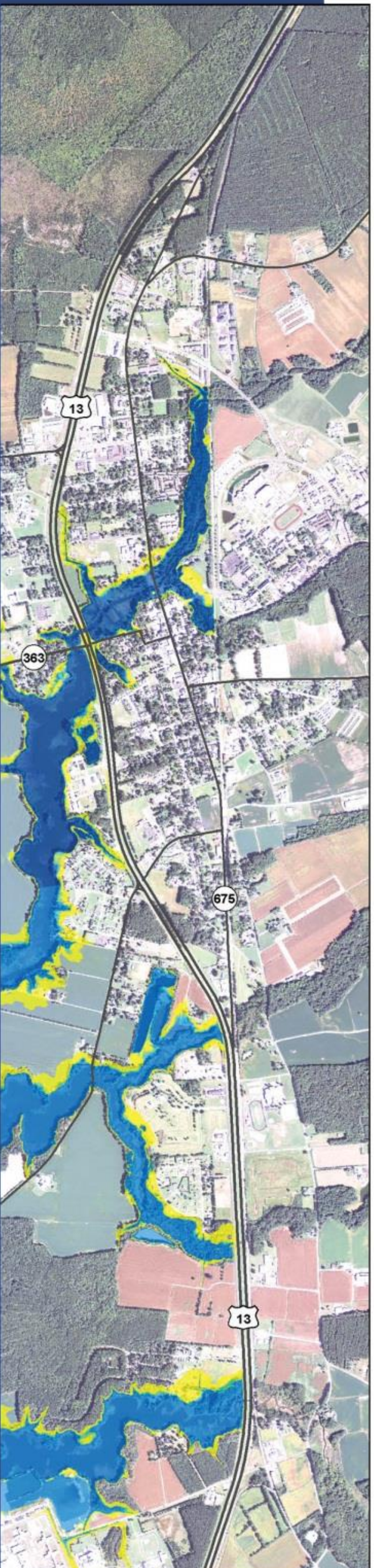

Maryland State Highway Administration

Climate Change Adaptation Plan with Detailed Vulnerability Assessment

Final Report – October 11, 2014

U.S. Department of Transportation
Federal Highway Administration

SHA State Highway Administration
Maryland Department of Transportation

About the Cover:

The graphic image on the cover is a Storm Surge Inundation Depth Grid using Hazus of a roadway segment in Somerset County, MD, which was part of the analysis to determine transportation asset vulnerability in this Pilot Study for the Maryland State Highway Administration.

Acknowledgements

The SHA Pilot Study is the result of a coordinated team effort between the Maryland State Highway Administration and its team members: Salisbury University Eastern Shore Regional GIS Cooperative and Stantec Consulting Services Inc. The SHA Pilot Study was led under the direction of Elizabeth Habic of SHA's Climate Change Program and Michel Ney Sheffer, GISP, CFM, SHA GIS Coordinator and developed in accordance with a grant from the Federal Highway Administration, Office of Natural Environment, Sustainable Transport & Climate Change Team.

Invaluable information was provided by the members of SHA's climate change working group, which included technical representatives from different SHA Divisions. A special thanks for the contributions made by each team member, which included: Dana Havlik, Highway Hydraulics Division, Karuna Pujara, Plan Review Division; Jeffrey Knaub and Lena Berenson, Structure Hydrology and Hydraulics Division; Erin Lesh, Data Services Engineering Division; and William Tardy, Environmental Planning Division. In addition, Salisbury University Eastern Shore Regional GIS Cooperative (ESRGC) was an integral part of the team and provided essential state-specific data using LiDAR, Hazus and GIS. Dr. Michael S. Scott, Ph.D, GISP, ESRGC Director, Dr. Arthur J. Lembo, Jr. Ph.D, Technical Director, ESRGC, and Brett Dobelstein, GIS Analyst were key contributors to the SHA Pilot Study by providing the Hazard Vulnerability Index and Hazus modeling data. Lastly a team of scientists and engineers (including climate change experts) from Stantec supported SHA to facilitate workshops, develop the framework, and to assess results of the vulnerability assessment, which cumulated in the development of this Final Report.

Disclaimer

How to Cite Reference

References were completed in accordance with the "National Highway Institute Style and General Standards Guide", a joint effort between NHI and FHWA, which recommends the *Chicago Manual of Style* formats for reference.

SHA Pilot Study, 2014. Maryland State Highway Administration Climate Chage Adaptation Plan with Detailed Vulnerability Assessment. Maryland State Highway Administration and Stantec Consulting Services Inc., 2014

Technical Report Documentation Page
Form Approved OMB No. 0704-0188

<table>
<tr><td>1. AGENCY USE ONLY</td><td>2. REPORT DATE
October 2014</td><td colspan="2">3. REPORT TYPE AND DATES
Final Report</td></tr>
<tr><td colspan="2">4. TITLE AND SUBTITLE
Maryland State Highway Administration Climate Change Adaptation Plan with Detailed Vulnerability Assessment</td><td colspan="2" rowspan="2">5. PROJECT ID NUMBER</td></tr>
<tr><td colspan="2">6. AUTHOR(S)
Maryland State Highway Administration</td></tr>
<tr><td colspan="2">7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Maryland State Highway Administration
707 North Calvert Street, Baltimore, Maryland 21202-3601
Stantec
6110 Frost Place, Laurel, MD 20707-2927 and
Salisbury University Eastern Shore Regional GIS Cooperative (ESRGC)
1101 Camden Ave, Salisbury, MD 21801</td><td colspan="2">8. PERFORMING ORGANIZATION REPORT NUMBER</td></tr>
<tr><td colspan="2">9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Maryland State Highway Administration (address above), and
Federal Highway Administration
1200 New Jersey Avenue, SE Washington DC, 20590</td><td colspan="2">10. SPONSORING/MONITORING AGENCY REPORT NUMBER</td></tr>
<tr><td colspan="4">11. SUPPLEMENTARY NOTES</td></tr>
<tr><td colspan="2">12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public on the FHWA website at
www.fhwa.dot.gov/environment/climate/adaptation/2015pilots/</td><td colspan="2">12b. DISTRIBUTION CODE</td></tr>
<tr><td colspan="4">13. ABSTRACT (Maximum 200 words)
This report presents the results of a Climate Resilience Pilot Project conducted by the Maryland State Highway Administration (SHA) and sponsored in part by the Federal Highway Administration (FHWA). The primary objectives of the Pilot Study are to assess the vulnerability of SHA's transportation assets (roads and bridges) to climate variables or stressors, to develop engineering approaches to address current and future climate induced risks and to make recommendations for policy or process changes to improve the resiliency of Maryland's highway system. This Pilot Study serves as a model from which SHA will be able to establish the framework and process for asset vulnerability assessment, prioritization, and adaptation in response to climate change. Another objective of the Pilot Study is interagency knowledge transfer and mutual capacity building. As such, the Pilot Study will share information on methods used and lessons learned with other state Departments of Transportations and government agencies for the purpose of expanding the transportation sector's ability to respond to ongoing climate change impacts across jurisdictions.

A framework was developed for the vulnerability assessment. Asset and climate information was compiled from a variety of reputable sources. Predictive models were developed using recent Light Detection and Ranging (LiDAR) information from the State of Maryland and Hazus modeling. Three primary assets were evaluated: bridges (including small structures), roadways, and small culverts/drainage conveyances. Each of the climate variables were reviewed and evaluated for their potential impacts on Maryland's transportation assets and it was determined that sea level change, storm surge from extreme weather events, and increased intensity in precipitation would have the greatest impact on the transportation assets under study.</td></tr>
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Executive Summary

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Executive Summary

> **Objectives of the SHA Pilot Study**
>
> (1) assess the vulnerability of SHA's transportation assets (bridges/small structures, roads, and small culverts/drainage conveyances) to climate variables or stressors,
> (2) develop engineering approaches to address current and future climate induced risks, and
> (3) make recommendations for policy or process changes to improve the resiliency of Maryland's highway system.

In the United States, Maryland is one of states most vulnerable to climate change due to its exposure to the Atlantic Ocean, Chesapeake Bay, and numerous tidal and non-tidal rivers. Most scientists agree, and the literature supports that the effects of climate change have begun. Increases in sea level, temperature, precipitation intensity, and extreme weather events will continue. According to the 2014 National Climate Assessment, the climate change trends described previously in the 2009 report have continued, and an increase in evidence has strengthened confidence in the conclusion that the warming trend is occurring. The report also summarizes that there is a clear increase in heavy precipitation and extreme heat events, and that such extremes will also rise in the future (Walsh, et al. 2014). The State of Maryland, led by Governor Martin O'Malley, has taken several important steps that demonstrate an understanding of the urgency and importance of preparing the state for the ongoing and predicted effects of climate change. Specifically, Executive Order 01.01.2007.07 created the Maryland Commission on Climate Change (*MCCC*). Since its institution, the *MCCC* has been responsible for several important and guiding climate change documents for the State of Maryland, with the state's 2008 *Climate Action Plan* being of highest importance. The *MCCC*'s *Climate Action Plan* has three spokes (research, adaptation, and reduction), and it focuses on three main questions:

- What can the scientific community and literature tell us about the nature of current and anticipated effects of climate change on the State of Maryland?
- How can the state adapt to current climate change impacts as well as those predicted to arise in the near future? Climate
- What can the state do to minimize its own greenhouse gas emissions, such that it can reduce Greenhouse Gas (GHG) loadings responsible for driving global warming? Recognizing the importance of reducing (mitigating) our GHG emission loadings, while we work to develop the additional resilience measures required to adapt to changes projected for our climate.

With this accepted understanding, decision makers are looking to identify the threats to their assets and identify adaptation strategies that can be put in place to minimize these impacts. The Maryland State Highway Administration (SHA) is taking a proactive stance by evaluating how impacts to its transportation infrastructure assets can be minimized if the extent of their climate vulnerability is understood and adaptation options are developed, assessed, and chosen for implementation. Transportation infrastructure can be greatly impacted by climate stressors, including but not limited to, an increase in temperature, increase or decrease in precipitation and the form of that precipitation (rain, snow, freezing rain), sea level change, extreme weather events, and more importantly the cumulative effect of several of these factors occurring simultaneously or in close succession. The purpose of the *SHA Climate Change Adaptation Plan with Detailed Vulnerability Assessment* (Pilot Study) is to assess the vulnerability of SHA's transportation infrastructure and identify adaptation measures, which is an objective in direct accordance with SHA's mission statement to "provide a safe, well-maintained, reliable highway system that enables mobility choices for all customers and supports Maryland's communities, economy and environment."

Pilot Study Objective

The primary objectives of the Pilot Study are to assess the vulnerability of SHA's transportation assets (roads, bridges and small culverts/drainage conveyances) to climate variables or stressors, to develop engineering approaches to address current and future climate induced risks and to make recommendations for policy or process changes to improve the resiliency of Maryland's highway system. This Pilot Study serves as a model from which SHA will be able to establish the framework and process for asset vulnerability assessment, prioritization, and adaptation in response to climate change. Another objective of the Pilot Study is interagency knowledge transfer and mutual capacity building. As such, the Pilot Study will share information on methods used and lessons learned with other state Departments of Transportations (DOTs) and government agencies for the purpose of expanding the transportation sector's ability to respond to ongoing climate change impacts across jurisdictions.

A framework was developed for the vulnerability assessment. Asset and climate information was compiled from a variety of reputable sources. Predictive models were developed using recent Light Detection and Ranging (LiDAR) information from the State of Maryland and Hazus modeling. Three primary assets were evaluated: bridges (including small structures), roadways, and small culverts/drainage conveyances. Each of the climate variables were reviewed and evaluated for their potential impacts on Maryland's transportation assets and it was determined that sea level change, storm surge from extreme weather events, and increased intensity in precipitation would have the greatest impact on the transportation assets under study. SHA is aware of the potential effect of temperature and the potential risks associated with other variables such as snowfall, but for the purposes of this study, the analysis focused on impacts to assets due to flooding.

Vulnerability Assessment and Screening

Once the parameters driving climate-induced vulnerability for assets within the Pilot Study were determined, an analysis was completed to assess the level of asset vulnerability to these climate stressors. Vulnerability assessment focused on two selected pilot counties: Anne Arundel and Somerset. These counties were selected based on their location and known exposure to the climate stressors driving transportation asset vulnerabilities. Somerset County, located on Maryland's Eastern Shore, serves as an example of what can be expected to occur for those low lying Eastern Shore counties between the Chesapeake Bay and Atlantic Ocean. The primary risk to Somerset County is posed by impacts of coastal inundation from sea level change and storm surge.

