TECHNICAL MEMORANDUM

FROM: Office of Intermodal Planning and Investment, Statewide Transportation Planning Section

TO: VTrans Stakeholders

SUBJECT: VTrans Vulnerability Assessment (Draft)

DATE: June 2021

1: CONTEXT AND OVERVIEW

1.1 Purpose of the Technical Memorandum

This technical memorandum serves the following purposes:

- Defines the terms "Vulnerability" and "Resiliency" to promote common understanding;
- Documents data sources, methods, and processes used to identify vulnerable transportation facilities; and,
- Identifies opportunities for improving the accuracy and expanding the scope of the assessment.

Transportation system vulnerabilities identified based on this analysis will inform the development of VTrans Strategic Actions that may contain process and policy recommendations for the Office of Intermodal Planning and Investment (OIPI)[1], Virginia Department of Transportation (VDOT), and Virginia Department of Rail and Public Transportation (DRPT).

1.2 Structure of the Technical Memorandum

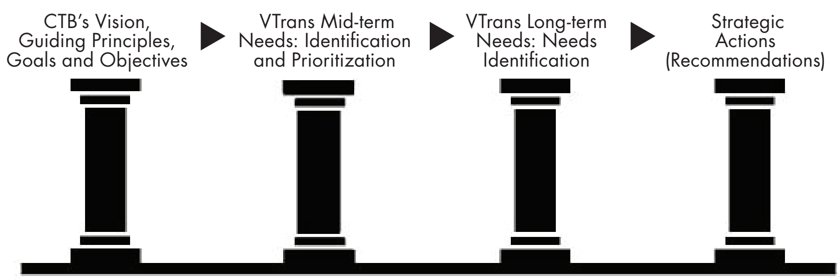
This technical memorandum includes the following appendices:

- Appendix A: List of Acronyms which list all acronyms used in this technical memorandum.
- Appendix B: Literature Review which summarizes literature review that informed the methodology outlined in this technical memorandum.
- Appendix C: Methodology for Creation of Extreme Inland/Riverine Flooding Scenario
- Appendix D: Relative Sea Level Change Scenarios
- Appendix E: Methodology to Assign Exposure Values to Roadway Segments
- Appendix F: Historical Weather Events Categories which provide details for one of the datasets used for the VTrans Vulnerability Assessment.

1.3 About VTrans

The VTrans Vulnerability Assessment is conducted as part of VTrans, Virginia's Transportation Plan, developed by the Commonwealth Transportation Board (CTB). The CTB, with assistance from OIPI, identifies mid-term and long-term transportation needs and also develops strategic actions to advance the CTB's vision and goals for the state's transportation system. This Vulnerability Assessment task informs VTrans mid-term needs and priorities, VTrans long-term needs, and VTrans Strategic Actions (Figure 1).

Figure 1: Major Components of VTrans



[1] Office of Intermodal Planning and Investment of the Secretary of Transportation established pursuant to § 2.2-229

1.4 Scope of the VTrans Vulnerability Assessment

This is a screening-level assessment of the vulnerability of Virginia's transportation system, more specifically all public roadways and VDOT-maintained structures (bridges and culverts) covered in the National Bridge Inventory (NBI), to projected sea level rise, storm surge, and inland/riverine flooding scenarios. The focus is on identifying and conveying the relative magnitude of risks to the transportation system to: (1) increase awareness; (2) identify strategic actions to increase readiness; (3) identify areas for data and research to improve accuracy and reliability of forecasted vulnerabilities.

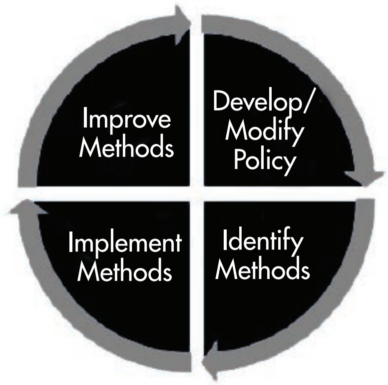
The VTrans Vulnerability Assessment is not intended to be used to develop location-specific recommendations for the following reasons:

- While this screening-level assessment narrows the universe of transportation infrastructure for further review, it does not replace the need for the collection of more precise location-specific data.
- The transportation system is one of the many infrastructure components impacted by the forecasted vulnerabilities. Therefore, it would be advisable to conduct a more comprehensive area-wide assessment for all components of physical and social infrastructure as some vulnerability mitigation strategies might require systematic solutions such as perimeter protection.

This assessment can form the basis for a few VTrans Strategic Actions (Figure 1) focusing changes to existing policies and processes for transportation infrastructure maintenance and development to allow for systematic risk mitigation.

1.5 Opportunities for Continuous Improvement

Figure 2: Opportunities for Continuous Improvement



The execution of the methodology outlined in this technical memorandum relies on data and computations to ensure transparent, data-driven, and replicable methods. The following should be noted:

- **Data:** The execution relies on data from state and national sources. Each of these sources relies on various methods, techniques, and technologies to develop its datasets and, therefore, has its own limitations such as:
  - Lack of readily usable data: There are instances in which the current completeness and accuracy of datasets makes it unsuitable used to execute the methodology outlined in this technical memorandum. For example, more information on roadway horizontal and vertical geometry will significantly improve quality and accuracy of the vulnerability assessment results. Similarly, availability of alternative routes will help provide more relevant data to determine the Adaptive Capacity of a facility (more details in Section 2) and thereby improve accuracy of the VTrans Vulnerability Assessment. Therefore, application of transportation planning or engineering judgment is recommended prior to developing solutions.
  - Scope of the task: The availability of data largely governed the scope of the task. For example, more precise information on transit and rail assets can help make the VTrans Vulnerability Assessment more multimodal in nature.
- **Computations:** The sheer size and magnitude of the effort relies on complex computations to perform an analysis on more than one million roadway segments. The effort requires synthesis, format conversions, and computations, such as in the following examples, that could result in inadvertent errors.
  - Units: Different data sources have different units. Some datasets are available by directional segment, whereas other datasets are available at the area or sub-area level.
  - Levels of aggregations: Some datasets are more aggregated than others. For example, historical weather data are available as point data and were aggregated and assigned to roadway segments (See Appendix F).
  - Frequency of data collection: Some datasets are collected in real time, whereas other datasets are updated once per year or even less frequently.
  - Frequency of data reporting: In addition to the variations in data collection schedule, some datasets are reported in real time, where other datasets are reported once a year.

- Data formats: Transportation assets are currently available in vector formats primarily as line or points features where weather related datasets are primarily in raster formats. One of the significant limitations of vector formats is that they are not ideal for data on continuous scales such as those available for weather, precipitation, etc. This limitation results in less accuracy (refer to Appendix E) and should be a higher priority for any future work.

The Statewide Transportation Planning Team at OIPI sees these considerations as opportunities for continuous improvement. Methods and techniques outlined in this memorandum can continue to evolve and improve based on advances in technology, data quality, data collection, and reporting tools.

2: DEFINITIONS

A first step in conducting the VTrans Vulnerability Assessment is to establish foundational definitions of the terms vulnerability and resilience.

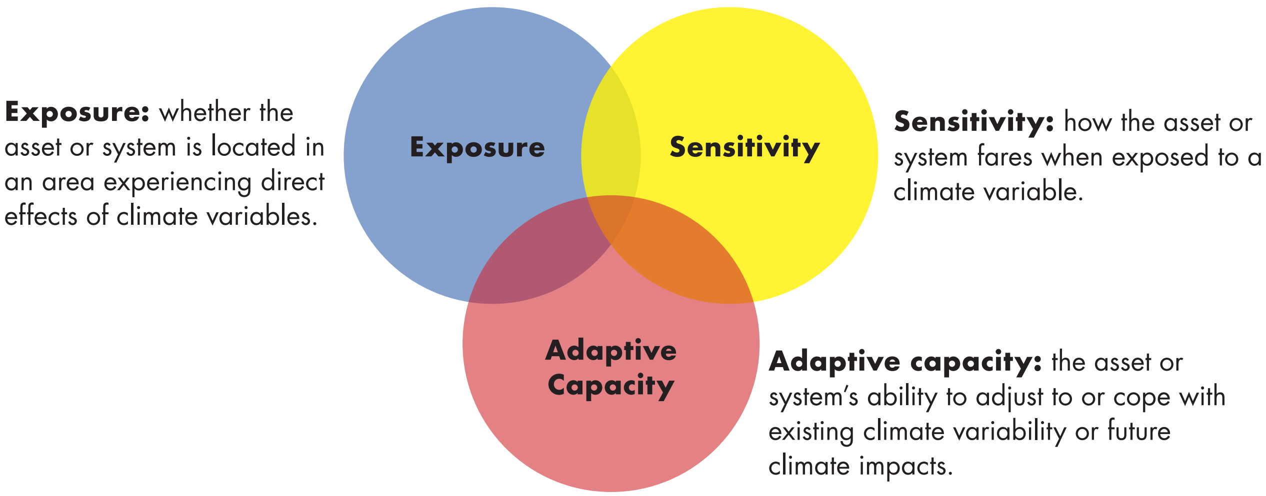
2.1.1 Definition of Vulnerability

The VTrans Vulnerability Assessment is based on the following definition of vulnerability: vulnerability is a function of exposure to a hazard(s), the sensitivity to the given hazard, and adaptive capacity or the system's ability to cope.

A system can be vulnerable to many natural and man-made hazards. This assessment's focus is specifically vulnerability to flooding due to sea level rise, storm surge, and inland/riverine flooding.

This definition is based on the Federal Highway Administration (FHWA)[2] definition that breaks down vulnerability as a function of an asset or system's exposure, sensitivity, and adaptive capacity (Figure 3).

Figure 3: Components of Vulnerability



- **Exposure:** whether the asset or system is located in an area experiencing direct effects of climate variables. For example, a road that could experience flooding and inundation due to its location in a low-lying area. The nature and degree to which an asset is exposed to significant climate variations (i.e., asset location relative to a stressor).
- **Sensitivity:** how the asset or system fares when exposed to a climate variable. For example, a tunnel could be more sensitive to flooding due to challenges removing water. (i.e., if all assets were equally exposed, which assets would experience the greatest damage?).
- **Adaptive capacity:** the asset or system's ability to adjust to or cope with existing climate variability or future climate impacts. For example, redundant or alternative routes that could be used to reach the same location would increase adaptive capacity compared to a route that is the only source of access. The ability of a system or asset to adjust to the impacts of climate change to moderate potential damages, to take advantage of opportunities, or to cope with consequences.

2.1.2 Definition of Resilience

The VTrans Vulnerability Assessment is based on the following definition of resilience or resiliency: the capability to anticipate, prepare for, respond to and recover from extreme weather event(s) with minimum damage to social well-being, infrastructure, the economy, and the environment.

