHILLIPS ST	1,842	198	44	34	43	2,161	4.80	Yes	Yes	Principal Art.	4.40	9.20
3	NEWPORT	AMERICAS CUP AVE	6,219	26	47	47	86	6,426	4.90	No	Yes	Principal Art.	4.04	8.93
4	NEWPORT	ON RAMP RI-138 W	1,647	217	151	131	114	2,259	4.39	No	No	Freeways	4.39	8.78
5	BRISTOL	HOPE ST	5,350	241	562	432	737	7,321	4.33	Yes	Yes	Principal Art.	4.40	8.73
6	PORTSMOUTH	STATE HWY 24 N	1,267	1,480	2,176	1,280	365	6,569	4.18	No	No	Freeways	4.53	8.70
7	WARWICK	CENTERVILLE RD	700	47	83	56	41	927	4.24	Yes	Yes	Principal Art.	4.40	8.64
8	NARRAGANSETT	NARRAGANSETT AVE	1,104	57	63	69	66	1,358	4.39	No	No	Principal Art.	4.19	8.58
9	WARREN	MAIN ST	2,363	120	447	535	517	3,982	4.18	Yes	Yes	Principal Art.	4.40	8.58
10	JAMESTOWN	STATE HWY 138 W	1,264	845	290	145	110	2,653	4.42	No	No	Freeways	4.12	8.54

Figure 16: Cumulative Municipal Road SLR Vulnerability

Rank	City or Town	Sum of Vulnerability
1	WARWICK	537.98
2	NARRAGANSETT	389.79
3	NEWPORT	386.86
4	BARRINGTON	369.14
5	PROVIDENCE	325.02
6	WESTERLY	271.40
7	SOUTH KINGSTOWN	250.83
8	NORTH KINGSTOWN	226.42
9	CHARLESTOWN	197.46
10	WARREN	191.91
11	PORTSMOUTH	185.53
12	BRISTOL	137.66
13	TIVERTON	108.90
14	JAMESTOWN	91.62
15	EAST PROVIDENCE	88.68
16	CRANSTON	57.53
17	LITTLE COMPTON	53.11
18	NEW SHOREHAM	48.73
19	MIDDLETOWN	32.25
20	EAST GREENWICH	20.87
21	PAWTUCKET	19.30

Figure 17: Municipal Road Vulnerability to a 100-Year Storm Surge Event Plus SLR

Rank	City or Town	Sum of Vulnerability
1	WARWICK	2,710.98
2	BARRINGTON	1,809.78
3	NEWPORT	1,150.66
4	NARRAGANSETT	1,110.32
5	NORTH KINGSTOWN	1,021.52
6	EAST PROVIDENCE	816.83
7	PORTSMOUTH	763.00
8	WESTERLY	740.79
9	WARREN	740.78
10	SOUTH KINGSTOWN	670.73
11	CHARLESTOWN	559.13
12	BRISTOL	436.20
13	CRANSTON	372.25
14	TIVERTON	321.25
15	PROVIDENCE	313.16
16	JAMESTOWN	287.32
17	LITTLE COMPTON	208.07
18	MIDDLETOWN	149.50
19	NEW SHOREHAM	131.89
20	PAWTUCKET	63.16
21	EAST GREENWICH	62.14

When the vulnerability scores in each municipality are summed and ranked, a very different view of the relative scale of vulnerability in each city or town is revealed. In both sea level rise and storm surge scenario sets, different municipalities top the rankings when contrasted with the asset focused rankings. In fact, rather than being concentrated on the East Bay, the top vulnerable municipalities are fairly evenly spread out. For example, Warwick stands out as the municipality with the most potential vulnerability to sea level rise and storm surge, despite not having a road in the vulnerability top ten. The other municipalities highly vulnerable to sea level rise are fairly evenly spread around the state.

The difference between the list of ranked individual roads and the vulnerability summed by town shows the scale of the problem faced by local decision makers. Warwick, and the other West Bay cities and towns, benefit from a road network that is in many ways more resilient than that in the East Bay. Critical assets are farther from the coast, making individual assets less vulnerable. But this has not prevented heavy settlement along the bay, served by roads of moderate or low level criticality. Though these roads lack systemic importance, and thus contribute less to the vulnerability of the system as a whole, they do have value and are vulnerable to inundation. While individually less of a vulnerability risk, when taken as a mass they present a real source of vulnerability for those who are charged with their maintenance. The sheer number of these smaller roads has a cumulative vulnerability that is hidden in the rankings of individual assets.