Anne Arundel County is a representative county that abuts the Chesapeake Bay and is at risk for impacts by sea level change, storm surge, and riverine flooding. The analysis was carried out on two levels, corresponding to different levels of detail and referred to as Tier I and Tier II analyses. The Tier I analysis was a desktop analysis that allowed screening out (elimination) of assets not likely to be impacted by climate change, and the development of a Climate Change Impact Zone to signify where assets could be considered potentially vulnerable. The Climate Change Impact Zone was created by overlaying the outer limits of the 2100 Mean Higher High Water sea level; Sea, Lake and Overland Surges from Hurricanes (SLOSH) for Category 3 hurricane; and the 100-year FEMA floodplain boundary. Anything outside of a 50-foot buffer of this Climate Change Impact Zone was considered a low risk of exposure to selected climate stressors. The higher detail, quantitative assessment was referred to as a Tier II analysis and involved evaluating the selected bridges using the United States Department of Transportation (U.S. DOT) Vulnerability Assessment Scoring Tool (VAST) and the identified roads using Hazard Vulnerability Index (HVI) . VAST is a Microsoft Excel based tool that provides an assessment of vulnerability based on the input of details about the assets and climate stressors. Parameters such as exposure, sensitivity, and adaptive capacity were used to calculate the assets overall vulnerability score for the considered assets.

The results from use of VAST and HVI will provide SHA with the information needed to determine which assets should move into the next phase of analysis, referred to as Tier III analysis. Tier III analysis involves higher levels of engineering and site-specific data to specify adaptation measures to address vulnerable assets on a site-specific basis. A holistic approach using more detailed hydraulic modeling and detailed design information is needed to fully assess vulnerabilities, recommend site specific adaptation measures, and to conduct a meaningful cost to benefits analysis of different alternatives. This Pilot Study does not include Tier III analysis, which will be a likely next step. The HVI and VAST results will ideally be used to aid SHA in prioritizing the transportation network sections at risk that should move into this next step.

Climate Stressors and Assets Evaluated

Climate stressors drive impacts that can alter the operating environment for transportation assets. These stressors therefore affect bridges/small structures, roadways, and small culverts/drainage conveyances differently and provide different challenges and vulnerabilities that require understanding and proactive planning. Understanding these climate-infrastructure interactions offers insight into an infrastructure asset’s adaptive capacity and potential options for adaptation strategies. For example, bridges are impacted by sea level rise, storm surge, and riverine flooding with potential to cause increased scour, overtopping, and corrosion from saltwater intrusion resulting in damage or reduced service life of the asset. The use of roads and bridges could be interrupted for periods of time due to inundation, rendering the asset unavailable for its intended purpose.

Engineering Workshops

A key component of the Pilot Study was to engage the knowledge and operational experience on SHA assets within SHA's engineering teams responsible for the transportation infrastructure under consideration. Two engineering/planning workshops were held to gain technical input into the process. The first workshop served as an introduction to the Pilot Study for the engineers and focused on vulnerability and adaptation. Three site specific scenarios were evaluated during the workshop to determine likely vulnerabilities and explore adaptation measures. The second workshop focused on risk and prioritization approaches. Similar to the first workshop session, three scenarios were presented and participants were asked to rank the severity of an asset failing from the given climate stressor. From this activity, a series of climate-infrastructure interactions were prioritized in terms of importance. These outputs from the second workshop helped to identify and rank the vulnerability indicators utilized within the VAST tool for the Pilot Study.

Vulnerability Assessment Methodology and Results for Two Pilot Counties

VAST and HVI was used to assess vulnerability of transportation assets and score or categorize the assets for the two counties. The screening performed by VAST examined the impact of climate change and extreme weather on bridges and small structures, and demonstrated how those assets or their components responded to changes in climate that may cause damage to the asset. HVI was used to identify those roadway segments at high risk.

This Pilot Study resulted in the development of a vulnerability assessment framework and methodology to assist SHA with prioritizing assets at risk to changes in climate. Potential data sources were immense and in some cases superfluous. The selected data sources were utilized because they provided direct information about the current and predicted condition of the assets. Data sources such as the SHA Geographic Information System (GIS), Highway Hydraulic Drainage Complaints and Investigations Database, Drainage and Stormwater Assets Inventory Database and Coordinated Highways Action Response Team (CHART) road closure information provided local knowledge about the assets and their historical exposure to flooding. Climate data specific to the Pilot Study counties allowed for the analysis to predict impacts caused by the climate stressors.

The Pilot Study resulted in a general understanding of the assets vulnerability to potential impacts from the climate stressors. Potential impacts were gathered from literature review and past events with the assets vulnerability to these impacts identified based on literature and the professional experience of transportation engineers and planners. The VAST indicators were also based on the indicator library that was developed for the *Gulf Coast Study Phase II* (U.S. DOT 2011). The workshop participants ranked the indicators based on how important the indicator is in relation to assessing an asset's vulnerability. A ranking of 1 indicated a low significance, ranking of 2 was a medium significance, and ranking of 3 was a high significance. These results were averaged, and the indicators with the highest averages were given more weight then the other indicators with low average scores. This exercise helped refine and define VAST to better match Maryland climate conditions, as well as the characteristics and data available about SHA's assets. If data for a significant indicator was found, the indicator was inserted into VAST and included in the analysis.

For the VAST assessment, precipitation exposure indicators lacked any modeled data that identified or separates assets that will be exposed to increased precipitation in the years 2050 and 2100. In contrast, location in the 100-year floodplain and the asset clearance were the defining factor for asset's exposure vulnerability. These values were very similar in many of the assessed structures, which explain the low variation in the overall vulnerability scores among assets. The results shows that the vulnerable structures are scattered around the counties and there is no certain trend in relation to structures location.

Key Lessons Learned

Many lessons were learned during the execution of the Pilot Study and most center on the challenges associated with data collection, development of climate stressors, and use of different tools developed by others for the assessment. Data on bridges is readily available and easily obtained using existing SHA GIS and National Bridge Inventory (NBI) data, while information on smaller culverts and drainage conveyances was limited and only available for those counties that had permit requirements for reporting under theNational Pollutant Discharge Elimination System (NPDES). The workshops conducted during the Pilot Study were a very useful way to get comprehensive feedback from the experienced personnel in all departments within SHA and the other transportation agencies. The asset specific historic information provided by maintenance staff was exteremly valuable and was utilized to validate the model results. Collaboration between policy makers, climate scientists, and engineering planners at all stages of policy making is crucial for leveraging the findings arising from the latest climate change scientific research into policies that will increase SHA's resilience and mitigate future impacts to its assets. Another lesson learned centers on the selection of climate stressors in the assessment of impacts. As explained previously the flood related stressors analyzed in this study were selected because they were determined to have the greatest impacts on Maryland's transportation infrastructure assets in terms of extreme weather events and sea level change. Other climate variables including temperature, snow and drought may have secondary effects on the transportation assets and would be considered in future studies.

Next Steps/Recommendations

> The implementation of recommendations in this Pilot Study will help SHA to fulfill its responsibilities as a steward of Maryland roadway network, meet the State's requirments for Climate Change, and satisfy the agencies mission to provide a safe, well maintained, reliable highway system that enables mobility choices for all customers and supports Maryland's environment.

The next steps focus on expansion of this study through additional targeted data collection and enhanced monitoring programs, an expanded range of study area (statewide), more detailed (Tier III) analysis on high risk areas, and integration into standards, policies, education, and public outreach. The Pilot Study identified required data and available data sources to assess an asset's sensitivity to a given climate stressor, and infrastructure characteristics to assess criticality based on the assets adaptive capacity. SHA's asset management systems should maintain these data sets in a format that can be used specifically for adaptation planning and vulnerability assessment. The Pilot Study vulnerability framework could be integrated with the asset management system and incorporated into SHA's practice as part of its climate change risk reduction program.

A comprehensive review of SHA's existing policies, procedures, and engineering design criteria is needed to identify changes to incorporate climate change considerations and adaptive measures into planning, design, operations, maintenance and implementation policies. Also, eventually a formal training series should be developed, appropriate for different audiences, to further educate the planners, design engineers and, maintenance staff on the impacts of climate change on transportation infrastructure and adaptation planning. This step will help inform the decision makers on time and cost effective techniques to design climate change resilient structures. Educating the staff also provides them the opportunity to provide feedback into the system regarding actual asset vulnerabilities and adaptation measures. Lastly, climate change adaptation should be a coordinated effort with information sharing occurring throughout the process. As part of the Climate Change Program, coordination with local planning departments would be helpful to gather information and share strategies on long-range planning to maintain mobility and acceptable levels of services to local residents. The implementation of these measures will help SHA to prepare for the future and work toward making their assets more resilient.

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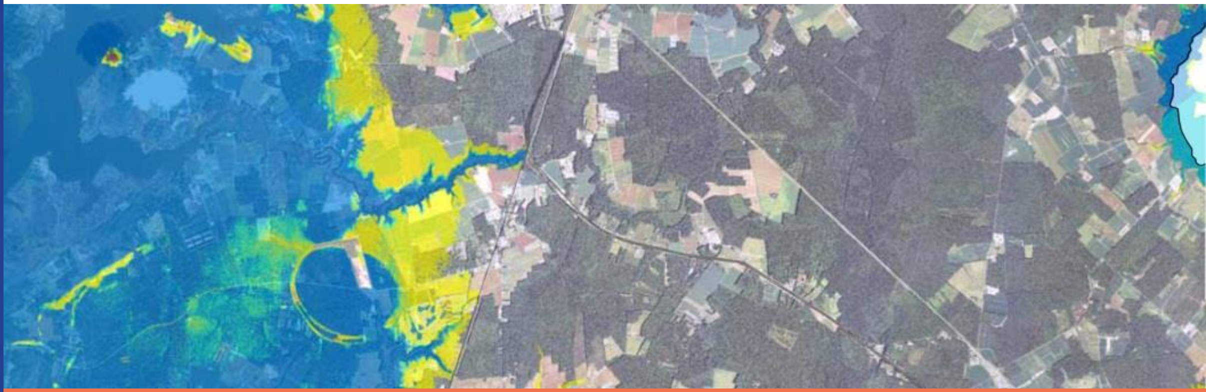
Introduction



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1 Introduction

Climate change is an issue at the forefront of the nation's conversation and more specifically is an important issue for the State of Maryland. Climate-induced impacts to the public infrastructure, particularly transportation networks, have been taking place globally with increasing severity, and many of these impacts occur within the State of Maryland. Maryland's Governor Martin O'Malley issued public statements on the serious need for proactive management of climate-related risks to infrastructure, and has taken several steps to demonstrate the importance of this issue to the state. The creation of the Maryland Commission on Climate Change (*MCCC*) and the resulting *Climate Action Plan* directs state agencies to implement climate change action plans into their procedures and policies. The *Maryland State Highway Administration Climate Change Adaptation Plan with Detailed Vulnerability Assessment* (Pilot Study) is an assessment of the vulnerability of transportation assets to specific climate variables and the identification of adaptation measures that can be implemented to reduce the risks associated with current and future climate impacts. The Pilot Study was completed with the assistance of a Federal Highway Administration (FHWA) grant and generally followed the approach outlined in *FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework Draft 2012* (FHWA Framework). The FHWA Framework incorporates the lessons learned from five previous pilot studies funded in part by FHWA. It is a synthesis of the various methodologies utilized in previous studies for use in customizing a vulnerability assessment utilizing state specific data.

Transportation infrastructure engineering design standards have traditionally considered historic weather patterns when setting design requirements for an asset's operating environment. An asset is defined in this document as a transportation element specifically roadways, bridges and culverts/small drainage conveyances. As the climate shifts away from historical patterns, engineering design for assets must account for the impacts of a wider range of climatic conditions. Increasingly, decision makers are looking at projected future conditions to consider the effects of climate change and manage the risks associated with these changes. They are also viewing proactive adaptation strategies to reduce asset vulnerabilities. These strategies focus on developing adaptive measures that can be taken to prevent and minimize system failures. Policy makers are starting to evaluate the cost of preventive adaptation measures versus the costs of reconstruction and clean up after an extreme weather event. Due to the expected long service life of transportation

About the State Of Maryland

The State of Maryland has approximately 7,920 linear miles of roadways, and it is projected that 156 miles, or 2% of the state-maintained roadways will be impacted by sea level rise in 2050. By 2100 the total is projected to be 371 miles or 4.5% of the state-maintained roadways. In addition to roadways, Maryland bridges and drainage structures will be impacted by sea level rise, changes in precipitation patterns, and extreme weather events.

infrastructure and the long lead time to secure funding, it is imperative that adaptive measures that reduce a system's vulnerability to climate change be implemented before further climate change effects are noticeable (GAO 2013). In this sense, the business case for implementing adaptive measures that will reduce damages and protect the expected service life of impacted infrastructure is becoming more attractive to infrastructure managers.