[2] Federal Highway Administration, Vulnerability Assessment and Adaptation Framework 3rd Edition

3: VULNERABILITY SCENARIOS AND METHODOLOGY

3.1 Scenarios

Several factors influence the extent and frequency of exposure to sea level rise, storm surge, and inland/riverine flooding. Three scenarios were developed to account for the following uncertainties in the projections and to provide a range of vulnerability.

- Policy uncertainty: globally, countries are making commitments that may potentially reduce frequency and intensity of extreme natural events. However, there are uncertainties around timeframes for implementation and adherence to the commitments.
- Scientific uncertainty: Available literature indicates that the understanding of complex natural systems that govern climate is evolving. This imperfect understanding introduces another source of uncertainty.
- Model uncertainty: Even with a good understanding of scientific processes, it is difficult to represent them.

This Vulnerability Assessment applied the three (3) scenarios to each of the three (3) hazards, resulting in a total of nine (9) Vulnerability Scores.

Table 1: VTrans Vulnerability Scenarios

Hazard	Data Source of Projected Hazard	Scenario 1	Scenario 2	Scenario 3
Sea Level Rise	Virginia Institute of Marine Sciences (VIMS)	Intermediate sea level rise scenario (Year 2040)	Intermediate-High sea level rise scenario (Year 2040)	Extreme sea level rise scenario (Year 2040)
Storm Surge	National Hurricane Center (NHC)	Category 2 hurricane storm surge	Category 3 hurricane storm surge	Category 4 hurricane storm surge
Inland/Riverine Flooding	Federal Emergency Management Agency (FEMA) VDOT	100-year flood zone AND Historical Weather-Related Damages or Closures	500-yr flood zone AND Historical Weather-Related Damages or Closures	FEMA 500-yr flood zone with varying width buffer (10-200ft) based on floodplain width AND Historical Weather-Related Damages or Closures (Appendix F)

3.1.1 Data sources for Scenarios

- **Sea level rise:** The sea level rise scenarios are based on National Oceanic and Atmospheric Administration's (NOAA) 2017 report, Global and Regional Sea Level Rise Scenarios for the United States and one of the scenarios is consistent with Governor Northam's *Executive Order Number 24 (2018): Increasing Virginia's Resilience to Sea Level Rise*. The Virginia Flood Risk Management Standard (VFRMS) (Executive Order 45) satisfies the directive in Executive Order 24 by setting standards for State-owned buildings in coastal and inland flood prone areas based on the NOAA Intermediate-High scenario curve.

  The sea level rise scenarios utilized Sewells Point tide gauge to determine Relative Sea Level Change (RSLC). With a baseline year 2000, these RSLC values were added to today's mean high water (MHW) level to determine future MHW levels. These datasets were obtained from the Center for Coastal Resources Management at VIMS and include both the extent and depth of flooding. The 2017 NOAA report (Appendix D) provides six emission-based scenarios aligned with conditional probability storylines and global model projections, of which the following three were applied in the VTrans Vulnerability Assessment:

  - Intermediate, Relative Sea Level Change (RSLC) of 1.38 feet
  - Intermediate-High, RSLC of 1.78 feet
  - Extreme, RSLC of 2.46 feet

[3] Anthropocene Sea Level Change: A History of Recent Trends Observed in the U.S. East, Gulf, and West Coast Regions

- **Storm surge:** The storm surge scenarios are based on NHC hydrodynamic Sea, Lake and Overland Surges from Hurricanes (SLOSH) model which simulates storm surge from tropical cyclones based on present day sea levels. The SLOSH model uses a representative sample of hypothetical storms (up to 100,000) using varying intensity, forward speed, radius of maximum wind, storm direction, and tide level. Each storm combination is simulated at 5 to 10-mile increments along the coast. For each storm intensity (Category 1-5), the maximum storm surge height among all simulations is catalogued at each grid point in the model. The resulting Storm Surge Hazard Maps represent the worst-case flooding scenario during high-tide for each storm category.
- **Inland/riverine flooding:** The inland/riverine flooding flooding scenarios are based on a combination of FEMA Flood Zones derived from the Flood Insurance Rate Map (FIRM) via FEMA's National Flood Hazard Layer database, and observed historical weather events from Virginia's 511 system[1]. The scenarios also rely on historical flooding documented by VDOT.

3.2 Methodology

Key attributes of the VTrans Vulnerability Assessment methodology are outlined below:

- **Basis:** The VTrans Vulnerability Assessment is based on the FHWA Vulnerability Assessment Scoring Tool (VAST) for each of the three scenarios outlined in Section 3.1. This approach uses data on asset location and other key attributes as indicators of each of the three components of vulnerability: (1) Exposure; (2) Sensitivity; and, (3) Adaptive Capacity.
- **Approach:** the VTrans Vulnerability Assessment uses a point-based system to determine an asset's level of vulnerability. Similar to FHWA's VAST tool, the VTrans Vulnerability Assessment relies on an indicator-based approach. Indicators are representative elements such as location, existing flood protection, and projected climate stressors that can be used as proxy measurements for the exposure, sensitivity, or adaptive capacity of a specific asset. Indicators within each of the three main component categories (Exposure, Sensitivity, and Adaptive Capacity) were weighted within their respective category. Then each of the three main components are also given a weighting.

  Consistent with the scope outlined in Section 1, two sets of indicators were developed - one for roadways and one for structures because: (a) structures, as an asset type, have different characteristics and therefore different sensitivity; and, (2) generally, more precise and complete datasets are available for structures. Tables 2 and 3 list component and indicator weights for roadway segments and structures, respectively. If an asset is exposed to inundation, a three-point score is developed for each indicator which is then weighted and summed per the weighting in Tables 2 and 3 to calculate a vulnerability score for each asset by hazard type.

Table 2: Component and Indicator Weightings for Roadway Segments

Component	Component Weight	Indicator	Indicator Weight by Hazard Type		
			Sea Level Rise	Storm Surge	Inland/Riverine Flooding
Exposure	40%	Inundation from Sea Level Rise OR Storm Surge OR Inland/Riverine Flooding	100.0%	100.0%	100.0%
Sensitivity[2]	20%	Pavement Condition	5.0%	5.0%	5.0%
		Pavement Type	10.0%	10.0%	10.0%
		Historical Weather-Related Damages or Closures	85.0%	85.0%	85.0%
Adaptive Capacity[2]	40%	Functional Class	10.0%	10.0%	10.0%
		Hurricane Evacuation Route	15.0%	50.0%	0.0%
		Annual Average Daily Traffic (AADT)	20.0%	20.0%	20.0%
		Corridors of Statewide Significance (CoSS)	55.0%	20.0%	70.0%
Vulnerability Score	100%				

[1] See Appendix F.
[2] Scores for Sensitivity, Adaptive Capacity, and Vulnerability are only developed if Exposure component indicates risk of inundation.

Table 3: Component and Indicator Weightings for Structures

Component	Component Weight	Indicator	Indicator Weight by Hazard Type		
			Sea Level Rise	Storm Surge	Inland/Riverine Flooding
Exposure	40%	If Exposure to Sea Level Rise	100.0%	100.0%	100.0%
Sensitivity[1]	20%	*If Bridge:*			
		–Deck Rating	2.5%	2.5%	2.5%
		–Superstructure Rating	2.5%	2.5%	2.5%
		–Substructure Rating	5.0%	5.0%	5.0%
		If Culvert:			
		–Culvert Rating	10.0%	10.0%	10.0%
		Scour Criticality	20.0%	20.0%	35.0%
		Channel and Channel Protection	0.0%	10.0%	15.0%
		Waterway Adequacy	50.0%	40.0%	20.0%
		Historical Weather-Related Damages or Closures	20.0%	20.0%	20.0%
Adaptive Capacity[1]	40%	Hurricane Evacuation Route	15.0%	50.0%	0.0%
		Navigable Waterway	25.0%	10.0%	0.0%
		Importance Factor	60.0%	40.0%	100.0%
Vulnerability Score[1]	100%				

The following subsections describe the methods for assigning scores to each indicator on a three-point scale.

3.2.1 Exposure

The first component of the Vulnerability Assessment is an exposure analysis using a three-point scale that relies on the projected severity of impact (Table 4). For all roads and structures, a separate geospatial analysis for each hazard type is conducted. If an asset is determined to not be exposed, then the asset is not considered vulnerable and scores for sensitivity and adaptive capacity are not developed.

Table 4: Exposure Criteria

Indicator	Value	Score
Inundation from Sea Level Rise[2] Locations with greater projected depths of inundation are likely to be impacted by projected changes in climate sooner, including permanent inundation.	Worst one-third of the impacted directional mileage	3
	Middle one-third of the impacted directional mileage	2
	Bottom one-third of the impacted directional mileage	1
	Not inundated	N/A
Inundation from Storm Surge event[3] Locations with greater depths of estimated inundation during hurricanes are more likely to experience frequent inundation and be greatly affected by projected changes in climate.	Worst one-third of the impacted directional mileage	3
	Middle one-third of the impacted directional mileage	2
	Bottom one-third of the impacted directional mileage	1
	Not inundated	N/A
Location Relative to FEMA Flood Zone[4] AND Historical weather-related damages or closures[5] Assets located in a floodplain and that have experienced flooding in the past are more exposed than other assets.	In flood zone AND Exposed to Historical Flood Event	3
	Outside of flood zone AND/OR not exposed to historical flood event	N/A

[1] Scores for Sensitivity, Adaptive Capacity, and Vulnerability are only developed if Exposure component indicates risk of inundation.

[2] The Center for Coastal Resources Management at the Virginia Institute of Marine Science (VIMS). This dataset includes both the extent and depth of flooding.

[3] NHC SLOSH model which simulates storm surge from tropical cyclones based on present day sea levels. This dataset includes both the extent and depth of flooding.

[4] Federal Emergency Management Agency floodplain.

[5] VDOT Operations Division. Field Name: Weather events ("WX") in VATraffic (Virginia 511). Values indicate those in the dataset accessed on December 31, 2020 for Years 2015-2020. See Appendix F.

3.2.2 Sensitivity

The second component of the Vulnerability Assessment is a sensitivity analysis using a three-point scale that identifies the degree to which an exposed asset would be impacted by the exposure (i.e., if all assets were equally exposed, which assets would experience the greatest damage?). A separate weighting framework is applied to roadways and to structures, however the indicator values were applied consistently across exposure types. Table 5 and 6 summarizes the indicators, data sources, and scoring applied for both roadways and structures.