BRIDGES

Key Finding- Exposure

Assuming sea level rise and storm surge occur as predicted, the analysis shows that every coastal city or town in Rhode Island faces the potential of seeing some bridge assets exposed to inundation impacts except Little Compton. Statewide there are 90 bridges vulnerable to sea level rise, and 148 bridges vulnerable to storm surge, that cause concern because of either freeboard heights or accessibility.[9] Not considered in this report is how sea level rise may diminish freeboard height for bridges that are legally required to maintain a particular freeboard height for navigational purposes. Many of these impacts reach far inland, up tidal rivers and streams that might not seem obvious sources of vulnerability.

[9] The data on freeboard height for bridges over ocean water does not indicate whether the height measurement was taken at high tide, low tide, or somewhere in between.

As opposed to roads, where local assets are likely to be the most problematic, bridges tend to represent more systemically critical assets. This is likely because the expense required to build a bridge limits bridge construction to critical routes. In general, the bridges that lack heavy road traffic are rail or bicycle facilities, which are eligible for different types of funding from road facilities. Though this may complicate the funding picture for a municipality, it does mean that help is generally available for most, but not all, vulnerable bridge assets.

Key Finding- Vulnerability

Unlike the roadway vulnerability analysis, the bridge analysis offers a more balanced view of the state. While the most vulnerable individual bridges are again located in the East Bay, the top ten is a much more geographically diverse list. This reflects the tendency of bridges to be built only for roadways that are somewhat critical to begin with. This factor focuses bridge vulnerability into transportation hubs in the West Bay, such as Apponaug in Warwick or the Providence downtown, and into corridors in the East Bay. On the southern shore lines, which face out to the Long Island Sound and the Atlantic Ocean, there is a relative lack of critical assets exposed. This is a result of the relatively inland nature of the transportation network in this part of the state, and as a result the southern cities and towns have relatively low vulnerabilities in their bridge infrastructure. This said, the few bridges that do exist are likely to be important to the tourism industry.

Figure 18: Municipal Bridges of Concern by Inundation Scenario Assuming 7Ft SLR

Municipality	SLR	Surge Plus SLR
Barrington	6	6
Bristol	7	7
Charlestown	1	2
Cranston	2	6
East Greenwich	1	2
East Providence	8	19
Jamestown	4	4
Middletown	3	3
Narragansett	3	5
New Shoreham	2	2
Newport	3	8
North Kingstown	5	12
Pawtucket	1	2
Portsmouth	1	5
Providence	21	19
South Kingstown	3	9
Tiverton	5	8
Warren	2	2
Warwick	10	20
Westerly	2	7
Grand Total	90	148

Figure 19: Top 10 Bridges Vulnerable to Sea Level Rise

Rank	Bridge Name	Facility Carried	Feature Intersected	City or Town	Inches of Freeboard Relative to 7FtSLR	Terrain Crossed	Landing Access	Hazard Score	Intermodal Facility	Evacuation Route	AADT	System Score	Vulnerability Score
1	Barrington	RI 114/103 CNTY RD	BARRINGTON RIVER	Barrington	-10	MHHW	Problem	5.00	Yes	No	16,443	4.00	9.00
2	Warren	RI 114/103 CNTY RD	WARREN RIVER	Barrington	14	MHHW	Problem	5.00	Yes	No	34,118	4.00	9.00
3	Silver Creek	RI 114 Hope St	Tidal Inlet	Bristol	-20	Water	Problem	4.00	Yes	Yes	18,200	5.00	9.00
4	Apponaug	US 1 Post Rd	Apponaug River	Warwick	50	Water	Problem	3.60	Yes	Yes	12,500	5.00	8.60
5	Apponaug Mill	RI 117 Cntrvlle Rd	Apponaug River	Warwick	67	Water	Problem	3.60	Yes	Yes	22,600	5.00	8.60
6	Easton Beach	RI 138 Memorial Bd	Easton Pond Channel	Middletown	18	Water	Problem	3.60	Yes	Yes	8,000	5.00	8.60
7	C.L. Hussey Memorial	US 1A BSTN NCK RD	WICKFORD COVE	North Kingstown	-36	MHHW	Problem	5.00	Yes	No	25,883	3.10	8.10
8	Eagle Street	EAGLE ST	WOONASQUATUCKET RIVER	Providence	-8	MHHW	Problem	5.00	Yes	No	1,020	3.10	8.10
9	Round Swamp	North Main Rd	Tidal Inlet	Jamestown	-11	Water	Problem	4.00	Yes	Yes	22,500	4.10	8.10
10	Park Street	PARK ST	WOONASQUATUCKET RIVER	Providence	-25	MHHW	Problem	5.00	Yes	No	9,100	3.10	8.10