Changes in local weather conditions driven by climate change pose a variety of threats to transportation systems. Sea level change, increased precipitation, and increased frequency and severity of extreme weather events are all important examples. Greater precipitation can lead to increased risk of landslides, slope failures, floods, and erosion. Changes in temperature can result in pavement damage due to an increase in freeze-thaw events and softening of asphalt during extreme heat (GAO 2013). Sea level change has both a temporary effect (flooding of coastal roads and tunnels) and a long-term effect (erosion of coastal road bases and bridge supports). Lastly, heavy winds, precipitation, and storm surges that accompany extreme weather events can result in flooding (see Figure 1-1), damage to roads and bridges, and interruption of transportation services (National Cooperative Highway Research Program 2014).

Figure 1-1. Example of Coastal Storm Surge from Hurricane Sandy Topping Roadway in Oak Bluff, Massachusetts
Photo Source: (FEMA/Low 2012)

Maryland has 7,719 miles of shoreline (see Figure 1-2), making it extremely susceptible to the impacts of sea level change. Tide gauge records show that sea level has risen one foot over the last 100 years in Maryland, which is twice that of the global record, due in part to naturally occurring regional land subsidence **(Boesch, D F 2008)**. Maryland is the third most vulnerable state to sea level change, and impacts are already being felt along Maryland's coast **(Griffen, Halligan and Johnson 2008)**. Shoreline erosion is believed to be affecting 31% of the coastline **(Johnson 2000)**, and as sea levels increase it will result in increased erosion and vulnerability from storm events. Sea level change compounds coastal flooding, increasing the distance inland to which the storm water can extend, thereby increasing the vulnerability of larger numbers of inland assets. Inundation can have a large impact on the state's low lying areas and bay barrier islands and is already being observed in some areas of Dorchester and Somerset Counties. Lastly, sea level change effects other sectors of the economy due to salt water intrusion that could diminish freshwater drinking supplies, impact septic tanks, drain fields and tidal and non-tidal wetlands **(Boesch, D F 2008)**.

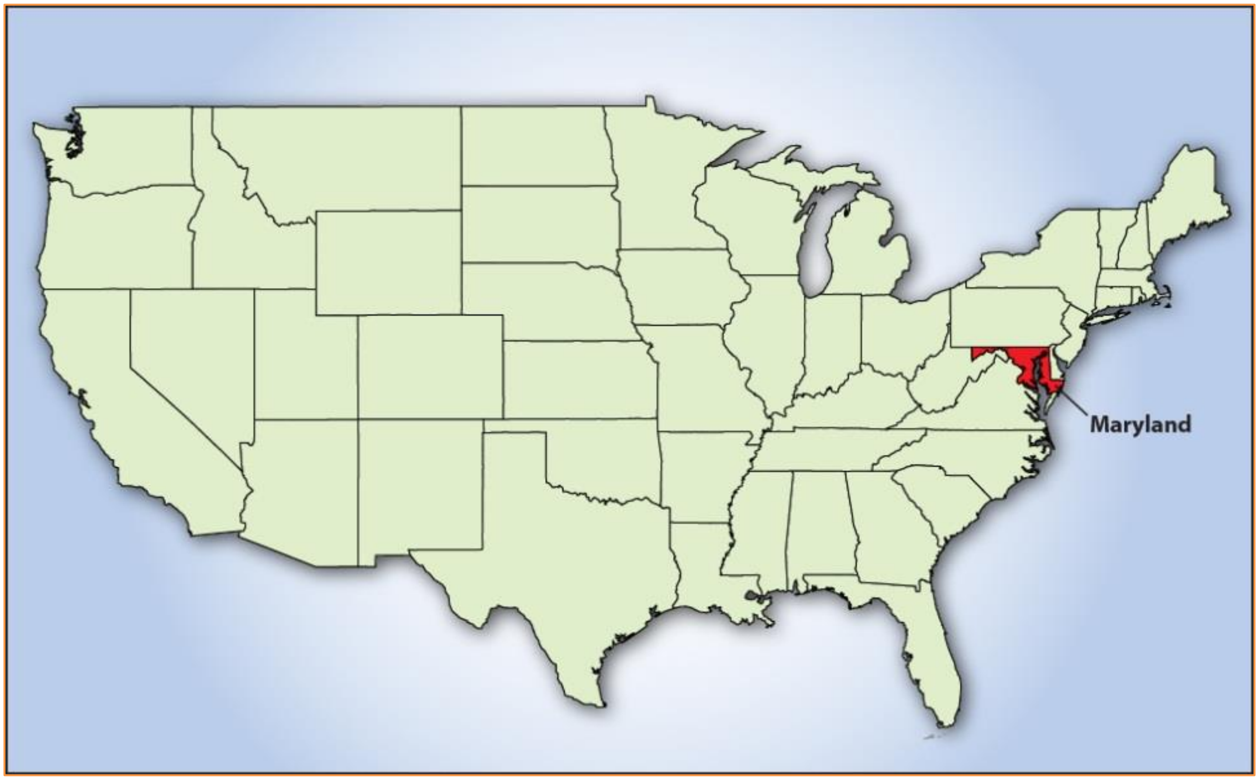

Figure 1-2. Location of the State of Maryland

This Pilot Study was initiated in 2013 to identify climate variables that could impact SHA's structures or bridges, evaluate the vulnerability of selected transportation assets, and develop engineering adaptive measures to address the identified vulnerabilities. The Pilot Study addresses the commitments made in the *Climate Action Plan* and further expounded upon in the SHA and Maryland Transportation Authority (MDTA) *Climate Change Adaptation Strategy* (SHA and MDTA 2013).

The Pilot Study is modeled after the FHWA Framework. Defining the objectives and scope of the project, assessing vulnerabilities, and integrating those vulnerabilities and corresponding adaptive measures into a decision making matrix were the key tasks completed within this vulnerability assessment.

1.1 Objectives of the SHA Pilot Study

The objective of the Pilot Study is to assess the vulnerability of SHA's transportation assets to climate stressors, develop engineering approaches to address current and future risks, and provide recommendations for policy or process changes to improve the resiliency of the Maryland highway system. The Pilot Study was initiated to further analyze vulnerability of the state highway network to flooding and develop adaptation options for the vulnerable locations. The Pilot Study serves as a model to establish a framework for assessing the vulnerability of Maryland's highway system to climate change risks, prioritizing those vulnerabilities, and then generating adaptation strategies. Application of a constant and repeatable framework will also provide the process to re-assess and review updated climate projections as they become available.

Specifically, the Pilot Study allows SHA to:

- Identify at risk transportation assets based on the existing weather related hazards and the projected impacts based on climate change.
- Establish a process for identifying the vulnerability of each asset type.
- Create a process for identifying adaptation measures that would reduce the vulnerability to climate change impacts for each asset and the method for identifying priority actions.
- Provide flexible methods to allow for revisions to the vulnerability assessment in the event of future availability of improved monitoring network data, and improved models for projected future climate conditions.
- Develop a list of asset failures and vulnerabilities specific to Maryland with corresponding adaptation practices that should be considered.
- Identify next steps and recommendations including changes in policy, procedures and operations to implement vulnerability assessment and adaptation measures for SHA's infrastructure statewide.

1.2 State of Maryland Directive and Adaptation Planning

In 2007, Governor Martin O'Malley's Executive Order 01.01.2007.07 created the Maryland Commission on Climate Change (*MCCC)*. The *MCCC* is responsible for advising the Governor and the General Assembly on all climate change matters and was tasked with developing an action plan to address the causes of climate change, to prepare for the impacts of climate change on Maryland and to develop benchmarks for the implementation of the Commission's recommendations (Maryland manual online).

Executive Order 01.01.2007.07 established three working groups: an Adaptation and Response a Working Group (ARWG), a Greenhouse Gas and Carbon Mitigation Working Group (MWG) and a Scientific and Technical Working Group (STWG). These three working groups were directed by the state to prepare a *Climate Action Plan* (see Figure 1-3). This Plan addresses three pivotal questions:

1. What can the scientific community and literature tell us about when and how climate change will affect Maryland's citizens and natural resources?
2. How can the state adapt to these predicted changes?
3. How can the state reduce their GHG emission and impacts thereby reversing the trend (Boesch, D F 2008)?

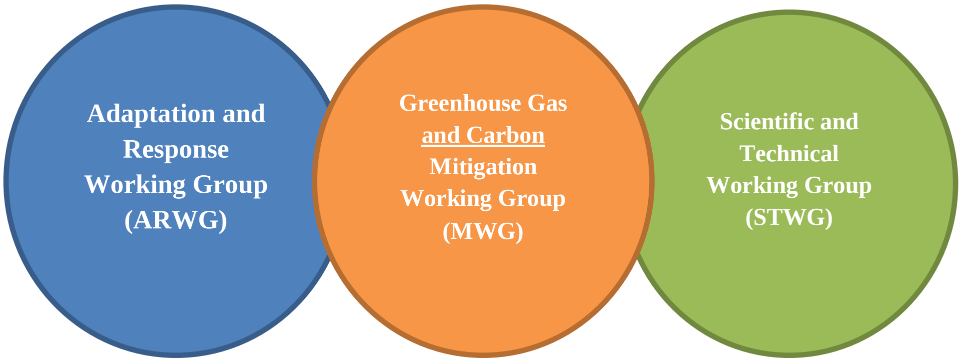

Figure 1-3. *MCCC* Three Main Working Groups

The focus of the ARWG is to develop adaptation strategies. The adaptation strategies outline the actions necessary to protect the environmental heritage, public safety, and future economic status of the state. The adaptation strategies focus on two main issues: sea level rise and environmental resilience. Sea level rise adaptation was addressed in the *Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change, Phase I Sea-level Rise and Coastal Storms*, published in 2008. Within this document, the Maryland Department of Transportation (MDOT) committed to assess Maryland's critical transportation facilities and their vulnerability to sea-level rise and extreme weather damage.

The *Climate Action Plan* and the subsequent documents produced by the *MCCC* address the predicted scope of climate change, the expected consequences from its impacts, and the response actions necessary to maintain services provided by its infrastructure. In 2012, Maryland's Governor Martin O'Malley issued the Climate Change and "Coast Smart" Construction Executive Order (EO 01.01.2012.29). The EO enacts a number of policy directives to increase the resilience of the State's investments to sea level rise and coastal flooding, as well as, direct the DNR, Chair of the MCCC Adaptation and Response Working Group, to provide "Coast Smart" construction guidance, including recommendations for the siting and design of State structures, as well as other infrastructure-based projects.

- The 2014 *Climate Change and Coast Smart Construction: Infrastructure Siting and Design Guidelines* contain recommendations to employ Coast Smart practices when constructing all new State structures, reconstructing or rehabilitating substantially damaged State structures, or making other major infrastructure improvements in Maryland's coastal zone, such as roads, bridges, sewer and water systems, drainage systems and essential public utilities. The term "structures" within Coast Smart is defined as walled or roofed buildings and does not include highway bridges. Coast Smart is defined as a construction practice in which preliminary planning, siting, design, construction, operation and maintenance, and repair of a structure avoids or minimizes future impacts associated with coastal flooding and sea level rise.

Further strengthening the Coast Smart plan, House Bill 615 established a Coast Smart Council in the Maryland Department of Natural Resources (DNR). The Council will be responsible for developing "Coast Smart" siting and design criteria related to sea level rise and coastal flood impacts on capital projects. Effective July 1, 2015, all state capital construction or reconstruction projects will be required to meet the siting and design criteria established by the Council**Invalid source specified.**.**Invalid source specified.**

1.3 Overview of SHA

SHA is a modal of the Maryland Department of Transportation, and is responsible for maintaining, improving, designing and constructing designated state roads in Maryland's 23 counties. The highway system is the primary linkage that connects key activity centers and transport amenities including; local roads, the Port of Baltimore, Baltimore/Washington International Thurgood Marshall Airport, transit centers and train stations (DOT 2012). The state is divided into seven SHA Districts to allow for a more localized coverage of service throughout the state.

SHA Mission Statement
"Provide a safe, well maintained, reliable highway system that enables mobility choices for all customers and supports Maryland's environment.