Table 5: Sensitivity Criteria for Roadways

Indicator	Value	Score
Pavement Condition[1] Assets in poor condition are more likely to be damaged when exposed to flooding events.	Very Poor / Poor	3
	Fair	2
	Good / Excellent	1
Pavement Type[2] Reinforced pavements are less likely than non-reinforced pavements to be damaged when exposed to flooding events.	Asphalt	3
	Joint Reinforced Concrete Pavement	2
	Continuously Reinforced Concrete Pavement	1
Historical weather-related damages or closures[3] Assets that have experienced flooding in the past are likely to be sensitive in the future.	4+ historical events	3
	2-3 historical events	2
	1 historical event	1

Table 6: Sensitivity Criteria for Structures

Indicator	Value	Score
Deck Rating (Bridges Only)[4] Structures in serious condition are more likely to be damaged when exposed due to the exacerbation of pre-existing weaknesses.	0 (Failed Condition) 1 (Imminent Failure Condition) 2 (Critical Condition) 3 (Serious Condition) 4 (Poor Condition)	3
	5 (Fair Condition) 6 (Satisfactory Condition)	2
	7 (Good Condition) 8 (Very Good Condition) 9 (Excellent Condition)	1
	N (Not Applicable)	No Data
Superstructure Rating (Bridges Only)[5] Structures in serious condition are more likely to be damaged when exposed due to the exacerbation of pre-existing weaknesses.	0 (Failed Condition) 1 (Imminent Failure Condition) 2 (Critical Condition) 3 (Serious Condition) 4 (Poor Condition)	3
	5 (Fair Condition) 6 (Satisfactory Condition)	2
	7 (Good Condition) 8 (Very Good Condition) 9 (Excellent Condition)	1
	N (Not Applicable)	No Data

[1] VDOT Maintenance Division. Year: 2020. Field Name: CONDITION_TEXT. Values indicated in Table 5 are based on dataset accessed on April 13, 2021. Roadways where pavement condition was not available were assigned a score of 2

[2] VDOT Maintenance Division. Year 2020. Field Name: PAVEMENT_TYPE. Accessed on April 13, 2021. Roadways where pavement type was not available were assigned a score of 3.

[3] VDOT Operations Division. Field Name: Weather events ("WX") in VaTraffic (Virginia 511). Values indicate those in the dataset accessed on December 31, 2020 for Years 2015-2020. Refer to Appendix F.

[4] VDOT Structure & Bridge Division. Year 2020. Field Name: DKRATING. Values indicated in Table 6 are based on dataset accessed on accessed on December 23, 2020.

[5] VDOT Structure & Bridge Division. Year 2020. Field Name: SUPRATING. Values indicated in Table 6 are based on dataset accessed on accessed on December 23, 2020.

Indicator	Value	Score
Substructure Rating (Bridges Only)[1] Structures in serious condition are more likely to be damaged when exposed due to the exacerbation of pre-existing weaknesses.	0 (Failed Condition) 1 (Imminent Failure Condition) 2 (Critical Condition) 3 (Serious Condition) 4 (Poor Condition)	3
	5 (Fair Condition) 6 (Satisfactory Condition)	2
	7 (Good Condition) 8 (Very Good Condition) 9 (Excellent Condition)	1
	N (Not Applicable)	No Data
Culvert Rating (Culverts Only)[2] Culverts with condition deficiency are more likely to be exposed due to the exacerbation of pre-existing weaknesses.	0 (Structure closed; replacement necessary) 1 (Structure closed; corrective action may put back in light service) 2 (Integral wing walls collapsed, severe settlement of roadway due to loss of fill; failure; corrective action is required to maintain traffic) 3 (Any condition described in Code 4 but which is excessive in scope)	3
	4 (Large spalls, heavy scaling, wide cracks, considerable efflorescence, or opened construction joint; considerable settlement; considerable scouring or erosion; significant distortion) 5 (Moderate to major deterioration; noticeable scouring or erosion; significant distortion)	2
	6 (Deterioration; local minor scouring) 7 (Insignificant damage not requiring corrective action; minor scouring) 8 (No noteworthy deficiencies; insignificant scrape marks) 9 (No deficiencies)	1
	N (Not applicable; use if structure is not a culvert)	No Data
Scour Criticality[3] Scoured assets are more likely to experience impacts when exposed.	0: Scour critical. Structure has failed and is closed to traffic. 1: Scour critical; failure of piers/abutments is imminent 2: Scour critical; extensive scour has occurred at structure foundations 3: Scour critical; foundations determined to be unstable for calculated scour conditions.	3
	4: Foundations determined to be stable for calculated scour conditions; action required to protect exposed foundations from effects of additional erosion and corrosion 5: Foundations determined to be stable for calculated scour conditions; scour within limits of footing or piles.	2
	7: Countermeasures have been installed to correct a previously existing problem with scour. Structure is no longer scour critical. 8: Foundations determined to be stable for scour conditions; calculated scour is above top of footing 9: Foundations well above flood water elevations T: Over “tidal” waters that has not been evaluated for scour but considered low risk. N: Structure not over waterway	1
	6: Scour calculation/evaluation has not been made U: Unknown	No Data

[1] VDOT Structure & Bridge Division. Field Name: SUBRATING. Values indicated in Table 6 are based on dataset accessed on October 1, 2020.
[2] VDOT Structure & Bridge Division. Field Name: CULVRATING. Values indicated in Table 6 are based on dataset accessed on October 1, 2020.
[3] VDOT Structure & Bridge Division. Field Name: SCOURCRIT. Values indicated in Table 6 are based on dataset accessed on accessed on October 1, 2020.

Indicator	Value	Score
Channel and Channel Protection[1] Structures over channels with deterioration or damage are likely to be sensitive due to exacerbation of pre-existing weaknesses.	0 (Structure closed because of channel failure; replacement necessary) 1 (Structure closed because of channel failure; corrective action may put back in light service) 2 (Structure is near a state of collapse) 3 (Bank protection has failed; river control devices have been destroyed; streambed aggravation, degradation or lateral movement threaten structure and/or approach)	3
	4 (Bank and embankment protection is severely undermined; river control devices have severe damage; large deposits of debris are in the waterway) 5 (Bank protection is being eroded; river control devices and/or embankment have major damage; trees and brush restrict the channel) 6 (Bank is beginning to slump; river control devices and embankment protection have widespread minor damage; minor streambed movement evident; debris restricting waterway)	2
	7 (Bank protection is in need for minor repairs; river control devices and embankment protection have a little minor damage; banks and/or channel have minor amounts of drift) 8 (Banks are protected or well vegetated; river control devices such as spur dikes and embankment protection are not required or are in stable condition) 9 (No noticeable or noteworthy deficiencies)	1
	N (Not applicable; use only when the structure is not over a waterway)	No Data
Waterway Adequacy[2] Structures that frequently overtop and contribute to delays are likely to be sensitive in the future.	2 (Frequent overtopping) 3 (occasional overtopping of approaches and deck; significant delays) 4 (occasional overtopping of approaches; significant delays) 5 (occasional overtopping of approaches; insignificant delays)	3
	6 (slight chance of overtopping approaches and deck) 7 (slight chance of overtopping approaches and deck) 8 (Slight chance of overtopping approaches)	2
	9 (Remote chance of overtopping) 0 (structure closed)	1
	N (Not Applicable)	No Data
Historical weather-related damages or closures[3] Assets that have demonstrated sensitivity in the past are likely to be sensitive in the future.	Sea level rise: 1+ historical events Storm surge: 4+ historical events Inland/riverine flooding: 5+ historical events	3
	Storm surge: 2-3 historical events Inland/riverine flooding: 3-4 historical events	2
	Storm surge: 1 historical event Inland/riverine flooding: 1-2 historical events	1

[1] VDOT Structure & Bridge Division. Field Name: Channel_and_Channel _Protection. Values indicated in Table 6 are based on dataset accessed on October 1, 2020.

[2] VDOT Structure & Bridge Division. Field Name: WATERADEQ. Values indicated in Table 6 are based on dataset accessed on October 1, 2020.

[3] VDOT Operations Division. Field Name Weather events ("WX") in VaTraffic (Virginia 511). Values indicate those in the dataset accessed on December 31, 2020 for Years 2015-2020. See Appendix F.

3.2.3 Adaptive Capacity

The third component of the Vulnerability Assessment is an adaptive capacity analysis using a three-point scale that identifies the ability or inability of a system or asset to adjust to the impacts of exposure. A separate weighting framework is applied to roadways and structures; however, the indicator values are applied consistently across exposure types. Tables 7 and 8 summarize the indicators, data sources, and scoring applied for both roadways and structures.

Table 7: Adaptive Capacity Criteria for Roadways

Indicator	Value	Score
Roadway Functional Class[1] The transportation system may be less able to absorb impacts to assets of higher functional classification.	Interstate, other freeways or expressways (01, 11, 12) Other principal arterial (02, 14)	3
	Major and minor collector, minor arterial (06, 07, 08, 16, 17)	2
	Local (09, 19)	1
Hurricane Evacuation Route[2] Assets that are part of evacuation routes will cause greater disruption to the system if damaged.	Yes	3
	No	0
Annual Average Daily Traffic (AADT)[3] Assets with large amounts of average daily traffic are highly significant routes that are less able to cope with changes caused by climate impacts.	16,800 or higher	3
	9,100 - 16,799	2
	9,099 or lower	1
Corridors of Statewide Significance (CoSS)[4] Assets of statewide significance to the transportation network have less redundancy and therefore lower adaptive capacity.	Yes - Primary CoSS or Connector	3
	Yes - CoSS Component (nor primary)	2
	No	1

Table 8: Adaptive Capacity Criteria for Structures

Indicator	Value	Score
Hurricane Evacuation Route[5] Assets that are part of evacuation routes will cause greater disruption to the system if damaged.	Yes	3
	No	0
Navigable Waterway[6] Assets over navigable waterways are more likely to experience navigation issues under future climate conditions.	Yes	3
	No or N/A	0
Importance Factor (IF)[7] Assets with a greater Importance Factor will cause greater disruption to the system if damaged.	Top one-third of the total number of structures	3
	Middle one-third of the total number of structures	2
	Bottom one-third of the total number of structures or not available	1

[1] VDOT Transportation Planning and Mobility Division. Values indicated in Table 7 are based on dataset accessed on October 1, 2020.
[2] Virginia Department of Emergency Management. Field Name: Hurricane Evacuation Routes
[3] VDOT Traffic Engineering Division. 2019 Data. Roadways where AADT was not available were assigned a score of 1.
[4] Office of Intermodal Planning and Investment.
[5] Virginia Department of Emergency Management: Hurricane Evacuation Routes (Contraflow(Y/N))
[6] VDOT Structure & Bridge Division: Navigable Waterway (Navigable Waterway)
[7] VDOT Structure & Bridge Division: Bridge Importance Factor (IF)

APPENDIX A: LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
CDOT	Colorado Department of Transportation
CoSS	Corridor of Statewide Significance
CTB	Commonwealth Transportation Board
DOT	Department of Transportation
DRPT	Department of Rail and Public Transportation
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FIRM	Flood Insurance Rate Map
GMSL	Global Mean Sea Level
HRPDC	Hampton Roads Planning District Commission
IF	Importance Factor
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Laser Imaging Detection and Ranging (system)
MassDOT	Massachusetts Department of Transportation
MPO	Metropolitan Planning Organization
NBI	National Bridge Inventory
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
OIPI	Office of Intermodal Planning and Investment
SANDAG	San Diego Association of Governments
SLOSH	Sea, Lake and Overland Surges from Hurricanes
TMPD	Transportation Planning and Mobility Division.
USGCRP	U.S. Global Change Research Program
VAST	Vulnerability Assessment Scoring Tool
VDOT	Virginia Department of Transportation
VFRMS	Virginia Flood Risk Management Standard
VIMS	Virginia Institute of Marine Sciences

APPENDIX B: LITERATURE REVIEW

B.1: Definition of Vulnerability

According to the Intergovernmental Panel on Climate Change (IPCC), vulnerability is "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt."[1] The U.S. Global Change Research Program (USGCRP) defines vulnerability as "the degree to which physical, biological and socio-economic systems are susceptible to and unable to cope with adverse impacts of climate change."[2]

In the context of transportation systems, vulnerability refers to the susceptibility of a system to hazards, including the physical vulnerability of users and the potential damage or change in service provision of the transportation system.[3] In the academic literature and transportation studies, the definition of vulnerability used by Berdica (2002) is referenced commonly. This definition states that the "vulnerability of a road transportation system is the susceptibility to incidents that can result in a considerable reduction in road network serviceability."[4]

FHWA provides a comprehensive definition that breaks down vulnerability as a function of an asset or system's exposure, sensitivity, and adaptive capacity. This definition reflects the current state of the practice for State Department of Transportations (DOT) and Metropolitan Planning Organizations (MPO).