Figure 20: Top 10 Bridges Vulnerable to a 100-Year Storm Surge Event Plus 7Ft SLR

Rank	Bridge Name	Facility Carried	Feature Intersected	City or Town	Inches of Freeboard Relative to 7FtSLR	Terrain Crossed	Landing Access	Hazard Score	Intermodal Facility	Evacuation Route	AADT	System Score	Vulnerability Score
1	Warwick Ave	RI 117 WARWICK AV	PAWTUXET RIVER	Cranston	-80	MHHW	Problem	4.50	Yes	Yes	18,888	5.00	9.50
2	Newport Bridge Authority	RI 138	EAST PASSAGE NARR BAY	Jamestown	-216	MHHW	Problem	4.50	Yes	Yes	20,010	5.00	9.50
3	Silver Creek	RI 114 Hope St	Tidal Inlet	Bristol	-185	Water	Problem	4.00	Yes	Yes	18,200	5.00	9.00
4	Easton Beach	RI 138 Memorial Bd	Easton Pond Channel	Middletown	-115	Water	Problem	4.00	Yes	Yes	18,000	5.00	9.00
5	Apponaug	US 1 Post Rd	Apponaug River	Warwick	-118	Water	Problem	4.00	Yes	Yes	18,200	5.00	9.00
6	Apponaug Mill	RI 117 Cntrvlle Rd	Apponaug River	Warwick	-101	Water	Problem	4.00	Yes	Yes	19,000	5.00	9.00
7	Carpenters Corner	RI 117 Cntrvlle Rd	Tuscatucket River	Warwick	-93	Water	Problem	4.00	Yes	Yes	27,700	5.00	9.00
8	Cottage Home	RI 117A Warwick Av	Buckeye Brook	Warwick	-71	Water	Problem	4.00	Yes	Yes	20,600	5.00	9.00
9	Babbitt Farm	US 1 Post Rd	Cocumcussoc Brook	North Kingstown	19	Water	Problem	3.60	Yes	Yes	22,500	5.00	8.60
10	Barrington	RI 114/103 CNTY RD	BARRINGTON RIVER	Barrington	-190	MHHW	Problem	4.50	Yes	No	19,999	4.00	8.50

Figure 21: Cumulative Municipal Vulnerability Ranking for Bridges Potentially Affected by 7FT of SLR

Rank	City or Town	Sum of Vulnerability	Exposed Bridges
1	Providence	119	21
2	Warwick	53	10
3	East Providence	44	7
4	Bristol	42	8
5	Barrington	40	6
6	North Kingstown	32	5
7	Tiverton	29	4
8	Jamestown	29	5
9	Narragansett	21	3
10	South Kingstown	19	3
11	Middletown	18	3
12	Newport	18	3
13	Warren	14	2
14	New Shoreham	13	2
15	Westerly	10	2
16	Cranston	9	2
17	Portsmouth	8	1
18	Charlestown	7	1
19	Pawtucket	6	1
20	East Greenwich	4	1
	Grand Total	542	90

Figure 22: Cumulative Municipal Vulnerability Ranking for Bridges Potentially Affected by 100-Year Storm Surge Plus 7Ft of SLR

Rank	City or Town	Sum of Vulnerability	Exposed Bridges
1	East Providence	119.40	19
2	Warwick	112.20	20
3	Providence	103.20	19
4	North Kingstown	70.30	12
5	Newport	50.40	8
6	Tiverton	50.30	8
7	South Kingstown	47.10	9
8	Cranston	46.80	6
9	Bristol	44.60	7
10	Barrington	42.90	6
11	Westerly	37.00	7
12	Narragansett	36.00	5
13	Portsmouth	32.90	5
14	Jamestown	31.40	4
15	Middletown	19.70	3
16	Warren	14.60	2
17	Pawtucket	13.00	2
18	East Greenwich	12.40	2
19	Charlestown	11.70	2
20	New Shoreham	11.20	2
	Grand Total	907.10	148