SHA is also responsible for many non-tolled bridges in the State of Maryland. This responsibility includes, but is not limited to: maintenance or replacement of the pavement structure, drainage facilities (*e.g.*, inlets and manholes), stormwater management facilities, and bridge structures (*e.g.*, super structures, substructure and foundations). SHA's transportation assets include more than 17,000 lane-miles of roadway and 2,576 bridges and small structures. Lane-miles represent the linear mileage down a route's center line, multiplied by the number of lanes for that route. SHA also maintains support buildings (*e.g.*, maintenance shops). The SHA system carries approximately 65 percent of the state's traffic and 85 percent of the state's truck freight movements**Invalid source specified.**. To give an order of magnitude of the size of SHA's programs, a breakdown of the allocations within SHA's overall budget for FY2014 is provided in
Table 1-1.

Table 1-1. SHA Budget for FY2014

Major Budget Item	Amount
Total Budget	$1.38 Billion
Major Projects Budget	$129 Million
System Preservation Budget	$742 Million
Development and Evaluation Budget	$57 Million
Operations and Maintenance Budget	$217 Million

1.4 Study Area (State of Maryland)

The unique geography and climate in Maryland creates specific challenges to transportation infrastructure, and drives the selection of certain assets, variables, and adaptive measures for the Pilot Study. The State of Maryland is located in the Mid-Atlantic Region on the eastern seaboard of the United States. Maryland's total land area is only 9,844 square miles, making it one of the smallest states in the country. However, Maryland is one of the nations most densely populated with 550 inhabitants per square mile (MDNR 2014). The state consists of six physiographic provinces that are categorized into different regions: the Atlantic Coastal Plain which is divided into the Eastern Shore and Western Shore; the Piedmont; and the Blue Ridge, Valley and Ridge and the Appalachian Plateau (see Figure 1-4).

Despite its small geographic footprint, Maryland has over 7,000 miles of shoreline and is therefore particularly vulnerable to coastal and climate related hazards. Tide gauge records show that Maryland's median sea level has risen by 1 foot over the past 100 years. This rate is twice the global average, and is due in part to naturally occurring land subsidence (Boesch, D.F. 2008). Maryland's average monthly temperatures currently range from the mid to low 20s (Fahrenheit) in the winter to the mid to upper 80's in the summer. Maryland receives approximately 41 inches of rain each year with relatively little seasonal distribution, and approximately 21 inches of snow every year, but the distribution average is geographically variable (Maryland State Archives 2013).

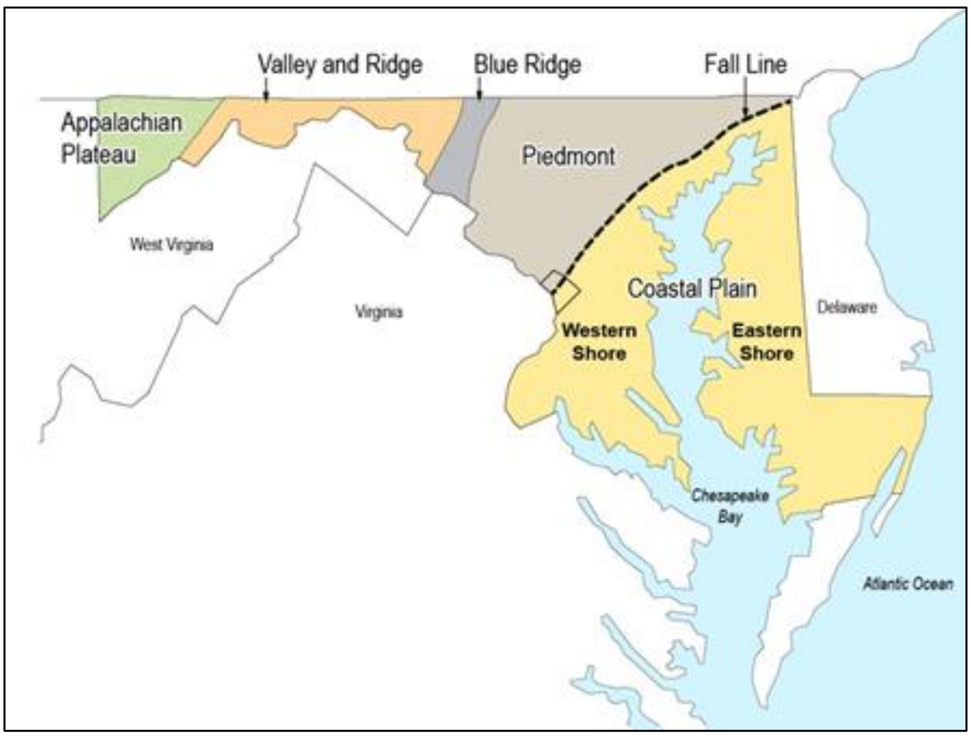

Figure 1-4. Physiographic Provinces of Maryland

Data Source: (STWG, 2008)

1.5 Scope of SHA's Pilot Study

SHA initiated the Pilot Study to further analyze vulnerability of the state highway network to flooding and develop adaptation options for the vulnerable locations. FHWA provided grant funds that required matched state funds for the Pilot Study. The 2013 FHWA grant supports two types of projects: Type I: Vulnerability Assessment Pilots and Type II: Adaptation Options and Integration Pilots. SHA was awarded funding for a Type II pilot. FHWA sponsored five (5) Type I pilot projects from a 2010 grant and utilized these pilot studies to draft the FHWA Framework for vulnerability and risk assessment analysis.

The design of the Pilot Study was staged to allow for soliciting and integrating input from multiple Offices within the SHA and to incorporate data obtained and lessons learned throughout the process. After the project initiation, data was collected from various sources including current literature, Geographic Information Systems (GIS) data layers, and online resources. Data gaps and the usefulness of the available data were evaluated. The objective of the literature review was to identify the relevant climate stressors through review of reports detailing transportation infrastructure-specific climate interactions. The focus of the Pilot Study on flood impacts lead to the identification of three climate stressors that met the criteria: sea level change, storm surge, and increase in precipitation frequency and intensity.

Although temperature was not a focus of this study, it is a climate variable with scientific data that supports future impacts to the state highway network. Temperature is expected to rise in the State of Maryland, but the extent is dependent on the rate of emission loading in the future. More consecutive days with temperatures exceeding 90 degrees Fahrenheit can soften asphalt causing rutting and buckling (GAO 2013). Increases in winter temperature extremes can result in acceleration of potholes due to increased frequent freeze-thaw cycles. Although the damage due to temperature can be substantial, it is not as eminent of a threat as the other three variables of concern. Because flooding was the focus of the pilot study, temperature was removed as an evaluated variable in this report.

1.5.1 Study Focus

Using the identified key climate stressors relevant for the State of Maryland, an assessment of the potential impacts by type of asset for Maryland's transportation asset was conducted. Three main transportation assets were the focus of this study; (1) bridges/small structures, (2) roadways, and (3) small culverts and drainage conveyances. These assets were selected based on the primary role they hold in the state's transportation system and their potential vulnerability to the selected climate stressors. Bridges and small structures were grouped based on the fact that they shared a common data source, the National Bridge Inventory (NBI). Smaller culverts and drainage conveyances were grouped because the main source of data was National Pollutant Discharge Elimination System (NPDES) asset data. The assessment looked at typical types of impact such as sea level change by type of asset in various combinations to achieve an understanding of the possible outcomes. The assessment also identified group failures by cause such as maintenance, age, utilities, or debris. Considering these vulnerabilities, those assets were identified most at risk to climate change and the resulting severe weather.

The assessment provided a clear understanding of the asset's vulnerability, allowing for strategies to be formulated reducing the risk to specific assets or a group of assets. Types of adaptive measures consist of various engineering based adaptations as well as maintenance and operational changes. Future the adaptive engineering options should consider a cost-benefit analysis and/or life cycle cost analysis compared to the cost of inaction based on the potential risks.

1.5.2 Planning Workshops

As part of the Pilot Study, SHA hosted engineering workshops on April 10, 2014 and May 15, 2014 (see Figure 1-5). The purposes of the workshops were to introduce a broader audience of SHA employees to the Pilot Study, and to ask for their expertise to guide the study. A total of 31 participants attended the first workshop on April 10th and a total of 29 participants attended the second workshop on May 15th. The SHA offices represented included: Office of Construction, Office of Highway Development, Office of Structures, Office of Planning and Preliminary Engineering, Office of Maintenance, District 7, Office of Operations and Traffic Systems, and Office of Materials and Technology.

Figure 1-5. SHA's Workshop on May 15, 2014

The purpose of the first meeting was to provide the audience with a background of the Pilot Study and to use the multidisciplinary engineering expertise to develop adaptation measures for three real scenarios of transportation assets that could be impacted by climate change and extreme weather. The purpose of the second meeting was to introduce the audience to FHWA's Vulnerability Assessment Scoring Tool (VAST), and to the concepts of risk assessment and asset prioritization. After participants were introduced to these topics, they were asked to rank VAST indicators and to conduct a risk assessment and asset prioritization exercise for one of three scenarios. Detailed Vulnerability Assessment of Anne Arundel and Somerset Counties.

Anne Arundel and Somerset Counties have large areas that are identified as Climate Change Impact Areas by the DNR resulting from their location on the Chesapeake Bay (see Figure 1-6). These areas have been identified as being susceptible to sea level change, storm surge, flooding, drought, and rising temperatures (MDNR 2014). Anne Arundel and Somerset were chosen to serve as representative counties because their location and exposure to the evaluated climate stressors represent two different scenarios within the state. Somerset County represents the conditions typical of counties on the eastern shore. Due to its location along the Chesapeake Bay and presence of larger tributaries within urban watersheds, Anne Arundel County serves as a representative county that will be affected by both sea level change and riverine flooding.

Figure 1-6. Location of Anne Arundel and Somerset Counties, Maryland

The eastern portion of Anne Arundel County is largely surrounded by tidal and non-tidal waterways (over 530 total miles of shoreline) leaving it vulnerable to the effects of sea level change, precipitation, and extreme weather events. It has approximately 4,810 lane miles of road that are maintained by SHA, the City of Annapolis, MDTA, and the Anne Arundel County Department of Public Works (Anne Arundel County 2008). Anne Arundel County prepared a *Sea Level Rise Strategic Plan* in November 2011. This plan was completed in partnership with the DNR through the Coastal Communities Initiative Program and evaluated potential sea level rise impacts and possible adaptation strategies (Anne Arundel County 2011). This study concluded that the County would experience minimal impacts under a 0-2 foot sea level rise scenario; however, 35 miles of local and collector roads are potentially at risk under a scenario of 0-5 foot sea level rise (Anne Arundel County 2011).

Somerset County is the southernmost county in Maryland, and is bounded along its entire western side by the Chesapeake Bay. Somerset County prepared the *Rising Sea Level Guidance Document* in 2008 using a grant from the DNR. This guidance document assessed the County's vulnerability to sea level rise and proposed adaptive measures to be implemented into the County's plans, development codes, and regulations. This guidance document identifies Route 362 leading to Mount Vernon, Route 363 leading to Chance and Deal's Island, and Route 361 leading to Frenchtown-Rumbly as areas that are currently experiencing some problems with flooding and are most likely to be severely affected by the year 2100 (URS and RCQuinn Consulting, Inc. 2008).

1.6 SHA's Study Team

SHA serves as the Pilot Study proponent, and the agency will ultimately use this document to guide future actions regarding its transportation assets. SHA supported monthly working groups and larger engineering workshops. In addition, SHA played a vital role in leading the data collection effort and being an active team member central to all decision making. SHA's project manager is the designated climate change program manager for SHA and led an interdisciplinary team of experts in developing this Pilot Study and Final Report. SHA assigned a working group to support the Pilot Study comprised of senior level staff from different SHA Offices.

Other team members included the Salisbury University Eastern Shore Regional GIS Cooperative (ESRGC), which provided predictive models using the most recent LiDAR information from the State of Maryland. Specifically, the ESRGC developed two statewide water surfaces for the 2050 and 2100 projected sea level change (SLC) and flood depth grids for coastal flooding/storm surge. Salisbury University also developed riverine flood services for drainage basins as well as the Hazard Vulnerability Index. The methodology section presented in Chapter 2 provides a more detailed description of the methodology employed by the ESRGC for the Pilot Study.

Stantec Consulting Services Inc. is the prime consultant for this Pilot Study and for the preparation of this Final Report. Stantec was tasked with identifying the climate stressors, conducting the vulnerability assessment for each pilot county, facilitating the working group meetings, and supporting SHA to prepare the Final Report. The Stantec project team is made up of experts in the fields of climate change, coastal engineering, hazards mitigation planning, GIS, hydraulic engineering, regulatory permitting, and highway/bridge design. Roles and qualifications of SHA, Salisbury University, and Stantec team members can be found in Chapter 8.