- **Exposure:** whether the asset or system is located in an area experiencing direct effects of climate variables. For example, a road that could experience flooding and inundation due to its location in a low-lying area.
- **Sensitivity:** how the asset or system fares when exposed to a climate variable. For example, a tunnel could be more sensitive to flooding due to challenges removing water.
- **Adaptive capacity:** the asset or system's ability to adjust to or cope with existing climate variability or future climate impacts. For example, redundant or alternative routes that could be used to reach the same location would increase adaptive capacity compared to a route that is the only source of access. Note that this component of vulnerability is optional and often redundant with criticality. Criticality, which is independent from vulnerability, captures the importance of an asset to the transportation system or region as a whole. Criteria for evaluating an asset's criticality may include: average daily traffic, functional classification, goods movement levels, access to employment/ educational/medical facilities, degree of redundancy, and role in emergency management.

While some transportation systems have directly used the FHWA definition, others modify it. For example, the Hampton Roads Planning District Commission (HRPDC) defines vulnerability as a combination of sensitivity and adaptive capacity.[5] Under the HRPDC definition, a system or area would be considered more vulnerable if it is highly sensitive and has low adaptive capacity. Other possible definitions of vulnerability may not include adaptive capacity or may substitute criticality (i.e., identifying which assets are of the greatest importance, such as an evacuation route upon which a significant population depends) in their assessments.

B.2: Definition of Resilience

FHWA defines resilience or resiliency as "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions."[6] When defining resilience, most State DOTs, MPOs, and the other transportation organizations use a similar approach to FHWA, focusing on the ability to prepare for and recover from disasters and disruptive events.

Table B-1: provides examples of how DOTs and MPOs define resilience, while Table B-2 provides examples of how agencies have incorporated resilience into their goals and objectives. The FHWA report, Integrating Resilience into the Transportation Planning Process: White Paper on Literature Review Findings, provides additional examples of resilience definitions and

[1] Intergovernmental Panel on Climate Change. *Glossary.* Accessed 13 January 2019.
[2] U.S. Global Change Research Program. *Glossary.* Accessed 13 January 2019.
[3] Cova, Thomas J., and Steven Conger. 2003. *"Transportation hazards" in Transportation Engineers' Handbook.* Ed. Myer Kutz.
[4] Berdica, Katja. 2002. *An introduction to road vulnerability: what has been done, is done and should be done.* Transport Policy, Elsevier, vol. 9(2), pages 117-127. =
[5] Hampton Roads Planning District Commission. 2010. *Climate Change in Hampton Roads: Impacts and Stakeholder Involvement.*
[6] Federal Highway Administration. December 2014. *FHWA Order 5520*.

goals. The greatest differences between definitions among the DOTs and MPOs is how the agencies propose to build that ability. Some emphasize the importance of system adaptive capacity and robustness, while others prioritize swiftness in the recovery response. The tables identify the core components of the definitions and goals, including whether the statement is focused on community or transportation resilience (or both), and whether it includes advance preparation for disruptions, reaction (e.g., response and recovery) or both.

Table B-1: Examples of How Agencies Define Resilience and the Core Components of the Definition

Agency	Definition	Community	Transportation	Preparation	Reaction
Alaska DOT	We will improve system resiliency of freight and passenger transportation to reduce the safety and security risks of natural events such as earthquakes, climate change, and man-made disasters (e.g., accidents)[1]		•	•	
Anchorage Metropolitan Area Transportation Solutions (Anchorage, AK)	Resilience means "how to work around outcomes to get back up running quickly"[2]		•		•
Arkansas DOT	The ability to reduce the possibility of failure, adapt and recover from a disruptive event and/or gradual external changes over time. It also implies transformation, so not only is the infrastructure service able to survive or recover but it can adapt to a changing environment in which it operates[3]		•	•	•
Baltimore Regional Transportation Board (Baltimore, MD)	Resilience means the transportation system is "better able to adapt to a variety of potentially significant future changes."		•	•	
Delaware DOT	Encompass[ing] the ability to withstand and recover from an incident in order to provide critical transportation services during the incident and through the recovery process[4]		•	•	•
Caltrans	Resilient transportation facilities: Transportation facilities that are designed and operated to reduce the likelihood of disruption or damage due to changing weather conditions.		•	•	
Colorado DOT	Resiliency incorporates extreme weather, economic adversity, emergency management, and security[5]		•		•
Hampton Roads Planning District Commission	The ability to recovery quickly with minimal lasting damage from an event[6]		•		•

[1] Alaska DOT. December 2016. Alaska Statewide Long-Range Transportation Policy Plan.
[2] Anchorage Metropolitan Area Transportation Solutions. May 2012. 2035 Metropolitan Transportation Plan.
[3] Arkansas Highway and Transportation Department. 2016. Arkansas Long Range Intermodal Transportation Plan.
[4] DelDOT. 2017. *Strategic Implementation Plan for Climate Change, Sustainability and Resilience for Transportation.*
[5] Colorado Department of Transportation. Statewide Transportation Plan.
[6] HRPDC. 2010. Climate Change in Hampton Roads: Impacts and Stakeholder Involvement.

Agency	Definition	Community	Transportation	Preparation	Reaction
Iowa DOT	Not explicitly defined, though it is contextualized in climate change and extreme weather: "resiliency has become increasingly important at all levels of planning, from designing projects to withstand extreme weather events to having plans in place for responding to emergency weather situations;" "System resiliency requires a proactive approach to extreme weather events and other large-scale incidents that threaten the continuity of system operations. The Iowa DOT seeks to minimize the impact of extreme weather by intentionally designing and managing certain routes to be resistant to extreme weather, and to move people and goods throughout the state both during and after extreme weather events.")[1]		•	•	•
Metropolitan Council (St. Paul, MN)	Resilience strategies recognize the difficulty of predicting what the impacts of climate change will be and emphasize increasing our flexibility to survive and thrive regardless of how climate change develops[2]	•		•	•
Metropolitan Planning Commission (Oakland, CA)	Enhance climate protection and adaptation efforts, strengthen open space protections, create healthy and safe communities, and protect communities against natural hazards[3]	•		•	•
Minnesota DOT	Reducing vulnerability and ensuring redundancy and reliability to meet essential travel needs[4]		•	•	•
Northeast Ohio Areawide Coordinating Agency (Cleveland, OH)	Resiliency is a process for managing complex infrastructures rather than a single outcome… As such, a resiliency framework takes an adaptive life-cycle approach to tackling the dynamic challenges that confront today's complex infrastructure systems. Embedded in it is the capability to protect its assets, anticipate and detect threats, prevent risks of known failures, withstand unanticipated disruptions, and respond and recover rapidly when the worst does happen[5]	•	•	•	•
Rockingham Planning Commission (Exeter, NH)	Capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment[6]	•	•	•	•
San Diego Association of Governments (SANDAG, San Diego, CA)	Making our region more resilient to the consequences of climate change means increasing the capacity of our communities, economy, and environment to cope with hazardous events such as storms, heat waves, wildfires, and ongoing drought[7]	•		•	•
Tennessee DOT	Resilience is the ability of the transportation system to withstand and recover from incidents[8]		•	•	•

[1] Iowa DOT. *Iowa in Motion 2045*.
[2] Metropolitan Council. *2040 Thrive MSP: One Vision, One Metropolitan Region.*
[3] Metropolitan Planning Commission. *Plan Bay Area 2040.*
[4] Minnesota DOT. January 2017. *Minnesota Statewide Multimodal Transportation Plan 2017 to 2036.*
[5] Northeast Ohio Areawide Coordinating Agency (NOACA). June 2017. *Aim Forward 2040.*
[6] Rockingham Planning Commission. September 2017. *2040 LRTP Public Comment Draft.*
[7] San Diego Association of Governments (SANDAG). *San Diego Forward: The Regional Plan.*
[8] Tennessee DOT. TDOT 25-YEAR LONG-RANGE TRANSPORTATION POLICY PLAN: Safety, Security, and Transportation Resilience Policy Paper

Agency	Definition	Community	Transportation	Preparation	Reaction
USGCRP	A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment[1]	•	•	•	•
Wisconsin DOT	A resilient transportation system is able to quickly respond to unexpected conditions and return to its usual operational state[2]		•		•

Table B-2: Examples of How Agencies Incorporate Resilience into Goals and Objectives, and the Core Components of the Goals

Agency	Resilience Goals & Objectives	Community	Transportation	Preparation	Reaction
Boston MPO	The MPO has incorporated resilience into its system preservation goal by giving projects points for improving important evacuation routes, addressing flooding issues related to sea level rise, and helping to implement part of a climate adaptation plan[3]	•	•	•	•
Caltrans	Caltrans states that it encourages resilience planning to reduce the likelihood, magnitude, duration, and cost of disruptions associated with extreme weather and other effects of changing climatic conditions to the transportation system[4]		•	•	•
Colorado DOT (CDOT)	CDOT identifies resiliency as a key strategic policy action which addresses multiple goals, such as its safety, mobility, and system maintenance goals. The Strategic Action Plan states that all modes could be enhanced by improving the resiliency and redundancy of the transportation system to address the potential effects of extreme weather and economic adversity, emergency management, and security[?]	•	•	•	•
Massachusetts DOT (MassDOT)	Within their Long-Range Transportation Plan, Statewide Intelligent Transportation Systems Strategic Plan, MassDOT has several resilience-related goals and objectives: ▪ MassDOT is planning for the resilience of the system as they respond to the growing impacts of climate change through Vulnerability Assessments and the incorporation of climate and sea level considerations into planning processes and construction practices. ▪ A core function of government and transportation organizations is to ensure public safety and to secure the total system against natural and man-made catastrophes.[5]	•	•	•	•

[1] U.S. Global Change Research Program. Glossary. Accessed 13 January 2019.
[2] Wisconsin DOT. October 2009. Connections 2030.
[3] Boston Region MPO. 2015. Long-range Transportation Plan
[4] Caltrans. 2016. California Transportation Plan 2040.
[5] MassDOT. 2013. Statewide Intelligent Transportation Systems Strategic Plan.