Next Steps

There are two main reactions to the kind of data represented in this analysis. The data can seem overwhelming; too much needs to get done and resources are limited. Alternatively, a century may seem like such a long time as to present no realistic concern. But by planning ahead, state and municipal officials can ensure that infrastructure being built today will be prepared for the conditions it will face throughout its life cycle. By dealing with the problems presented gradually, using the time available to make wise and thoughtful investments that align with a particular vision about the best way to manage this hazard.

To allow this kind of thoughtful policy making, more study is likely to be needed, and further study will require some additional data. Some of this data has already been highlighted in the limitations section of this paper: data and methodologies necessary for modeling erosion, precipitation, riverine flooding, and the changing return period. More mundane data are also needed. Geographic data on the location of smaller culverts and storm water detention ponds would be a key immediate need. Beyond wider implications to public health, these features could seriously undermine roadways in sea level rise or storm surge conditions, and could allow the movement of water in additional or dispersed directions. More accurate data on shore protection structures would be important for similar reasons. This analysis used available data to identify bridges of concern, but more data inputs are required to understand better the impact of sea level rise on bridges (e.g. scour, materials, bridge structure and design, etc.). Many of these data sets are already in the process of being assembled, and municipal planners may have others available for their analysis, so it should be understood that this paper is not the last word on the subject. Even if all of these data needs were met, a high level analysis such as the one presented in this paper is no substitute for an engineering study on individual assets. This paper only seeks to direct local decision makers as to the specific assets that are in need of further analysis.

Once analysis has been completed, a variety of medium and long term policy approaches are available to help the local decision makers in managing sea level rise risk to transportation assets. This approach would allow a more comprehensive view of the assets under consideration, and might allow the deployment of land use based strategies that would make transportation decisions less contentious. Realistically, the state and its cities and towns will make series of decisions for individual assets and groups of assets over time, learning from their results while taking a longer look at where to spend transportation dollars. Both of these approaches are ultimately complimentary and necessary to proper decision making, and many planners and municipal officials are already working on similar issues around the country. This section presents some of the results of that work in the context of broad policies that can be used to move ahead, and specific opportunities available to the cities and towns of Rhode Island.

Adaptation Strategies and Tactics

"Adaptation" is a term to describe the general ways of responding to sea level rise or storm surge threats. General adaptation options fall into four major categories: protect, accommodate, retreat, and do nothing. These descriptions can be applied on both a broad, strategic policy level, as well as on the tactical level of a specific asset or area. In reality most municipalities are going to need to deploy a variety of these tactics, no matter the wider strategic policy, in order to best respond to the variety of threats faced by the transportation infrastructure in a way that maintains their constituents' quality of life and economic base. For example, a broad strategic policy of retreat in the face of sea level rise could still involve investments to protect vital transportation assets vulnerable to storm surge.

There are several options to consider in the context of any decision about a policy or transportation facility (e.g. degree of impact if lost, expense associated with different adaptation options). Decisions will need to be timed with other ongoing transportation investments and asset management planning used by transportation decision-makers.

Protect: armor. Often armoring is the initial thought to protect roads and transportation assets from sea level rise. Hard armoring includes protections like sea walls and bulkheads. Hard armor solutions may be necessary to protect critical transportation infrastructure, but they are not a realistic coast-wide solution, given the expense of building and maintenance, the adverse impacts experienced by neighborhoods close to the infrastructure, and the impact to ecological services and systems. Additionally, such defenses must be designed correctly for the threats they are likely to face. For example, an asset adequately protected from sea level rise could subsequently be destroyed by storm surge.

Protect: enhance natural protections. Natural protections include mimicking natural buffers like building dunes and wetlands, re-nourishing beaches, and preserving existing ecosystems that provide protections from ocean waters. While natural protections offer similar if not superior protection to that promised by hard armored solutions, with fewer aesthetic and ecological consequences, they are also not universally applicable. Local topography and land use may make certain areas inappropriate for natural protections, while the fiscal costs of natural protection may remain significant. Ultimately, natural protections may only help infrastructure "buy time" as high tides rise and come closer to infrastructure locations.