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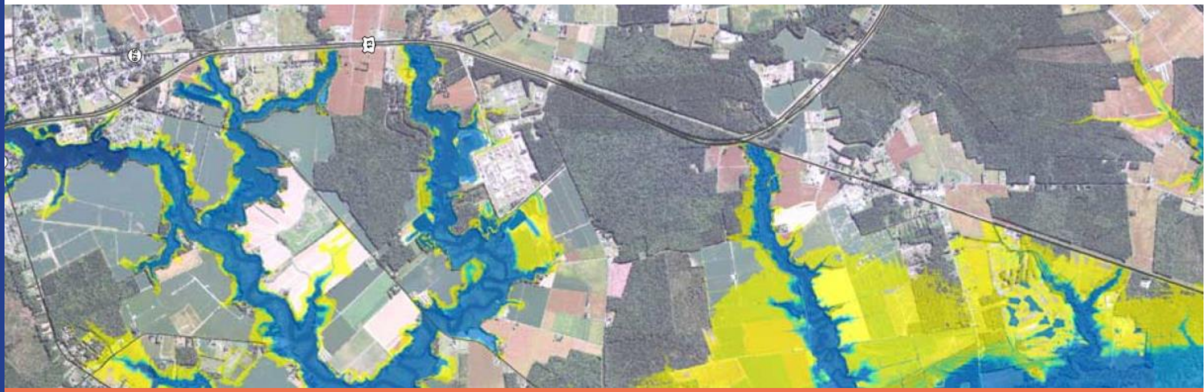
Chapter 2

Vulnerability and Adaptation Framework and Methodology



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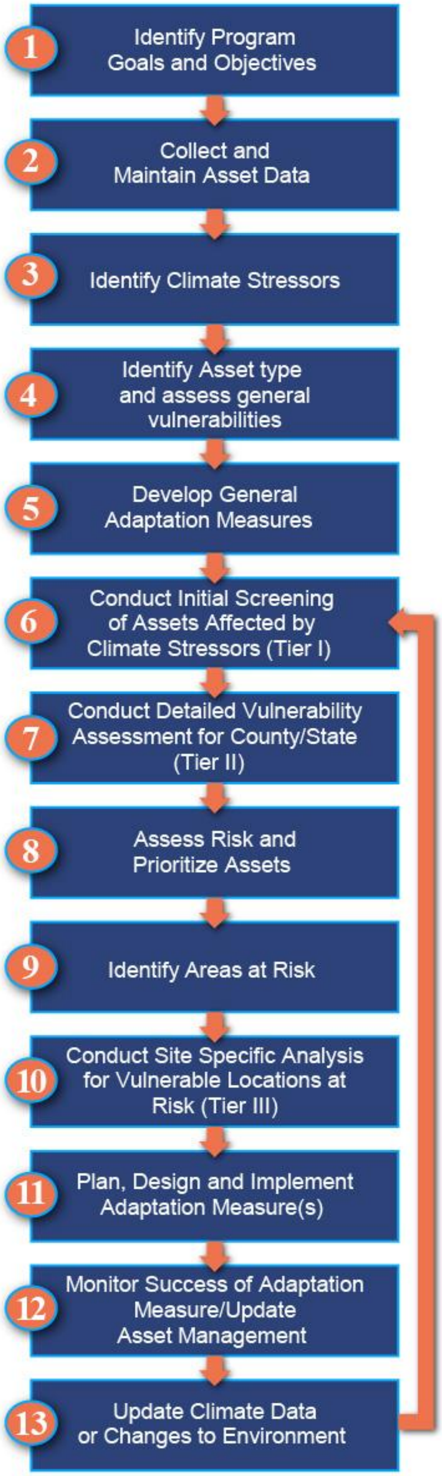


Figure 1-1. Vulnerability and Adaptation Framework developed for the Pilot Study

2 Vulnerability and Adaptation Framework and Methodology

2.1 General Framework

A successful planning framework should be capable of organizing not only information, but also the activities which generate and review that information. To create the framework for this Pilot Study, SHA used a wide variety of resources, including: *FHWA Climate Change & Extreme Weather Vulnerability Assessment Framework*, *NCRHP Report 750 Volume 2: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report*. The framework is a step-by-step approach for assessing climate change impacts at a broad, systems-level perspective and then using that assessment to identify individual elements of the highway system likely to be impacted by climate change (see Figure 1-1).

In recognition of the rapid progression of climate change science, the Pilot framework and methodology is structured to allow revisions. This objective is intended to allow for updates to the vulnerability assessment at appropriate future intervals as new data or improved projected climate datasets become available. The framework provides sufficient details and documentation of assumptions to help facilitate this process.

A short description of each step within the framework is provided in the following sections and the results of each framework step completed as part of this Pilot Study are presented in Chapters 3, 4, 5, and 6. Steps 1-9 were completed within the timeframe of the Pilot Study for all assets in the two pilot counties.

Step 1 - Identify Program Goals and Objectives

Starting with the goals and objectives outlined in *SHA/MDTA Adaptation Strategy*, objectives were reviewed and tailored specific to climate change vulnerability and adaptation. The program goals and objectives are described in Section 1.1 of this report. The objectives are considered as guidance to help to identify the scope of the vulnerability assessment and the goals highlight what is most important for SHA to accomplish as part of its adaptation planning.

Step 2 – Collect Asset Data

The level of detail and accuracy of the vulnerability assessment hinges on the data available and its ability to describe an asset's vulnerability to the different climate stressors. Geographic Information System (GIS) software was used to organize, present, and analyze data in a single, cohesive format. SHA sources of data include the asset data warehouse, the National Pollution Discharge Elimination System (NPDES) database, road closure records compiled by the Coordinated Highway Action Response Team (CHART), and SHA's Highway Hydraulics Complaint Database. The National Bridge Inventory (NBI) was a useful source of data.

Step 3 – Identify Climate Stressor (Variables)

Using methods described later in this chapter, climate stressors were identified specific to the study area. In many cases, existing state or regional information, such as the *Maryland's Sea Level Change Report*, formed the foundation of these analyses. To maximize the assessment of the study area, SHA chose to update data with more site specific information. The augmented data came from recent Light Detection and Ranging (LiDAR) surveys, and future climate projections generated by the Coupled Model Inter-comparison Project (CMIP) Climate Data Processing Tool (CDPT), which was used to project changes in precipitation and temperature conditions. Detailed methodologies used for developing the climate stressors are presented in Section 2.2.

Step 4 – Identify Asset Type and Assess General Vulnerability

Once SHA identified the climate stressors most important in the study area, the next step was to identify the types of highway assets that are likely to be exposed and sensitive to these stressors. This review identified three main groups of assets: bridges and small structures (*e.g.* culverts); roadways; and small drainage conveyances (e.g. drain pipes). These categories were chosen based on the type of service they provide (*e.g.* managing stormwater), their typical siting characteristics (*e.g.* over bodies of water), and how they react to climate stressors. Once asset types were selected, a general (non-site specific) vulnerability review was conducted for each asset category. Based on the results of the review, a table of potential asset failures was developed for each asset category.

Step 5 – Develop General Adaptation Measures

Using the table of asset failures developed in Step 4, a list of adaptation options were researched and developed that could be implemented within the context of Maryland's geography, climate stressors, and highway management practices. This list is intended to provide a starting point for transportation planners and engineers during the development of more site specific adaptation measures (see Appendix A).

Step 6 – Conduct Initial Screening of Assets Affect by Climate Stressors (Tier I)

SHA is responsible for a very large number of assets, and some will be more impacted by climate stressors than others. To explore how the risk of impact is distributed across the state, SHA conducted a Tier 1 initial asset screening. This initial screening utilized digital maps and GIS programs, rather than site vests and field surveys, to identify important environmental conditions. As a result, screenings such as this are often referred as a "desktop level" reviews. Based on the results of the Tier 1 screening, a Climate Change Impact Zone was developed. The datasets which most strongly drive the identification of the Impact Zone include the 2100 mean higher high water sea level change projections; Sea, Lake and Overland Surges from Hurricanes (SLOSH) models for a Category 3 hurricane; and FEMA 100-year floodplain boundaries. Figure 2-2 and Figure 2-3 present the Climate Change Impact Zones developed for Anne Arundel and Somerset Counties in Step 6. Since the focus of Pilot Study was on water related climate stressors (sea level, storm surge, and increased precipitation intensity) anything outside of this zone was considered to be at low risk of exposure to these climate stressors and accordingly, could be eliminated from the more detailed analysis in Step 7.

Step 7 – Conduct Detailed Vulnerability Assessment by County/State (Tier II)

At this stage of the assessment, the focus transitions from a more general analysis to a more detailed quantitative analysis of individual assets (referred to as a Tier II assessment). To utilize the best asset data available, SHA focused the analysis on the bridge and small structure asset group within the two pilot counties. The assessment was conducted using FHWA's Vulnerability Assessment Scoring Tool (VAST). VAST is a Microsoft Excel-based analytical tool that uses key asset information (*e.g.* bridge age), climate data (*e.g.* flood elevation), and other vulnerability indicators (*e.g.* current frequency of flooding) to develop a composite vulnerability score. The scores VAST generates can be broken down into three components: asset exposure, sensitivity, and adaptive capacity. To complement VAST, SHA also produced a Hazard Vulnerability Index (HVI), as described in Section 2.5 for roadways within the two pilot counties which fall within the Climate Change Impact Zone. Additional GIS reviews were also conducted for small culverts/drainage conveyances.

Step 8 – Assess Risk and Prioritize Assets

Using VAST, SHA refined the Tier II vulnerability assessment by assigning weighting factors to different vulnerability indicators. Based on these weights, VAST generated a preliminary risk assessment for the bridges and small structures in the two pilot counties. The detailed methodology used for the application of VAST is provided in Section 2.2.4. In addition, the HVI was used to populate maps showing categorical risk scores for roadway segments in the pilot counties. Due to limited information regarding site hydraulics, risk assessments for small drainage conveyances could not be completed at this time.