B.3: Review of Virginia Transportation Vulnerability Assessments

The following studies were reviewed:

- The *Commonwealth of Virginia Hazard Mitigation Plan*, which profiles 13 hazards, including communicable disease, drought, earthquake, flooding, flooding due to impoundment failure, karst, landslide, land subsidence, non-rotational wind, solar storm, tornado, wildfire, and winter storm.[1]
- The Virginia Institute of Marine Science (VIMS), Center for Coastal Resources Management, and William & Mary *Recurrent Flooding Study for Tidewater Virginia* report, which assesses flood risk across the coastal zone of Virginia.[2]
- Strauss et al. (2014)'s report, *Virginia and the Surging Sea: A vulnerability assessment with projections for sea level rise and coastal flood risk*, which assesses the vulnerability of systems to sea level rise and coastal flooding, including roads (all), local roads, secondary roads, state roads, and federal roads.[3]
- The *Climate Change Vulnerabilities in the Coastal Mid-Atlantic Region* study, which evaluated the vulnerability of 63 counties and independent cities along coastal areas of Delaware, Maryland, New Jersey, New York, Pennsylvania, and Virginia to sea level rise.[4]
- Vulnerability studies from Hampton Roads, Virginia, including: *Climate Change in Hampton Roads: Impacts and Stakeholder Involvement (Phase I);*[5] *Climate Change in Hampton Roads, Phase II: Storm Surge Vulnerability and Public Outreach;*[6] and *Climate Change in Hampton Roads, Phase III: Sea Level Rise in Hampton Roads, Virginia.*[7]
- VDOT, the University of Virginia, Virginia Center for Transportation Innovation and Research (VCTIR), HRPDC, and Hampton Roads Transportation Planning Organization (HRTPO) *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot*, which assesses the impacts of climate change on transportation infrastructure in the Hampton Roads region.[8]
- The Hampton Roads Metropolitan Planning Organization *Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads,* which determined where flooding is expected on roadways, structures, and tunnels within in the Hampton Roads Metropolitan Planning Area by 2045 as a result of relative sea level rise and storm surge.[9]
- The Accomack-Northampton Planning District Commission *Eastern Shore of Virginia Transportation Infrastructure Inundation Vulnerability Assessment*, which evaluates the risk of flooding due to sea level rise on transportation infrastructure (primary and secondary roads, structures, causeways, railroad, culverts and ditches, signalization infrastructure, and utilities and right-of-way).[10]
- The Northern Virginia Regional Hazard Mitigation Plan *Vulnerability Assessment* uses FEMA HAZUS software to estimate losses from hurricane winds and earthquakes. The study qualitatively assessed risks for identified hazards in local communities.[11]
- Metropolitan Washington Council of Governments' report on *Climate Change Adaptation in the Metropolitan Washington Region: Draft Transportation Sector Vulnerabilities*, which aims to identify possible impacts of climate change to the transportation sector.[12]

[1] Virginia Department of Emergency Management. 2018. Commonwealth of Virginia Hazard Mitigation Plan.

[2] Center for Coastal Resources Management, Virginia Institute of Marine Science (VIMS), and William & Mary. 2013. *Recurrent Flooding Study for Tidewater Virginia*.

[3] Strauss, B., C. Tebaldi, S. Kulp, S. Cutter, C. Emrich, D. Rizza, and D. Yawitz. 2014. *Virginia and the Surging Sea: A Vulnerability Assessment with projections for sea level rise and coastal flood risk. Climate Central Research Report, pp. 1-29.*

[4] Colgan, Charles S., Juliano Calil, Hauke Kite-Powell, Di Jin, and Porter Hoagland. 2018. *Climate Change Vulnerabilities in the Coastal Mid-Atlantic Region. Middlebury Institute of International Studies at Monterey.*

[5] Hampton Roads Planning District Commission. 2010. *Climate Change in Hampton Roads: Impacts and Stakeholder Involvement.*

[6] Hampton Roads Planning District Commission. 2011. *Climate Change in Hampton Roads, Phase II: Storm Surge Vulnerability and Public Outreach.*

[7] Hampton Roads Planning District Commission. 2012. *Climate Change in Hampton Roads, Phase III: Sea Level Rise in Hampton Roads, Virginia.*

[8] Virginia Department of Transportation (VDOT), University of Virginia, Hampton Roads Planning District Commission (HRPDC). 2012. *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot.*

[9] Hampton Roads Transportation Planning Organization. 2016. *Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads.*

[10] Accomack – Northampton Planning District Commission. 2015. *Eastern Shore of Virginia Transportation Infrastructure Inundation Vulnerability Assessment. Virginia Coastal Zone Management Program.*

[11] Northern Virginia Regional Hazard Mitigation Plan. *Vulnerability Assessment.*

[12] Metropolitan Washington Council of Governments. *Climate Change Adaptation in the Metropolitan Washington Region: Draft Transportation Sector Vulnerabilities.*

B.3. Exposure Data and Timelines

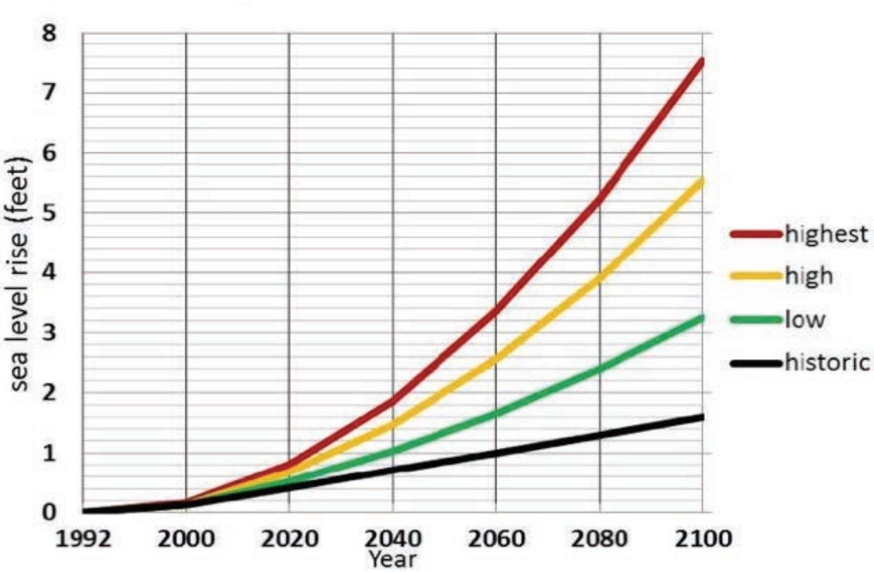
The studies reviewed employed a range of exposure data, including various sea level rise and storm surge projections and inland/riverine flooding data. The sea level projections used in the *Climate Change Vulnerabilities in the Coastal Mid-Atlantic Region* study are shown in Table 4-1, which represent the most comprehensive and recent studies. These projections are commonly used in coastal vulnerability assessments.

Table B-3: Sea Level Scenarios for Virginia

Study	Variables Considered	Sea Level Rise Scenarios
2017 – ADAPT-VA: *Sea Level in Virginia, Historic Data and Projections*[1]	**GMSL Sea Level Rise Factors:** Thermal Expansion Ice Sheet Mass Changes Glacier mass changes **Local Sea Level Rise Factors:** Land subsidence	**2100 Projections** Low: 1.9 ft. Medium Low: 2.5 ft. Medium: 4.2 ft. Medium High: 5.8 ft. High: 7.5 ft. Extreme: 9.1 ft.
2013 – Recurrent Flooding Study for Tidewater Virginia[2]	**GMSL Sea Level Rise Factors:** Factors included in NCA report (2012): Ocean thermal expansion Ice melt **Local Sea Level Rise Factors:** Land subsidence	**2033-2063:** 1.5 ft. **2100:** Low: 3.2 ft. High: 5.5 ft. Highest: 7.5 ft.

As part of the *Recurrent Flooding Study for Tidewater Virginia*, VIMS developed sea level rise scenarios for Virginia by using the four scenarios developed by the National Climate Assessment and modifying them with land subsidence estimations for southeastern Virginia. In the future, land subsidence rates are anticipated to remain relatively constant (2.7 millimeters/ year or 0.1 inch/year) while rates of sea level rise are expected to increase. Figure B-1 shows the sea level rise projections adjusted for southeastern Virginia.

Figure B-1: Sea Level Rise Projections for Southeastern Virginia



The Virginia and the Surging Sea study used data on projected local sea level rise based on Tebaldi et al. (2012)[3] and models and scenarios that NOAA prepared for the National Climate Assessment (Parris 2012).[4] For Virginia, local sea level rise is projected to be 1.2 to 1.5 feet by 2050 and 4.0 to 4.8 feet by 2100, based on a 2012 baseline. The study also used statistics on historical extreme water level patterns combined with projected sea level rise, and high-resolution, high-accuracy laser-based elevation data from the National Elevation Dataset. Additional Laser Imaging Detection and Ranging (system) (LIDAR) data was commissioned for southeast Virginia by the U.S. military and published by the U.S. Geological Survey.

[1] ADAPT Virginia. 2017. Virginia Sea Level.

[2] Mitchell, Molly, Carl Hershner, Herman Julie, Dan Schatt, Pam Mason, and Emily Eggington. 2013. "Recurrent Flooding Study for Tidewater Virginia." Virginia Institute of Marine Science, Center for Coastal Resources Management, William and Mary. doi:10.21220/V5TG79.

[3] Tebaldi, C., Strauss, B. H., & Zervas, C. E. (2012). "Modelling sea level rise impacts on storm surges along US coasts." Environmental Research Letters,7(1), 014032.

[4] Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss (2012). "Global Sea Level Rise Scenarios for the US National Climate Assessment." NOAA Tech Memo OAR CPO-1. 37 pp.

The *Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads* study involves mapping the potentially submerged areas under three scenarios using the best available elevation data:

- Scenario 1: 2.0 feet relative sea level rise
- Scenario 2: 2.0 feet relative sea level rise + 25-year storm surge
- Scenario 3: 2.0 feet relative sea level rise + 50-year storm surge

The *Eastern Shore of Virginia Transportation Infrastructure Inundation Vulnerability Assessment* used four sea level rise projections from the VIMS 2013 study in combination with local subsidence rates (see Table B-4).

Table B-4: Sea Level Rise Scenarios for the Eastern Shore

Sea Level Scenario above MHHW	Projected Date of Occurrence
1 foot	= 2025-2050
2 feet	= 2045-2090
3 feet	> 2060
4 feet	> 2070
5 feet	> 2080
6 feet	> 2090
Note: Projections from the VIMS Recurrent Flooding Study for Tidewater Virginia (2013) and adjusted for local subsidence rate for Wachapreague, VA (1.6 mm/year) based on Holmdahl and Morrison (1974).	