Accommodate in place. Many accommodation strategies are already in use and could be oriented toward the challenge of accommodating sea level rise. For example, increasing the size of culverts, planning pavement materials to minimize life-cycle costs, and enhancing scour protection on bridges are ongoing activities of transportation planners and engineers that can be adjusted to accommodate rising high tides. However, these strategies are not always appropriate for facilities that will regularly be exposed to high tide.

For roads and other facilities that will frequently be exposed to high tide, accommodate in place may mean elevating the transportation asset. For example, the entire roadbed could be elevated, although this is likely to exacerbate wave and storm surge impacts for structures on either side and interrupt ecological processes. Or a causeway-type structure could allow tidal water to flow underneath, but at significant cost and with negative repercussions for transportation connectivity and view sheds behind the causeway.

Accommodation-in-place strategies also include day-to-day management of sea level rise impacts in place. This category of responses includes putting out traffic markers and deterrents at high tide (or at astronomical high tide), identifying alternative routes to take at high tide, weathering the roadbed to withstand regular saltwater inundation, and managing erosion and debris at the edge of the roadway. These practices can be incorporated into operation and maintenance (O&M) manuals.

Accommodate through realignment. Transportation assets can be realigned out of the path of sea level rise. Realignment is easiest for flexible infrastructure which can be diverted onto new routes, such as RIPTA bus routes. Realignment is slightly more challenging for bike infrastructure, and fairly challenging for roads and other types of infrastructure with firm rights of way. Road realignment may make better use of existing roadways and redundancies that are located further inland, or make use of topography to avoid low lying areas. Coastal communities in Rhode Island tend to have dense development and sensitive ecosystems, but there may be a small number of opportunities to reroute transportation facilities by building new infrastructure further inland.

Retreat. Communities may decide that maintaining transportation facilities that are regularly, or constantly, under tidal water is infeasible. Though not examined in this project, storm surge from weather events with much smaller return periods might also make continued use of an asset untenable. Private stakeholders may take on maintenance responsibilities, or the presence of tidal water may indirectly diminish or eliminate the need for a given transportation asset (e.g. if homeowners or commercial property owners leave the area). This is usually the most fiscally efficient solution for society as a whole, and when combined with a more holistic effort to reorganize land use at the water line can pay dividends in terms of new parks and green space left open ahead of rising water levels. Unfortunately this type of strategy is also the most politically and legally complicated. The issues associated with retreat are being closely examined by researchers and policymakers at the time of writing.

Do nothing. Communities may also choose to take no action in response to rising sea levels. In practice this approach may closely resemble retreat. Some transportation facilities may be regularly under tidal water, effectively rendering them unusable in a relatively short time. The resulting impacts on residents and businesses could have significant economic effects on communities, as could the fiscal strain of attempting regular repairs of topographically compromised assets.

The strategy considered most appropriate depends on the circumstances of the individual city or town. In cases where the vulnerability is concentrated into a relatively discrete area, protective solutions may be worth the expense. In cases where vulnerability is characterized by a long corridor, such solutions may be infeasible. It must be remembered that in these changing conditions, not all assets can be given equal protection.

Opportunities to Use Sea Level Rise Information in Decision-Making

Turning the above strategies and tactics into a built reality requires the use of often limited resources. This is where the 100-year long planning horizon is of particular value. There are five general ways that decision-makers and planners can utilize these data:

Spending. Transportation stakeholders are constantly evaluating how best to spend limited resources on transportation projects. Through asset management programs, planners and decision-makers can determine the soundest use of investment dollars, taking into account the expected lifetime viability of different coastal assets. Sea level rise and other climate considerations have been included in transportation planning project selection criteria for the FFY 2017-2025 State Transportation Improvement Program (STIP) and can be incorporated into local Capital Improvement Programs. By setting spending priorities to include awareness of sea level rise and storm surge issues, transportation decision-makers can better plan for the future in the face of sea level rise and storm surge events.