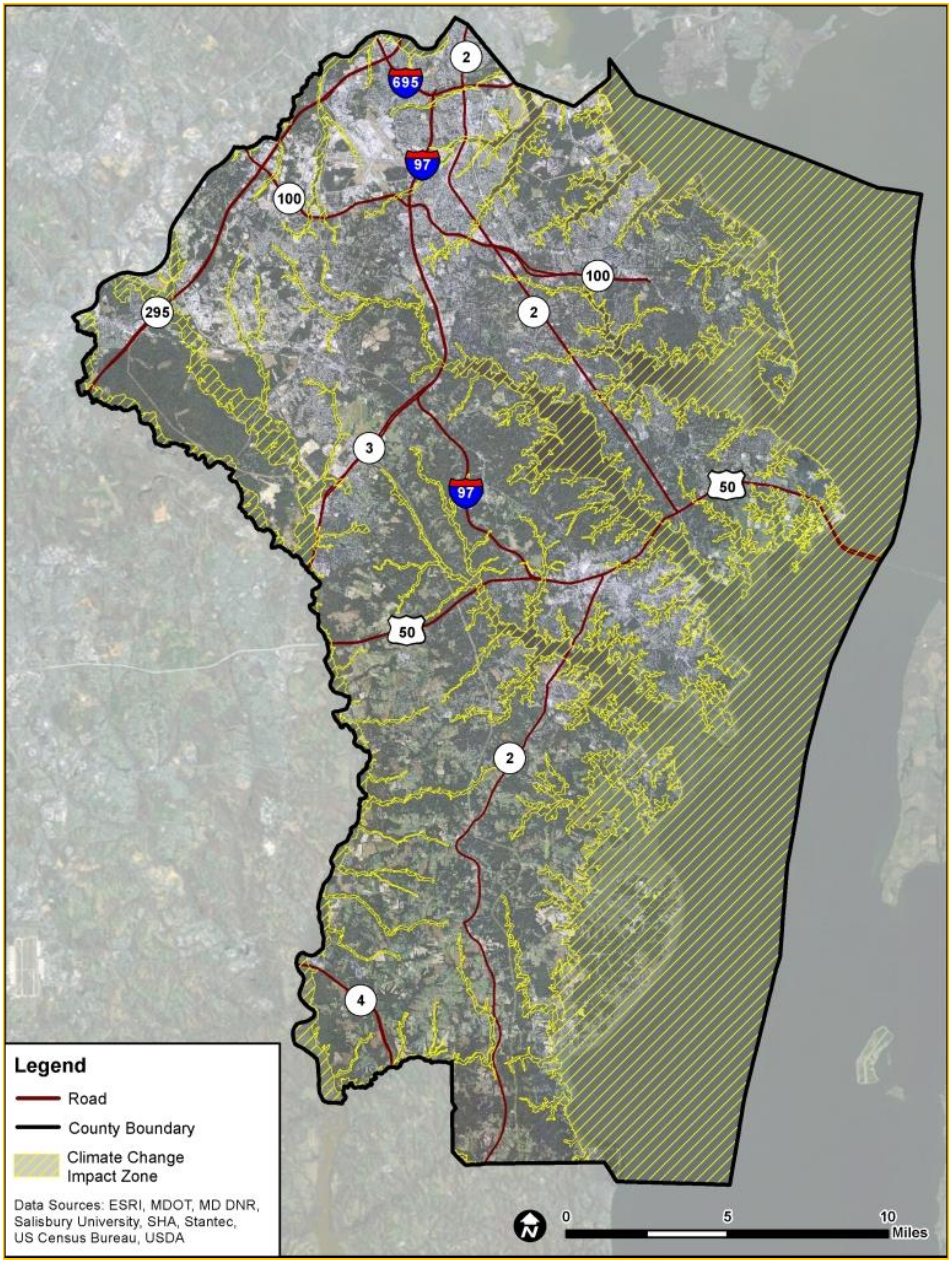


Figure 2-2. Climate Change Impact Zone for Anne Arundel County, MD

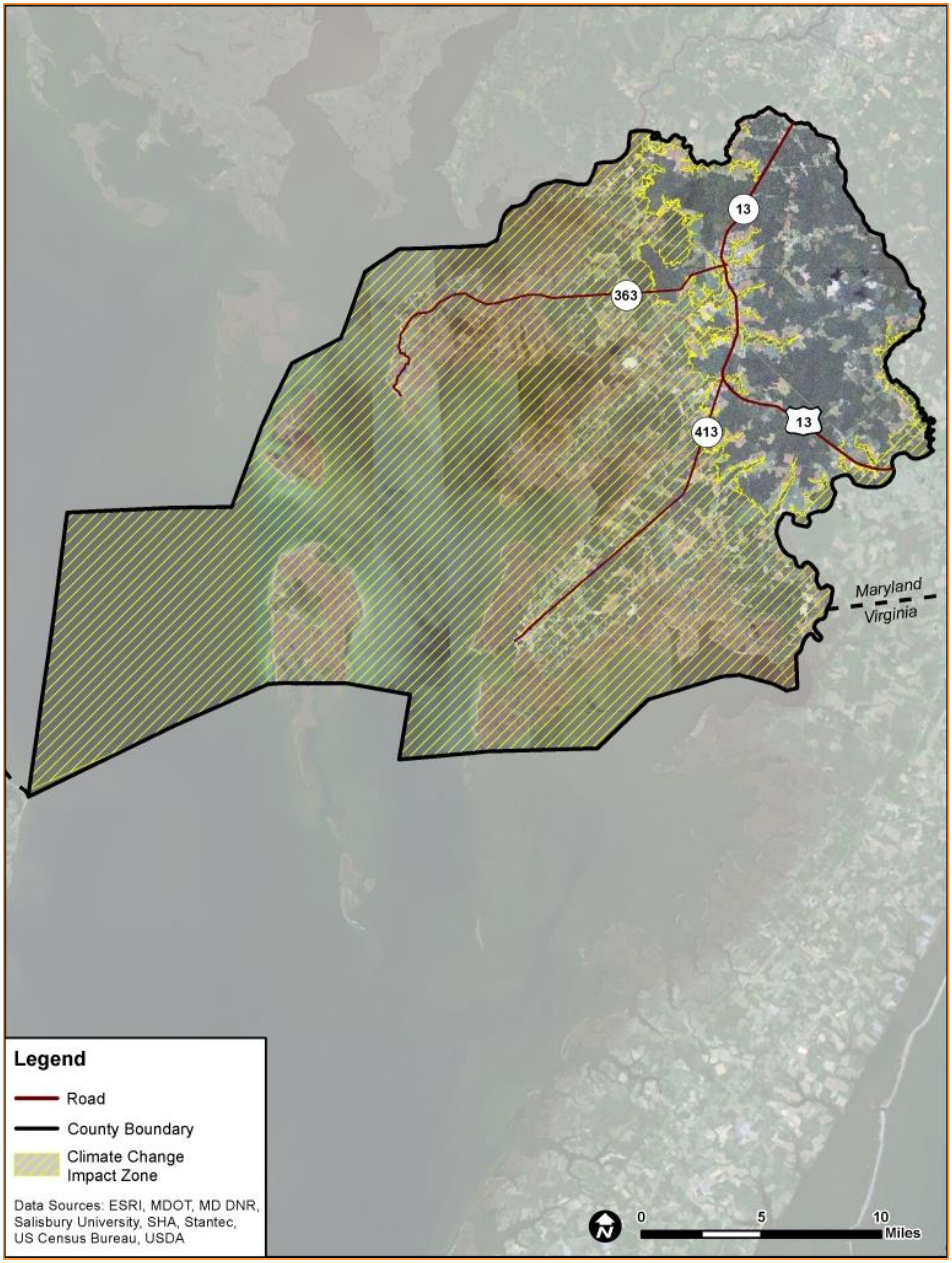


Figure 2-3. Climate Change Impact Zone for Somerset County, MD

Step 9 – Identify Areas at Risk

Once risks were prioritized, the assessment proceeded to identify those areas at high-to-medium risk within the pilot counties. Assets in the areas of high-to-medium risk were plotted on a map. Geographic areas with a large number of high-to-medium risk assets were determined to be "vulnerable locations at risk". Steps 1-9 were completed within the timeframe of the Pilot Study for all assets in the two pilot counties.

Step 10 – Conduct Site Specific Analysis for Vulnerable Locations at Risk (Tier III)

Climate Stressors rarely affect only one asset along a highway. In most cases, the vulnerability of one asset translates to vulnerability across a series of related highway systems. In recognition of this interdependence, Step 10 would focus on all the highway systems operating within a site (roads, bridges, and culverts) rather an individual asset. Specifically, Tier III analysis would include a detailed vulnerability assessment and adaptation feasibility study for a specific area using more detailed hydraulic modeling and detailed engineering information from as-built plans and survey information. Tier III represents the detailed engineering analysis required to confirm the feasibility and effectiveness of a given adaptation measure in a site-specific context.

Step 11 – Plan, Design, and Implement Adaptation Measures

After a detailed Tier III analysis is complete, the project would proceed with more detailed planning, design, and construction of recommended adaptation measures. Recognizing that adaptation measures might be non-traditional or result in added environmental impacts, early coordination with the regulatory agencies and public outreach should occur to educate stakeholders on the purpose and need for the adaptation measure. Step 11 could also include a Cost-to-Benefits Analysis to test the feasibility and relative strength of adaptation measures.

Step 12 – Monitor Success of Adaptation Measures/Update Asset Management

In Step 12, performance goals would be developed and incorporated into a larger asset management system and planning tool. Real time data on asset performance or failures during, or immediately following, severe weather events could be used to provide valuable planning and design information.

Step 13 – Update Climate Data and Changes to the Environment

The Pilot Study framework is intended to be a "living document" that is routinely updated. Revisions could be triggered by new data, improved monitoring networks, or advances in climate modeling providing improved model output. The frequency of revision would likely be driven by advances in climate science and new climate change policies. The essential steps for such a revision process could include updating the exposure, sensitivity, and adaptive capacity indicators in the VAST analysis and reassessing assets to determine those at high risk.

2.2 Methodologies

2.2.1 Data Collection (GIS)

Information derived from SHA's Asset Management is a key component to assessing vulnerability. For the Pilot Study, asset information was compiled from a variety of sources including the Maryland Department of the Environment (MDE) Bridge and Culvert Survey Database and the Federal Emergency Management Agency (FEMA) National Flood Hazard Layer GIS service. This information was used to populate VAST and to develop the HVI. Table 2-1 provides a list of the key data sources and their application.

Table 2-1. Asset Data Used for Vulnerability Assessment

Data Source	Asset Information	Usefulness
Average Annual Daily Traffic	Total number of vehicle traffic of a roadway divided by 365 days	Provides the mean number of vehicles using an asset (*e.g.*, bridge) which is a simple measure of how much a road is used. This is useful for estimates of disruption
General SHA GIS Data	SHA structures (bridges and culverts), transportation center lines, and points of interest (hospitals, police stations, fire stations, SHA maintenance facilities, etc.)	Identifies locations and attributes of structures, roads, and facilities that could be the focus points of a climate change study
Highway Hydraulic Complaint Database	Statewide record of any public complaint on drainage infrastructure performance and functionality	Determine current problem areas that could be exasperated by climate change
Road Closures	Reported state road closure records	When correlated with storm events, road closures can help identify problem flooding areas that could be exasperated by climate change
FEMA National Flood Hazard Layers	Spatial information of a probabilistic 100 year flood occurrence	FEMA riverine and coastal flood areas with current flood risks can identify areas at risk with climate change
National Bridge Inventory Database	Bridge data including condition ratings, scour rating, age of bridge, and repair information	Information used to rank assets within VAST

Data Source	Asset Information	Usefulness
NPDES Asset Information	National Pollutant Discharge Elimination System drainage assets and stormwater management facilities inventory database.	Information used to rank assets related to small culverts, drainage conveyances and water quantity control facilities
SHA Functional Classification of Roads	Maryland roads identified as one of seven FHWA Functional Classifications (*e.g.*, 1 – Interstate, 7 – Local)	Used to weight the road importance for the HVI analysis. Determine what roads and corresponding structures are SHA assets
Salisbury Sea Level Change (SLC) Depth Grids	Depth grids for projected sea level change in Anne Arundel and Somerset Counties for 2050 and 2100. Based on Hazus output.	Used to create SLC inundation areas and depths for structures and roads within Anne Arundel and Somerset Counties
Salisbury Storm Event Depth Grids	Depth grids for probabilistic storm events in Anne Arundel and Somerset Counties at projected SLC conditions for 2050 and 2100. Based on Hazus output.	Used to create SLC inundation areas and depths for structures and roads within Anne Arundel and Somerset Counties.
US Army Corps of Engineers Sea Level Change Values	Sea level change Values for Tidal Stations in Maryland including Annapolis (Anne Arundel County) and Cambridge (Somerset County). Mean sea level and mean higher high water values for 2050 and 2100 provided in feet above NAVD 1988.	Used to create Salisbury's sea level change and storm event depth grids. Provided the basis for SLC predictions for 2050 and 2100 in Anne Arundel and Somerset Counties.
SHA Points Structures 2012 and Clearance, Office of Structures	Inventory of SHA, county and local structures throughout Maryland. Location, average daily traffic (ADT) and other information provided for each structure. Clearance provided in 10 foot ranges.	Used to identify structures in Anne Arundel and Somerset Counties. Clearance data was used to filter bridges sufficiently above projected SLC and probabilistic storm event flood levels.
SHA Road Centerline Data	Inventory of SHA, county and local roads throughout Maryland. Provides spatial data for roads. Includes evacuation route information.	Used to identify roads included in evacuation routes. Centerline Data was combined with SHA Points Structures 2012 and available DEMs to estimate structure heights to a higher granularity than the provided 10 foot range.

Data Source	Asset Information	Usefulness
Digital Elevation Model (DEM)	Elevation data for Maryland. LiDAR-based data typically collected individually for each county. Provided in feet.	Used as the basis for current land feature elevations. Input into Hazus for SLC and Storm Event inundation determinations. Combined with SHA Road Centerline Data and SHA Point Structures 2012 to help estimate structure heights.
Maryland Department of the Environment (MDE) Bridge and Culvert Survey Data	Detailed Bridge and Culvert data for many SHA Structures. Available information includes Upstream and Downstream photos, deck thickness, structure material, overall height, under clearance, and stream information.	Used to help calibrate and verify estimated GIS-derived structures information including height and clearance. Suggested for use in more detailed analysis of structures. Limited to some, not all, structures included in this study.

2.2.2 Policy and Literature Review

There is a growing body of reports and guidance documents related to climate change, the vulnerability of transportation assets, and proposed adaptation measures. These reports are from federal agencies, the National Research Council, state agencies and local Metropolitan Planning Organizations (MPO). Maryland, as a leading state in the nation regarding climate change, has produced numerous guidance documents to support local and state governments with managing their infrastructure risk related to climate change. Below are summaries of several of the most important documents used for the Pilot Study.

The FHWA *Climate Change & Extreme Weather Vulnerability Assessment Framework* is a guidance document for transportation agencies that wish to assess the vulnerability of their infrastructure assets to climate change and extreme weather events. It provides an outline for completing vulnerability assessments. The three main steps in the FHWA Framework are the following:

1) Define study objectives and scope
2) Assess vulnerability
3) Incorporate results into decision making.