HRPDC completed three studies of vulnerability in the region. The assessments include elevation data from the National Elevation Dataset referenced to the North American Vertical Datum of 1988. HRPDC used a data set developed by the U.S. EPA to modify this data set to reflect local tidal conditions, since LiDAR was not available.[1] Projections for future sea level rise are based on equations from the 1987 National Research Council (NRC) report[2] and USACE guidance.[3] Historical sea level trends are from NOAA's Tides & Currents service. The three sea level rise scenarios are based on current rates of sea level rise – a low, an intermediate, and a high scenario (Table B-5).

Table B-5: Projected Sea Level Rise at Hampton Roads Water Level Stations, 2010-2100 (in meters)

Station	Low Scenario	Medium Scenario	High Scenario
Chesapeake Bay Bridge Tunnel	0.45	0.76	1.74
Gloucester Point	0.37	0.68	1.65
Kiptopeke	0.32	0.63	1.61
Portsmouth	0.34	0.65	1.62
Sewell's Point	0.39	0.70	1.67

The *Commonwealth of Virginia Hazard Mitigation Plan* determined flood probability based on the designated zones in Flood Insurance Rate Maps and determined risk based on whether assets are within established FEMA flood zones.

B.4. Assessment Approaches

The majority of studies reviewed completed an exposure analysis of sea level rise, storm surge, or inland/riverine flooding hazards. For example:

- The *Commonwealth of Virginia Hazard Mitigation Plan* profiles 13 hazards, including flooding, and then assesses vulnerabilities due to hazards and estimates the potential losses to populations and property.
- The *Recurrent Flooding Study for Tidewater Virginia* report uses historical records of past inundation, as well as potential future flooding based on topographic mapping. In order to determine which assets could be exposed to flooding, the study uses elevation maps and land use layers from the Coastal Change Analysis Program (C-CAP), which is a national standardized dataset of land cover and land use change that was developed through remotely sensed imagery.

[1] Titus, James G., and Jue Wang. 2008. Maps of Lands Close to Sea Level along the Middle Atlantic Coast of the United States: An Elevation Data Set to Use While Waiting for LIDAR. United States Environmental Protection Agency.
[2] National Research Council. 1987. *Responding to Change in Sea Level: Engineering Implications.* Washington, D.C. National Academy Press.
[3] U.S. Army Corps of Engineers. 2011. "Sea Level Change Considerations for Civil Works Programs." 1165-2-212. Washington, D.C.

- The *Virginia and the Surging Sea* study computes the length of each feature on land below a chosen water level to determine potential vulnerability.
- The *Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads* study aimed to determine where flooding is expected on roadways, structures, and tunnels within the Hampton Roads Metropolitan Planning Area by 2045 as a result of relative sea level rise and storm surge. The study uses HRPDC GIS elevation data from the most recent and highest resolution LiDAR data (which became available after the completion of vulnerability assessment studies by the HRPDC). The roadway dataset used is the road centerline database from the Virginia Geographic Information Network (VGIN). These maps are combined to identify segments of roadways that could be exposed under the different flooding scenarios.

A limited number of studies went beyond an initial exposure analysis to determine vulnerability based on additional factors. For example:

- The *Climate Change Vulnerabilities in the Coastal Mid-Atlantic Region* study uses a GIS model to overlay NOAA's sea level rise data for two sea level rise scenarios (3 feet and 6 feet) with socio-economic indicators (population, housing units, total employment, summer employment, summer housing, infrastructure, ocean economy employment, social vulnerability, and fishing community vulnerability) in order to determine the areas with highest and lowest levels of vulnerability.
- HRPDC completed three studies that included a range of vulnerability assessment activities. The study team developed a GIS tool that combined storm surge data, elevation, and socio-economic data on critical infrastructure, population, roads, and businesses. The work completed under the studies utilized the GIS tool to analyze the effects of sea level rise on various sectors, including the built environment and infrastructure, and provide recommended adaptation measures. The map-based exposure analysis identifies areas vulnerable to inundation and which assets could be exposed using NOAA's Coastal Inundation Mapping process. The assessment includes:
  - Elevation data from the National Elevation Dataset referenced to the North American Vertical Datum of 1988. HRPDC used a dataset developed by the U.S. EPA to modify this data set to reflect local tidal conditions, since LiDAR was not available.[1]
  - Projections for future sea level rise based on equations from the 1987 NRC report[2] and USACE guidance.[3]
  - Inundation maps based on projected sea level rise using GIS that overlay with maps of transportation infrastructure. VDOT's road centerline database is used as the base data to evaluate infrastructure risk. Roads are categorized as interstate, primary, secondary, and local or private using VDOT's classification system. To create the final evaluation of exposed roadways, roads vulnerable under each of the three scenarios were identified and the length of each exposed segment was calculated in miles. Total length of exposed road was summed by category for each locality and the region as a whole.
- *The Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot* assesses the impacts of climate change on transportation infrastructure in the Hampton Roads region. The report also includes recommendations on how to set priorities and reprioritize investments in the long-range transportation planning process. The key elements of the pilot were: (1) identifying the interactions between climate change and other factors such as economic recession, increased government regulation, maintenance/repair of existing infrastructure, technological innovation, and ecological degradation; (2) establishing the connection between these combinations of scenarios and transportation strategic planning; and (3) prioritizing limited resources such that an optimal allocation and timely intervention can be achieved. The project uses multicriteria decision analysis to perform the risk assessment. The majority of data input are from the 2034 long-range plan for HRTPO. Other data for climate scenarios were obtained through stakeholder sessions.
- The *Eastern Shore of Virginia Transportation Infrastructure Inundation Vulnerability Assessment* completed both a regional inundation vulnerability assessment and a community and critical facility accessibility assessment. The study mapped local sea level rise projections, critical facilities and communities to determine how they would be impacted.

1 Titus, James G., and Jue Wang. 2008. *Maps of Lands Close to Sea Level along the Middle Atlantic Coast of the United States: An Elevation Data Set to Use While Waiting for LIDAR*. United States Environmental Protection Agency.

2 National Research Council. 1987. *Responding to Change in Sea Level: Engineering Implications.* Washington, D.C. National Academy Press.

3 U.S. Army Corps of Engineers. 2011. "Sea Level Change Considerations for Civil Works Programs." 1165-2-212. Washington, D.C.

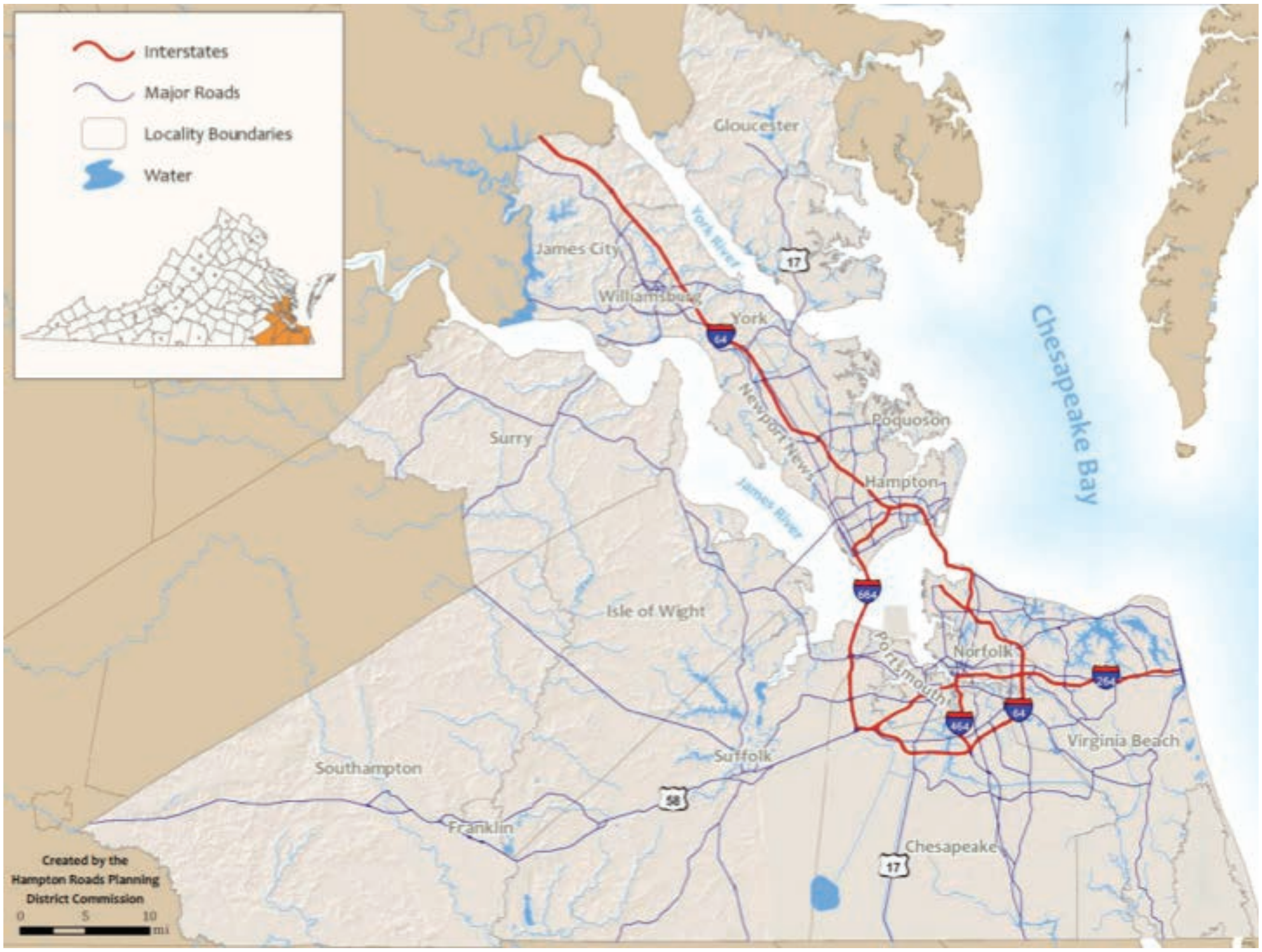
B.5. Key Findings

These studies include a range of key findings regarding sea level rise, storm surge, and inland/riverine flooding impacts to infrastructure in Virginia. For example, the *Recurrent Flooding Study for Tidewater Virginia* report concluded that sea level rise and storm surge is projected to lead to flooding of evacuation routes, increased hydraulic pressure on tunnels, and alteration of drainage capacity. Across 40 localities, 1,508 miles of road could be flooded by 1.5 feet of sea level rise and a 3-foot storm surge. In addition, navigation capacity may change, airport runways adjacent to tidal waters could be at risk due to storm surge flooding events, and railroads across marshes, swamps, or other low-lying land could also be impacted by sea level rise.