Planning. There are numerous opportunities to address sea level rise through planning. Local comprehensive plans are required to address natural hazards, including sea level rise, and the future land use map would be one opportunity for a municipality to use maps depicting sea level rise data. The data in this report is partly designed to allow cities and towns to fulfill their planning obligations under the recently updated state comprehensive plan requirements. The storm surge scenarios presented in this report should also be considered in municipal hazard mitigation plans, although there is no strict requirement to do so beyond the 100-year storm scenario. Finally, it would make sense to consider both sea level rise and storm surge in transportation decision-making relating to proposed methods for managing coastal climate hazards, such as overlay zones, transfers of development rights, and rolling easements.

Goal Setting. Transportation and government programs have become more performance management oriented in recent years. The State of Rhode Island, along with municipalities, might consider goals for the performance management of sea level rise or the incorporation of sea level rise into decision-making, with near-term performance metrics like referencing sea level rise in official plans and contracts and long-term goals of minimizing the impact of high tide on transportation infrastructure.

Communication and Capacity Building. There is a need in the state for planners, decision-makers, and citizens to build their understanding of sea level rise, the risks it poses to transportation infrastructure, and the options that we have for managing its progression and effects. This report's terminology and methodology is intended to help local officials better understand and communicate these realities to the public. Using maps and analysis specific to municipality's transportation assets helps to communicate the extent of sea level rise. Other tools such as STORMTOOLS or the NOAA sea level rise visualization tool CanVIS, also assist with the visualization and planning for sea level rise and storm surge. These "softer" uses of climate information are critical for building support and leadership on climate planning.

Additional Analysis. This report is intended as a first step in the ongoing analysis of the impacts of sea level rise and storm surge. There is a great need for additional analysis on individual assets and on the impact of sea level rise in conjunction with other coastal hazards like erosion, precipitation, and riverine flooding. This data, and the associated GIS coverage of sea level rise, are made available to any state agency or other office that wants to build upon them for further study.

Additional Resources

Many readers may wish to learn more about the topics discussed in this document. There are a variety of resources available online to help officials and members of the public alike in understanding and preparing for climate change and storm surge. In addition, Rhode Island is not the only area of the country studying sea level rise and its impact on infrastructure. Below is a list of other resources containing additional information on sea level rise and vulnerability.

- Caltrans. *Guidance on Incorporating Sea Level Rise: For Use in the Planning and Development of Project Initiation Documents*, 2011.
- Climate's Long-term Impacts on Metro Boston (CLIMB). *Infrastructure Systems, Services and Climate Change: Integrated Impacts and Response Strategies for the Boston Metropolitan Area*, 2004.
- Federal Highway Administration. *Screening Transportation Assets for Vulnerability: Impacts of Climate Change and Variability on Transportation Systems & Infrastructure*, 2012.
- ICLEI-Local Governments for Sustainability USA. *Sea Level Rise Adaptation Strategy for San Diego Bay*, 2012.
- North Jersey Transportation Planning Authority. *Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure*, 2011.
- Oregon Department of Transportation. *ODOT's Climate Change Adaptation Strategy Report*, 2012.
- Rhode Island Statewide Planning Program. *Technical Paper 164*: *Vulnerability of Transportation Assets to Sea Level Rise,* 2015
- Rhode Island Sea Grant. *Adaption to Natural Hazards & Climate Change in North Kingstown, Rhode Island*, 2014 [DRAFT].
- The San Francisco Bay Conservation and Development Commission. *Adapting to Rising Tides Transportation Vulnerability and Risk Assessment Pilot Project*, November 2011.
- Spaulding, Malcolm L. *Web Tools to Support Coastal Resilience Analysis and Planning for Storms and Sea Level Rise (StormTools),* 2013.
- Southeast Florida Regional Climate Change Compact. *Analysis of the Vulnerability of Southeast Florida to Sea Level Rise*, 2012.
- Wilmington Area Planning Council. *Sea-Level Rise: A Transportation Vulnerability Assessment of the Wilmington, Delaware Region*, 2011.

Additional Online Materials for Technical Paper 167

http://www.planning.ri.gov/geodeminfo/data/mun-slr.php: Main Project Web Page

http://www.planning.ri.gov/geodeminfo/data/mun-slr-fs.php: Location of municipal factsheets, a great resource for prompting discussion with people who are new to the topic

http://www.planning.ri.gov/geodeminfo/data/append.php: The Digital Appendix, which contains all the supplemental materials that would not fit in Technical Paper 167. Readers interested in learning more can customize the materials they gather in reference to their specific interests.