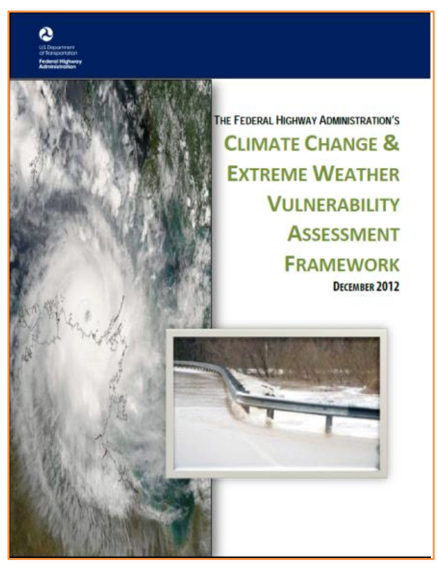


Figure 2-4. FHWA Framework for Vulnerability Assessments

The FHWA Framework was informed by several FHWA funded pilot studies. The first study, *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I* (known as The Gulf Coast Study) was published in 2008. The study is a regional study of climate change's effects on all modes of transportation along the Gulf Coast (from Galveston, TX to Mobile, AL). Climate stressors reviewed in the study include expected increases in temperatures, frequency of extreme precipitation events, and increases in sea level. Phase 2 of the report is currently in final review and will be available to the public later this year.

Following the release of Phase 1 of the Gulf Coast Study, FHWA created the grant program for this Pilot Study. Prior to the current round of funding, five pilot studies were conducted and reported on in 2011. These five studies were conducted in the San Francisco Bay Area in California, Hampton Roads in Virginia, two major corridors in New Jersey, the entire State of Washington, and the island of Oahu. Each of the five studies tested the application of the FHWA Framework as well as FHWA's Risk Assessment model:

- *Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project* evaluated the risk of the San Francisco Bay Area to sea level rise and climate change impacts. The goal was to increase the level of preparation and resiliency related to these impacts for the Bay Area communities.
- *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot*, focused on assets in the Hampton Roads region of Virginia. The analysis used four types of priority settings: 1) future transportation projects, 2) existing transportation assets, 3) long-term multimodal transportation policies, and 4) transportation analysis zones. The study resulted in a significant reprioritization of planned expenditures for Virginia.
- *Climate Change Vulnerability and Risk Assessment of New Jersey's Transportation Infrastructure* involved collaboration between several state agencies and Metropolitan Planning Organizations (MPOs). Two study areas, one in coastal New Jersey and a second in the Northeast Corridor, were selected. The report, among other suggestions, suggested that more detailed data should be collected on weather related disruptions, bridge heights, and culvert failures.
- The *Climate Impacts Vulnerability Assessment* is a report of the WSDOT's statewide Pilot Study. The geographic size of the study and its use of 14 workshops made it comparable to the size and scope of the Gulf Coast study effort. The assessment was determined to be a vulnerability assessment and not a risk assessment because it did not assign probability of an impact occurrence.
- The *Oahu Metropolitan Planning Organization Transportation Asset Climate Change Risk Assessment Project* used a two-day workshop to evaluate the vulnerability of the area's transportation assets across all modes of transportation and all government agencies. The workshop's 60 attendees represented universities, private consulting agencies, local DOTs, FHWA, Hawaii DOT, disaster centers, Oahu MPO, and National Oceanic and Atmospheric Administration (NOAA). The report found that the main limiting factors to the assessment were the short time period of the pilot project and the funds available for analysis.

The Government Accounting Office (GAO) published its report *Climate Change: Future Federal Adaptation Efforts Could Better Support Local Infrastructure Decision Makers* in April 2013. The report provides results of an investigation of issues related to climate change and infrastructure decision making. Although the report concluded that climate change has not yet been thoroughly incorporated into decision making, areas with access to climate change expertise and areas that had circumstances such as a recent, extreme event were highlighted as more likely to consider climate impacts within the planning processes. It includes examples of federal steps being taken to better inform adaptation decisions, and it suggests that the federal government could better coordinate the information to one central location so the best available information is easily ready for local decisions makers use.

In a research study published in 2014 and entitled *Climate Change, Extreme Weather Events, and the Highway System*, the National Cooperative Highway Research Program (NCHRP) and the American Association of State Highway and Transportation Officials (AASHTO) provided a detailed assessment of the implications of climate change for state DOTs (National Cooperative Highway Research Program 2014). The report provides arrangements, tools, approaches, and strategies for state DOTs to use in adapting their infrastructures and operations to reduce climate change impacts.

The State of Maryland has taken meaningful steps to address the potential risks imposed by climate change with two significant executive orders and two new laws. Governor Martin O'Malley signed Executive Order 01.01.2007.07 on April 20, 2007 and Executive Order 01.01.2012.29 on December 28, 2012. EO 01.01.2007.07, entitled "Commission on Climate Change", created the Maryland Commission on Climate Change (MCCC) and tasked the commission with developing a climate action plan. Executive Order 01.01.2012.29, *Climate Change and "Coast Smart" Construction*, outlines policy directives for long term resiliency to sea level rise and coastal flooding. Significant legislation includes the Maryland Greenhouse Gas Emissions Reduction Act of 2009 and *The Climate Risk Reduction Act*, which was signed into law on May 12, 2014.

"Commission on Climate Change", EO 01.01.2007.07, created hard standards and timeframes for implementation of a climate action plan. The 2008 *Maryland Climate Action Plan* is the document produced in response. Comprised of 16 state agency heads and six elected officials, the *MCCC* is comprised of three working groups developed to address the various aspects of climate change. The Science and Technical Working Group (STWG) focused on the probable impacts to the natural resources (*e.g.* agricultural industry and fisheries resources) and human health. The Adaptation and Response Working Group (ARWG) was responsible for developing a strategy to reduce Maryland's vulnerability to climate change. The Greenhouse Gas and Carbon Mitigation Working Group (MWG), in turn, has created 42 greenhouse gas reduction strategies to address the GHG mitigation side of the climate change strategy.

> *"Billions of dollars of investments in public infrastructure will be threatened if the State of Maryland fails to prepare adequately for climate change" Governor Martin O'Malley EO01.01.2012.29*

On May 7, 2009 the Governor O'Malley signed into law the *Maryland Greenhouse Gas Emissions Reduction Act of 2009*. The law requires the state to reduce GHG emissions to 25 percent below 2006 emission levels by 2020. The Act also requires MDE to produce a statewide emissions reduction plan. As part of the process, MDE generated agency specific greenhouse gas reduction targets. The MDOT is responsible for reducing 6.2 million metric tons of carbon dioxide equivalents by 2020.

Executive Order 01.01.2012.29 (signed on December 28, 2012) *Climate Change and "Coast Smart" Construction* and House Bill (HB) 615, *The Climate Risk Reduction Act*, (signed in to law on May 12, 2014) established the Coast Smart Council within the DNR. The Council's primary responsibility is to produce siting and design criteria for state projects within coastal floodplains. The siting and design criteria are largely detailed in the *Coast Smart Construction Siting and Design Guidelines* (Johnson, Z P 2013). Written as a guidance document, *Coast Smart* provides siting and design guidelines for the construction of new structures and the reconstruction of substantially damaged structures. The main guidelines related to the following recommended policies:

1. avoid siting "critical or essential facilities" within Special Flood Hazard Areas (SFHAs) and protect from damage and loss of access as a result of 500-year flood, and
2. identify, protect and maintain ecological features that serve as buffers from sea level change impacts, flooding and storm surge.

In addition, the siting and construction guidance indicates that designs are to:

1. avoid or minimize future impacts over the projected design life of the structure,
2. maintain 2-foot freeboard above 100-year Base Flood Elevation (from the National flood Insurance Program (NFIP)) for new structures or reconstruction of severely damaged structures,
3. consider flooding protection when selecting building materials, and
4. comply with construction standards for areas along the coast subject to inundation by the 1-percent-annual-chance-flood event with additional hazards associated with storm-induced waves, or V Zones, (FEMA) and when structures and infrastructure are proposed in the Limit of Moderate Wave Action boundary under NFIP.

Climate change policy for Maryland and other jurisdictions is in the early stages of development. The executive orders and laws passed in Maryland, as well as the pilot studies funded by FHWA, are making solid progress in planning for the impacts from climate change. These and future initiatives will contribute to further understanding of what to expect from climate change and extreme weather and will help shape policy and adaptation measures against these risks.

2.2.3 Determining Climate Variables

A range of climate variables including sea level change, coastal flooding, riverine flooding, and precipitation were reviewed for applicability in assessing risks to the infrastructure under consideration for the Pilot Study. This section details the process applied in determining these climate variables. A detailed narrative on climate variables considered in the Pilot Study is provided in Chapter 3.

<u>Methods for Sea-Level Change</u>

The following methodology was applied to determine inundation areas for both mean sea level (MSL) and mean higher high water (MHHW), for both 2050 and 2100, for all Maryland coastal counties. The process utilized observed tides, land elevations, and expected sea level change (SLC) to determine future shorelines. The applied SLC rates were developed using the U.S. Army Corps of Engineers (USACE) procedures as published in Circular No. 1165-2-212, *Sea-Level Change Considerations for Civil Works Programs* (USACE 2013).

Working in the ESRI GIS mapping environment, the best available LiDAR products (Table 2-2) were used to generate countywide Digital Elevation Models (DEM) for the study area. These DEMs, in ESRI grid format, serve as the base from which SLC is adjusted. Tidal reference stations throughout Maryland waters, having captured the industry standard 40+ years of historic data, contribute to establishing water levels during benchmark periods (MSL and MHHW). A vertical calibration (VC) brought water elevations observed at tidal stations in line with land elevations representing the North American Vertical Datum of 1988 (NAVD88). The Chesapeake City tidal station was assigned the average of all VC adjustments since none was available. A final correction (year 2015) for glacial isostatic adjustment and land subsidence brings the tidal stations observations current to the official project year, 2015. Tidal stations and their measurements are the work of NOAA.

Table 2-2. LiDAR Sources for Pilot Counties

County	Date	Source	Project Partners	Resolution	Vertical Accuracy
Anne Arundel	2011	ESRGC	Anne Arundel County	1 meter (3.28 feet)	15 cm RMSE
Somerset	2011	ESRGC	Funded by NRCS, contracted through USGS	1 meter (3.28 feet)	15.7 cm RMSE

Each county in the Pilot Study was assigned a representative tidal station, creating a locally observed MSL and MHHW. Thiessen polygons generated from tidal stations around the Chesapeake Bay acted as areas of influence. Counties were assigned the appropriate stations based on the station's area of influence.

Salisbury University used the tidal stations values and the USACE SLC rates to create SLC Values that can reclassify the current DEMs to be DEMs for both MSL and MHHW in 2050 and 2100. Formulas for SLC Values are presented below.

2050 MSL = USACE 2050 + VC + yr2015
2050 MHHW = USACE 2050 + VC + yr2015 + tidal station MSL to MHHW difference
2100 MSL = USACE 2100 + VC + yr2015
2100 MHHW = USACE 2100 + VC + yr2015 + tidal station MSL to MHHW difference

For data processing, each county's DEM was reclassified four times using the appropriate SLC Values. The DEM reclassification is: minimum value to less than or equal to SLC Value is 1 (meaning the elevation is less than the SLC elevation); values greater than SLC value is NoData. The resulting grid depicts elevations potentially vulnerable to SLC.

Salisbury University converted the grid to polygons (polygon simplification disabled to preserve area) to exclude vulnerable elevations free from SLC. Next, Salisbury University built a network dataset from countywide hydrologic flow lines using the Network Analyst extension. Then, Salisbury University selected network junctions intersecting the Chesapeake Bay and its tidal waters; after the surrounding

Chesapeake Bay and tidal tributaries were identified. The selected nodes were then used to generate a network solution. The network solution's lines represent a Chesapeake Bay connected river system.

The final step was to select from the inundation polygons where the network solution lines intersected. This selection represents vulnerable elevations that are connected to the bay and thus, subject to SLC. The final selection represents the area of inundation for that year and tide.

Methods for Coastal Flood Modeling

Salisbury University produced the following products for application in the Pilot Study, using tools including ArcGIS Suite - ArcInfo and ArcCatalog 10.0 (SP2) and Hazus-MH 2.1 (SP3):

- Depth grids for 10-, 25-, 50-, 100-, and 500-year flood, for both 2050 and 2100, for both MSL and MHHW – ESRI grid with 2m (6.56 feet) cell resolution
- Flood extent polygons 0.15 meters (6 inches) interval – ESRI Feature Class

The following methodology was applied to determine depth grids for MSL and MHHW, for 2050 and 2100, for Maryland coastal counties. The process utilizes land elevations and SLC values to model various flood scenarios.