The *Virginia and the Surging Sea* report indicates that 1,469 miles of road lie below 5 feet of elevation in the state and more than 4,500 miles of road are below 9 feet. The *Climate Change Vulnerabilities in the Coastal Mid-Atlantic Region* study found that, within Virginia, a 3-foot scenario exposes 24 miles of major road and 4.6 miles of rail to flooding. The 6-foot scenario exposes 30.4 miles of roads and 29.1 miles of rail lines. Hampton City in Virginia shows up as the most vulnerable in the 3-foot scenario for major roads.

A number of studies have focused on the Hampton Roads area. Figure B-2 shows the Hampton Roads region.

Figure B-2: Map of Hampton Roads Region



HRPDC completed three studies that found over 5,000 linear miles of road are exposed during Category 4 hurricanes. The studies found that a significant amount of transportation infrastructure in the region is potentially at risk of inundation due to sea level rise. Even with one meter of sea level rise above Spring High Tide, a large portion of the region's transportation infrastructure could be exposed to flooding, including 18 miles of interstate highways, 77 miles of state primary roads, 100 miles of secondary roads, and 684 miles of local and private roads.

The *Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads* study identifies segments of roadways that could be exposed under the different flooding scenarios. For planned roads in the 2045 Analysis Network, structures and elevated structures are not included, as the team used aerial photographs to identify which structures were misidentified. This was not done for existing infrastructure. The study summarized submergence risks for centerline miles flooded by 2045 by jurisdiction for three sea level rise and storm surge scenarios (see Figure B-6).

Table B-6: Potential Submerged Area of Roadways in Hampton Roads by 2045

Hampton Roads Jurisdiction	Total Centerline Miles	Scenario 1: 2 Ft Sea Level Rise		Scenario 2: 2 Ft Sea Level Rise + 25-Yr Storm Surge*		Scenario 3: 2 Ft Sea Level Rise + 50-Yr Storm Surge*	
		Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded
Chesapeake	1,213	3.1	0.3%	143.4	11.8%	177.3	14.6%
Gloucester County	653	15.7	2.4%	96.9	14.8%	106.1	16.2%
Hampton	698	3.6	0.5%	197.7	28.3%	247.5	35.5%
Isle of Wight County	680	0.4	0.1%	4.0	0.6%	4.5	0.7%
James City County	592	0.3	0.1%	8.6	1.5%	9.4	1.6%
Newport News	746	0.5	0.1%	15.8	2.1%	20.1	2.7%
Norfolk	948	5.2	0.5%	205.9	21.7%	272.9	28.8%
Poquoson	57	1.8	3.1%	48.4	84.5%	55.2	96.5%
Portsmouth	487	0.2	0.0%	114.3	23.5%	151.1	31.0%
Suffolk	854	0.2	0.0%	3.3	0.4%	4.3	0.5%
Virginia Beach	1,858	5.1	0.3%	129.6	7.0%	160.7	8.6%
Williamsburg	75	-	0.0%	0.1	0.1%	0.1	0.1%
York County	654	1.3	0.2%	45.0	6.9%	57.7	8.8%
	9,516	**37.5**	**0.4%**	**1,013.0**	**10.6%**	**1,267.0**	**13.3%**

*Centerline miles are cumulative for Scenarios 2 and 3. For example, Scenario 2 includes roadway segments from Scenarios 1 and 2. Scenario 3 includes roadway segments from Scenarios 1, 2, and 3.
**Existing Local Roadways include all other roadways not included in the 2045 Analysis Network, such as local and collector streets, ramps, and roads on military installations.

Based on the 2045 Analysis Network, only 0.1% (2.4 centerline miles) of the network is expected to be submerged with 2 feet of sea level rise. However, 5.9% (93.7 centerline miles) and 7.6% (119.8 centerline miles) of the network is expected to be submerged under more severe sea level rise and storm surge scenarios.

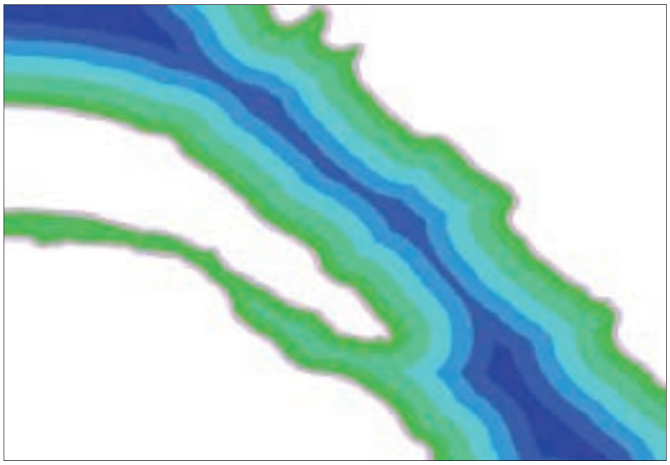
The *Eastern Shore of Virginia Transportation Infrastructure Inundation Vulnerability Assessment* identifies 33 miles of roads in the region that could be vulnerable to inundation between 2025 and 2050 with one foot of relative sea level rise. The number increases to 371 miles, or 24.5% of all roads vulnerable, as early as 2090 with six feet of relative sea level rise. The rail yard at Cape Charles is the only section of railway potentially vulnerable to inundation by the end of the century.

APPENDIX C: METHODOLOGY FOR CREATION OF THE EXTREME INLAND/RIVERINE FLOODING SCENARIO

One of the three scenarios for inland/rivering flooding relied on 500 year floodplain data and applied an additional buffer to create a scenario equivalent of extreme sea level rise, while limiting this buffer based on the width of the floodplain. This was done using the following GIS steps resulting in an additional buffer of 10-200 feet depending on width of the flood plain.

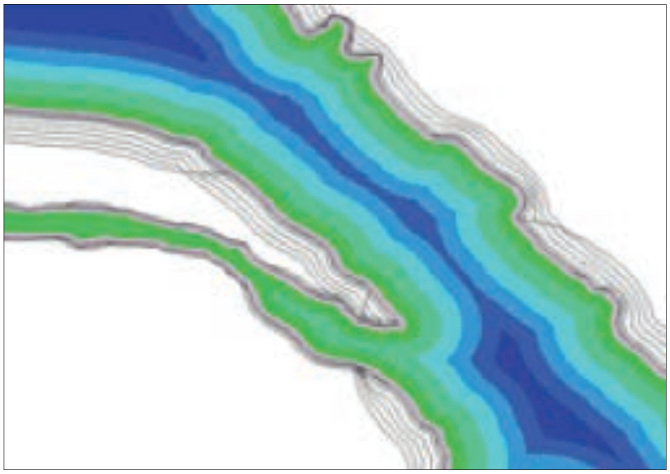
1. Generate negative-distance buffers at varying distances (25, 50, 100, 200, 300, 400, 500 feet) within the combined 100-year and 500-year floodplain area (Figure C-1). This is intended to capture areas that are more than 1,000 feet wide (see the dark blue below) all the way to 50 feet or less.

Figure C-1: Generate Negative-distance Buffers



2. Apply buffers to these inner rings equivalent to the distance needed to get back out to the edge of the floodplain + 20% of width (Figure C-2). This is as follows:
   - More than 1,000ft wide areas (500ft dark blue inner rings) get buffered at 500 + 200ft
   - 800ft wide areas (400ft inner rings) get buffered at 400 + 160ft
   - 600ft wide areas (300ft inner rings) get buffered at 300 + 120ft
   - (continue the same method)
   - 50 ft wide areas (or less) get a minimum buffer of 10ft from edge of floodplain

Figure C-2: Apply Buffers



3. Merge the buffers into one (Figures C-3 and C-4)

C-3: Merge Buffers (Sample 1)

C-4: Merge Buffers (Sample 2)

Buffer around 500 year floodplain

APPENDIX D: SEA LEVEL RISE SCENARIOS

The VTrans Vulnerability Assessment makes use of Year 2040 Intermediate, Intermediate High, and Extreme Scenario from NOAA. The sea level rise scenarios and their associated values are included as Figure D-1 and Table D-1 .

Figure D-1: Relative Sea Level Rise Scenarios Curves[1]

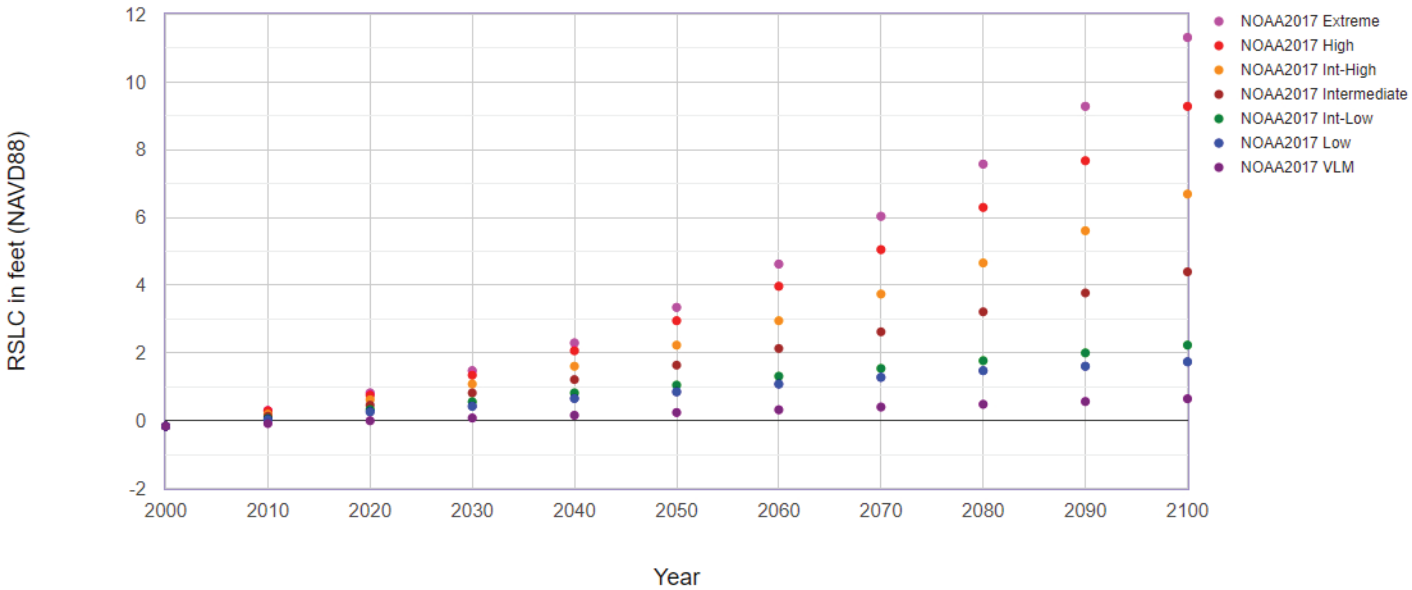


Table D-1: Relative Sea Level Rise Scenario Values for Global Sea Level Rise[1]