Information on the Digital Appendices

Materials were prepared to supplement Technical Paper 167 that provide crucial additional data for those professionally or personally interested in the topic. For practical reasons the Appendices cannot be directly contained in Technical Paper 167, and so these materials are contained online in a digital appendix. For those interested in further research, the following sections provide a short guide to the materials available in the digital appendix. Users of the digital appendix will be able to gather information pertinent to their specific interests, making analysis less complicated. The Digital Appendix can be found online at http://www.planning.ri.gov/geodeminfo/data/append.php

Appendix 1. Vulnerability Assessment Weights and Numeric Assignments

Appendix 1 consists of a PDF document providing a detailed explanation of the vulnerability assessment methodology, expanding on the discussion included in the text of Technical Paper 167. Beyond simply describing the process, the appendix provides the numeric assignments and weights used in the assessment, and a fully worked through example. Appendix 1 can be viewed in the online digital appendix, located at http://www.planning.ri.gov/geodeminfo/data/append.php, or printed for convenient reading.

Appendix 2. Statewide Maps and Tables

Appendix 2 contains raw data detailing the exposure and vulnerability of the transportation system in the State of Rhode Island on a statewide level. The first four pages of this appendix are large format PDF maps idealized for viewing electronically or for printing using a 42 inch map plotter. Printing at smaller sizes is possible but will result in a loss in resolution. These maps depict roads exposed to sea level rise, bridges exposed to sea level rise, roads exposed to a 100 year storm surge event and sea level rise, and bridges exposed to a 100 year storm surge event and sea level rise.

The rest of the appendix consists of tables depicting the exposure and vulnerability of roads exposed to sea level rise, bridges exposed to sea level rise, roads exposed to a 100 year storm surge event and sea level rise, and bridges exposed to a 100 year storm surge event and sea level rise. The assets are ranked by the vulnerability of the individual asset. It should be noted that the roads are divided at municipal boundaries, such that Rout 1 in Narragansett is ranked separately from Rout 1 in South Kingstown. Road exposure distance is described in terms of the linear feet of roadway first flooded in a given scenario. If, for example, 10 total linear feet of a road was flooded in the 1 foot scenario, and 20 total linear feet were flooded in the 3 foot scenario, the road will be listed in the tables as having 10 feet flooded under the 1 foot scenario, and 10 feet flooded in the 3 foot scenario. Bridge assessment was all done under the assumption of seven feet of sea level rise. Those interested in preforming further analysis, or in getting this data in a GIS format, will be able to download the data from the Rhode Island Geographic Information System, online at http://www.rigis.org/data.

The PDF version of the above described maps and tables can be found online at The Digital Appendix: http://www.planning.ri.gov/geodeminfo/data/append.php

Appendix 3. Municipal Analysis Documents

The Statewide Planning Program has prepared detailed analysis materials for each municipality, which can be viewed in PDF format online in The Digital Appendix or printed for convenient reading. These materials include four (4) detailed large format maps (scaled to size 11X17), and four (4) tables with information about the roads and bridges potentially affected by sea level rise or storm surge. There is one set of maps and tables for each of the following scenarios: roads exposed to sea level rise, bridges exposed to sea level rise, roads exposed to a 100 year storm surge event and sea level rise, and bridges exposed to a 100 year storm surge event and sea level rise. These materials have been prepared for each municipality exposed to sea level rise and storm surge with the exception of Little Compton. Little Compton contains no bridges threatened by sea level rise or storm surge, and so the preparation of maps and tables was deemed unnecessary for the bridge related scenarios. Little Compton's materials thus consist of two (2) maps and tables.

Within each municipality, the assets are ranked by the vulnerability of the individual asset. Road exposure distance is described in terms of the linear feet of roadway first flooded in a given scenario. If, for example, 10 total linear feet of a road was flooded in the 1 foot scenario, and 20 total linear feet were flooded in the 3 foot scenario, the road will be listed in the tables as having 10 feet flooded under the 1 foot scenario, and 10 feet flooded in the 3 foot scenario. Bridge assessment was all done under the assumption of seven feet of sea level rise. Those interested in preforming further a, or in getting this data in a GIS format, will be able to download the data from the Rhode Island Geographic Information System, online at http://www.rigis.org/data.

The PDF versions of the above described maps and tables can be found online at The Digital Appendix:
http://www.planning.ri.gov/geodeminfo/data/append.php