Scenarios for SEWELLS POINT
NOAA2017 VLM: 0.00810 feet/yr
All values are expressed in feet

Year	NOAA2017 VLM	NOAA2017 Low	NOAA2017 Int-Low	NOAA2017 Intermediate	NOAA2017 Int-High	NOAA2017 High	NOAA2017 Extreme
2000	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17
2010	-0.09	0.03	0.06	0.13	0.19	0.29	0.29
2020	-0.00	0.26	0.33	0.46	0.62	0.75	0.82
2030	0.08	0.42	0.56	0.82	1.08	1.34	1.47
2040	0.16	0.65	0.82	1.21	1.61	2.06	2.29
2050	0.24	0.85	1.05	1.64	2.23	2.95	3.34
2060	0.32	1.08	1.31	2.13	2.95	3.97	4.62
2070	0.40	1.28	1.54	2.62	3.74	5.05	6.03
2080	0.48	1.47	1.77	3.21	4.66	6.30	7.58
2090	0.56	1.61	2.00	3.77	5.61	7.67	9.28
2100	0.64	1.74	2.23	4.39	6.69	9.28	11.32

[1] USACE's Sea-level Change Curve Calculator (Version 2021.12)

APPENDIX E: METHODOLOGY TO ASSIGN EXPOSURE VALUES TO ROADWAY SEGMENTS

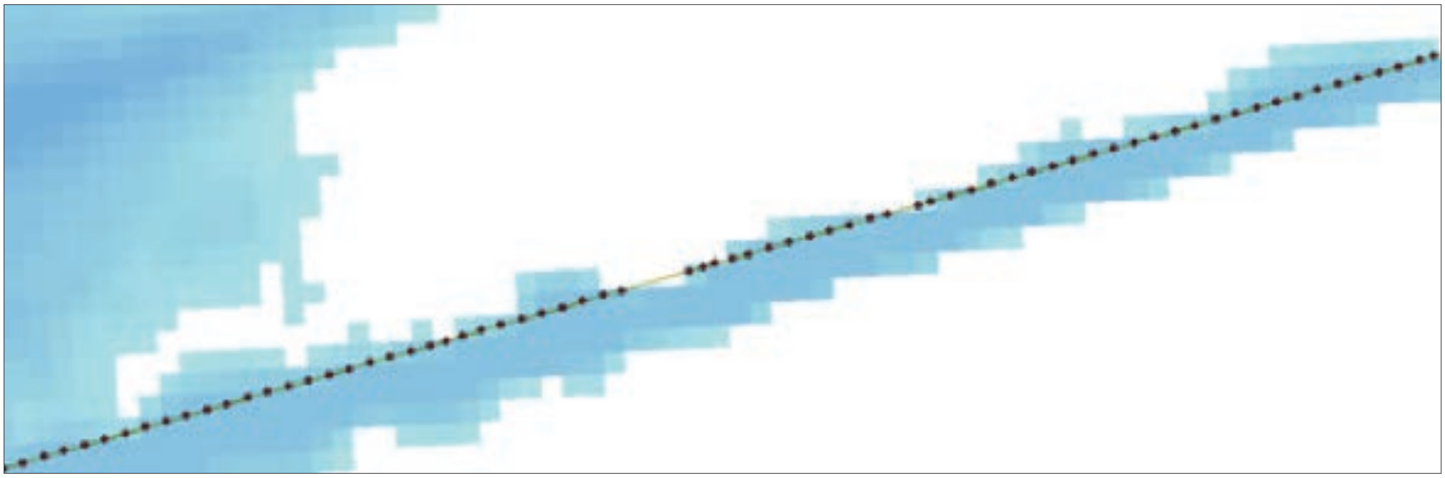
Exposure Assessment Methodology

This appendix outlines the GIS steps performed to assess statewide exposure to sea level rise, storm surge, and inland/riverine flooding for the Commonwealth of Virginia. As noted in Section 1.5, this method does not account for roadway vertical geometry which might be different than ground surface elevations.

- Sea Level Rise
  The following steps were performed to assess the maximum depth of sea level rise experienced by a roadway for a given scenario. Initially the "Zonal Statistics" GIS tool was considered for this analysis, however, it was discovered that this tool had limitations for processing overlapping lines or "zones" resulting in missing values. The following approach was used as an alternate:

  1. Conversion of sea level raster data to vector data
  2. Intersection of roadway network (VDOT LRS 19.1) with sea level rise vector data to capture only the roadways exposed
  3. Develop nodes along the exposed roadways at 1 meter internal (same resolution as raster cells)
  4. Sample the sea level rise raster data at each point on roadway network (VDOT LRS 19.1) by extracting values to points (Figure E-1).
  5. Summarize the result to obtain the maximum depth for each roadway segment in VDOT LRS 19.1.

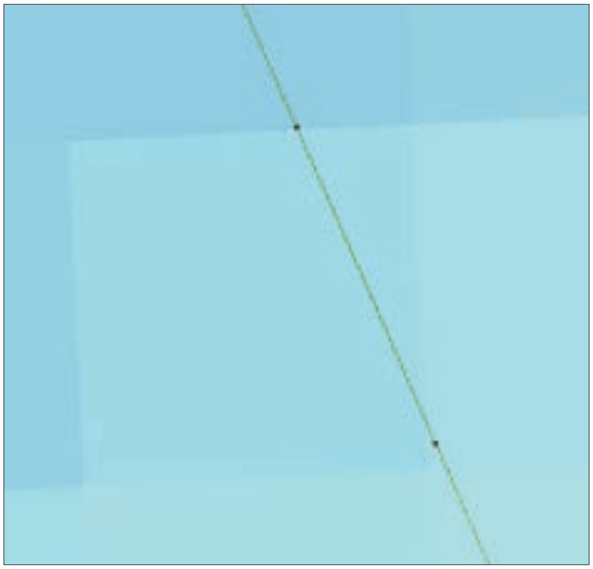
Figure E-1: Sampling of Sea Level Rise Data



- Storm Surge
  The following steps were performed to assess the maximum depth of storm surge experienced by a roadway segment for a given scenario. Initially the "Zonal Statistics" GIS tool was considered for this analysis, however, it was discovered that this tool had limitations for processing overlapping lines or "zones" resulting in missing values. The following approach was used as an alternate:

  1. Conversion of storm surge raster data to vector data
  2. Intersection of roadway network (VDOT LRS 19.1) with storm surge vector data to capture only the exposed roadway segments.
  3. Develop nodes along the exposed roadways at 30 meter internal (same resolution as raster cells)
  4. Sample the storm surge raster data at each point on roadway network (VDOT LRS 19.1) by extracting values to points (Figure D-2).
  5. Summarize the result to obtain the maximum depth for each roadway segment in VDOT LRS 19.1.

Figure E-2: Sampling of Storm Surge Data



The primary limitation of the method used for assigning storm surge exposure values to roadway segments is that using the same resolution for the line splits as the raster cells leads to the potential of a raster grid cell getting skipped depending on where it is crossed (Figures D-1 and D-2). This could result in a high value raster cell not being reflected in the maximum depth for a given segment, however this issue was not found to be widespread. This error could be reconciled on a subsequent run by shortening the line splits to less than the raster resolution. For example, the sea level rise analysis could be performed with segments of half a meter and the storm surge analysis could be shorted considerably.

This assessment defines exposure to inland/riverine flooding as meeting two conditions:

1. Being within a Location Relative to FEMA Flood Zone or buffer as outlined in Appendix C.
2. Exposed to a historical flood event as outlined in Appendix F.

- Inland/Riverine Flooding (IRF)
  This assessment assigned roadways as being either in or out of the floodplain as well as exposure to a historical weather-related event by means of a direct spatial intersect. Distance of flooded area was not considered at this time. All roadways that touch the floodplain and historical weather-related event buffer were scored a 1 and the rest 0.

APPENDIX F: UTILIZING HISTORICAL WEATHER EVENTS FOR INLAND/RIVERINE FLOODING EXPOSURE AND SENSITIVITY

The data for historic weather events was provided by the VDOT Traffic Operations Division via the VaTraffic (Virginia 511) reporting database. The weather data, including both "Traffic Incidents" and "Road Conditions" were queried from the reporting database by the unique identifier "WX_". All spatial points (latitude/longitude) with prefix "WX" were collected for the time period January 2015 to December 2020.

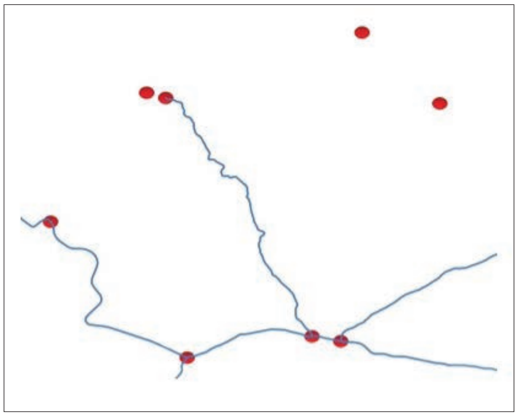
For the purposes of the VTrans Vulnerability Assessment, only "Traffic Incidents" or "Road Conditions" of the 'Event Type' shown below in Table B-1 were retained for the analysis:

Table F-1: Utilization of the VDOT Historical Weather Event Dataset

Category	Event Types (from data)
Flooding	'flood', 'Flood', 'Flooded', 'Flooding', 'Flooding / High Water'
High Tide	'Heavy fog & High Tide', 'High Tide', 'High tides', 'High Tides', 'Wind and High Tide', 'Wind and High Tides'
High Water	'High water', 'High Water', 'High Wind and Water'
Hurricane	'Coastal Storm', 'Hurricane', 'Hurricane Earl', 'Hurricane Irene'
Mudslide	'Mud', 'Mud in the road.', 'Mud Slide', 'Mudslide'
Washout	'Washout', 'Bridge Washout', 'Road Wash Out', 'Road washed out', 'Road Washed Out', 'Road Washed out/ pipe collapsed', 'Road Washout', 'Roadway is cracked and washing away', 'Roadway washout', 'wash out', 'Wash out', 'Wash Out', 'Washed out', 'Washed Out', 'Washed out bridge', 'washout', 'Washout'
Standing Water	'Standing water', 'Standing Water', 'Standing Water (Ponding)', 'Standing water and trees down'

The weather data described above was formatted a GIS point layer. A 400-foot buffer was developed for each point. Any roadway segments that intersect with any portion of a buffer were considered to be exposed to that historic weather-related event.

Image F-1: Example of Roadway Segments overlapping with Historical Weather Event Buffers



This layer was also used in the Sensitivity component development. The buffers were merged in order to determine the frequency of weather-related events in a single location, defined as any cluster of overlapping buffers dissolved into one GIS polygon feature. Each polygon was assigned the sum of the overlapping events as the frequency. This frequency was then assigned to the roadway segments that intersected with the merged polygon feature.

Image F-2: Example of Merged Weather Event Buffers Used to Determine Sensitivity