Data was setup working in Hazus-MH, a standardized methodology developed by FEMA for the National Institute of Building Sciences (NIBS) for estimating losses from events such as hurricanes and flooding. A new region was first created in the Hazus software. The hazard of interest for this project was always designated as "flood". Every scenario was run at the county level, so a single county had to be chosen. Salisbury University configured the hazard to be Coastal Only because the scenarios are coastal floods. Salisbury University used the in-software tool to determine the source DEM's required extent. Through the software, Salisbury University navigated directly to the National Elevation Dataset (NED), and then downloaded the necessary DEM.

Working in the ESRI environment, the NED download fulfills the DEM extent; however, its resolution is limited. Therefore, Salisbury University mosaicked a DEM with from the best available LiDAR, which does not have the required extent, and the NED DEM. During the mosaic process, the best available data was preserved and then resample the entire dataset was to 2 meter (6.56 feet) cells. The output dataset fulfilled the required extent and offered a resolution greater than the NED. Therefore, the mosaic dataset was used as the current DEM for that respective county, capable of running present day flood scenarios.

Salisbury University subtracted the established SLC values from the current DEM to model future flood events (e.g., 2050 MSL, 2050 MHHW, etc.). All negative values were reclassified to zero and represent the new water line.

Next, Salisbury University loaded the new DEM and defined the metadata (Vertical Units: Feet; Vertical Datum: NAVD88) in Hazus-MH. Once the DEM was accepted a new scenario was created. The shorelines were chosen for the region in question. The most recent FEMA Flood Insurance Study (FIS) was referenced to create shoreline breaks. Again, referring to the FIS, all corresponding stillwater elevations were entered for the four flood events (10-, 50-, 100-, and 500-year) at each break in the coastline. Likely wave setup was calculated by Hazus-MH from the stillwater elevations. Finally, the vertical datum was set to be NAVD88.

The floodplain was delineated with full suite return periods (10-, 50-, 100-, and 500-year). A successfully executed delineation produces the desired stillwater depth grids for that county, for that year, during that tide (*e.g.*, Somerset County 2050_msl).

<u>Methods for Riverine Flood Modeling</u>

Using ArcGIS Suite - ArcInfo and ArcCatalog 10.0 (SP2) and Hazus-MH 2.1 (SP3), Salisbury University produced the following products to support the Vulnerability Assessment:

- Depth grids for 10-, 25-, 50-, 100-, and 500-year flood, for precipitation estimates for both 2050 and 2100 – ESRI grid with 2 m cell resolution
- Flood extent polygons 6" interval – ESRI Feature Class

The following methodology was used to determine depth grids for estimated probabilistic 10-, 25-, 50-, 100-, and 500-year precipitation events for 2050 and 2100, for all Maryland coastal counties. Inputs to the riverine flood model in Hazus are the detailed, LiDAR-derived DEM, flood elevation cross-sections (preferably imported from a recent FEMA digital flood insurance study), and the 100-year floodplain boundary.

The general method to determine the depth of flood water from a riverine flood source is as follows:

1. Using the Flood Information Tool module in Hazus, the 100-year floodplain boundary was used to create a general study area boundary and centerline of flow.
2. The user then expanded the centerline of flow to depict the conveyance area of the floodplain.
3. Cross sections that include at least three flood elevations and corresponding discharge values were imported.
4. A preliminary flood depth grid was then generated from the model.

Finally, the flood depths were interpolated into the backwater areas that needed to be delineated by the user.

Methods for Determining Precipitation

The National Oceanographic and Atmospheric Administration (NOAA) is charged with monitoring and studying weather inside and outside the United States. As part of this effort, NOAA has produced a series of precipitation maps collectively referred to as Atlas 14, which is available through NOAA's Precipitation Frequency Data Server. Based on historical records, Atlas 14 estimates the likelihood that a certain amount of precipitation will fall during a given period at a particular location (with 90% confidence). These projections are referred as precipitation frequency estimates, and cover rainfall durations from 5-minutes to 60-days. Atlas 14 also provides supplementary information on temporal distribution (i.e. time of day) and seasonality analysis for various rainfall durations. Of the rainfall durations covered by Atlas 14, the 24-hour, 12-hour, and 6-hour durations were identified to be the most critical precipitation frequency for hydraulic analysis. The precipitation frequency estimates for the recurrence intervals were derived from weather observation stations at the Naval Academy in Annapolis, MD for Anne Arundel County, and in Princess Anne, MD for Somerset County (see Figure 2-5).

The Coupled Model Inter-comparison Project (CMIP) Climate Data Processing Tool (CDPT), a product of the World Climate Research Program (WCRP) that provides climate model review and data access, was used to project the changes in precipitation conditions for Anne Arundel and Somerset Counties for the Pilot Study years of 2050 and 2100. This was accomplished by converting daily climate data into projected changes in 13 precipitation variables. The daily climate data was obtained through the CMIP database and included historical daily weather information for Precipitation Rate (mm/day) for a 12km^2 (approximately 7.5 mile^2) grid cell.

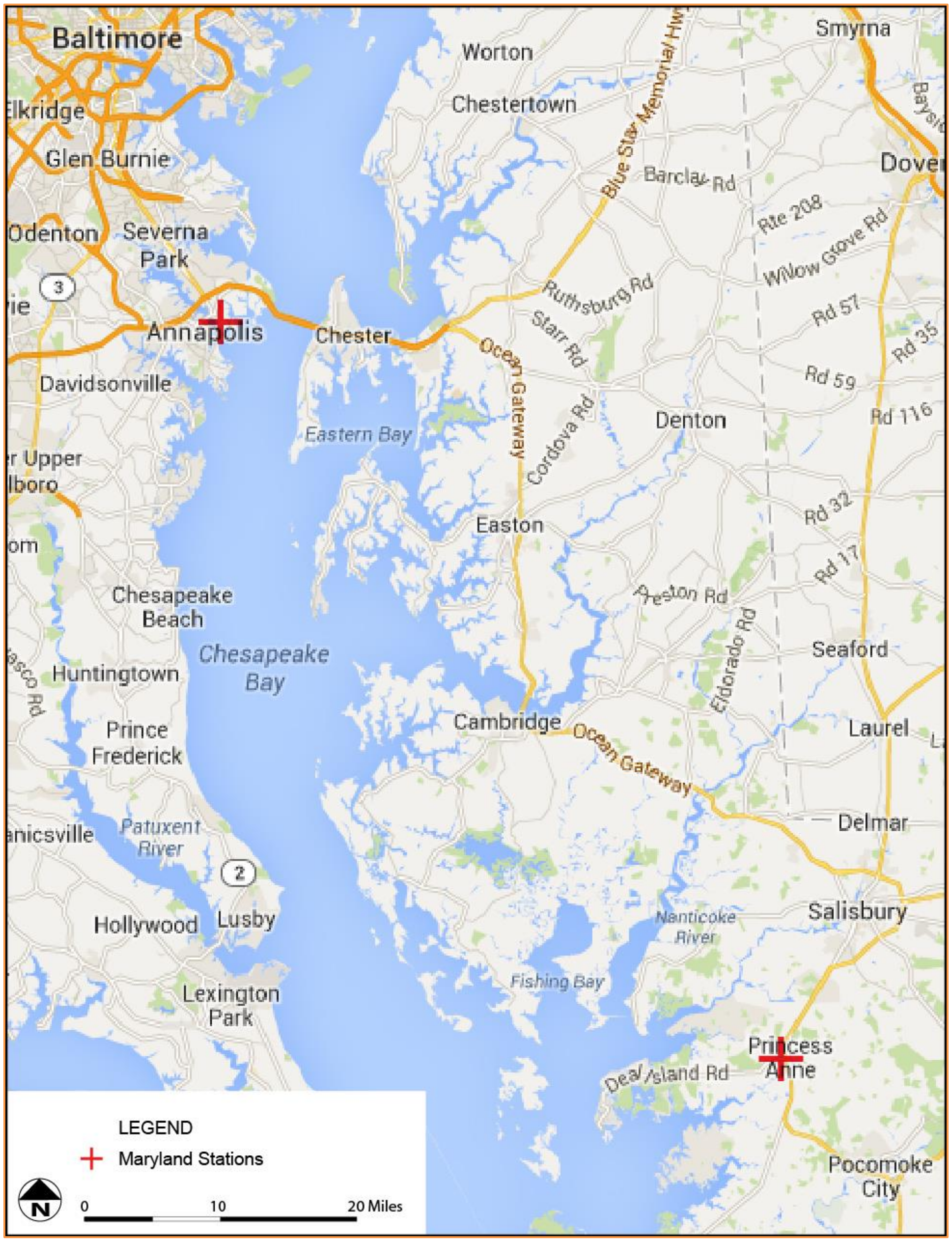


Figure 2-5. Atlas 14 MD Stations Used for Precipitation Frequency Analysis
Data Source: Google Maps

Phase three of CMIP (CMIP3) daily climate data was used to develop climate projections for the Pilot Study. Three locations (i.e. coastal, central and inland) for both Anne Arundel and Somerset Counties were analyzed. Their climate data was inserted into the CMIP CDPT and evaluated by several climate models for three future emission paths based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES): B1: Lowest emission path; A1B: Medium emission path and; A2: Highest emission path. A multidisciplinary team from SHA recommended that emission path FPA1B be used as the default path because of its conservative projections and eight climate models associated with this emission path were chosen for the simulations. Each location within the counties achieved similar results; therefore, the central location within the county was selected as the representative location.

The simulations provided projected values for changes in precipitation events for mid-century (2046-2065) and end-century (2081-2099). For the Pilot Study, the mid-century projections were used for year 2050 and the end-century projections were used for 2100. To present the projections in a format for transportation engineers, the U.S. Department of Transportation's CMIP CDPT version was used as applicable. Output for precipitation modeling included the following:

- Average Total Annual Rainfall
- "Very Heavy" 24-hr Precipitation Amount, in which very heavy is defined as the 95th percentile precipitation
- "Extremely Heavy" 24-hr Precipitation Amount, in which extremely heavy is defined as the 99th percentile precipitation
- Average Number of Baseline "Very Heavy" Rainfall Events per Year
- Average Number of Baseline "Extremely Heavy" Rainfall Events per Year
- Average Total Seasonal Rainfall
- Largest 3-Day Rainfall Event per Season

2.2.4 Vulnerability Assessment Scoring Tool (VAST)

In the Pilot Study, VAST was one of the tools used to determine the vulnerability of SHA transportation assets to climate change. VAST is used as a framework to help transportation planners and engineers conduct a quantitative and qualitative indicator based vulnerability screenings. These screenings help determine the degree and extent to which transportation infrastructure assets, or their components, are receptive to and unable to cope with the impacts of climate change (U.S. DOT 2014). The screening performed by VAST examined the impact of climate change and extreme weather on selected transportation assets, and demonstrated how those assets or their components responded to changes in climate that may cause damage to the asset.

The VAST uses qualitative data based on expert judgment and stakeholder input, in tandem with quantitative data generated by technical modeling to identify asset level vulnerability. In order to help Maryland transportation planners and engineers understand the impacts of climate change on their assets, the VAST inputs were refined to better reflect SHA's assets and Maryland's climate conditions.

<u>Concept of VAST</u>

As described in the draft *U.S. DOT Vulnerability Assessment Scoring Tool User's Guide* (U.S. DOT 2014), VAST was developed to examine the three components of vulnerability: exposure, sensitivity, and adaptive capacity. For the purpose of the Pilot Study, the three vulnerability components are defined as follows:

- **Exposure** is defined as the "nature and degree to which an asset is exposed to significant climate variations" (U.S. DOT 2014). Exposure indicators are related to climate conditions and whether the asset is located in an area that will be subject to impacts of climate change or extreme weather.

- **Sensitivity** is defined as "the degree to which an asset is affected, either adversely or beneficially, by climate related stimuli" (U.S. DOT 2014). Sensitivity is associated with the characteristics of the structure's design and material, as well as the threshold in which climate impacts are felt. The higher the threshold due to improved design and material, the more resilient the structure becomes. Sensitivity explains why some assets fail while other assets function well under exposure to the same changes in climate stressors.
- **Adaptive Capacity** is defined as "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" (U.S. DOT 2014). Adaptive Capacity is associated with the capacity of the asset's surrounding environment to adjust to the asset's failure or damage. If the rate of projected climate change is faster than the adaptability of a system, then the system is considered vulnerable.

To assess each of the three vulnerability components, VAST identified key asset and environmental characteristics. These characteristics are referred to as indicators, and be can qualitative or quantitative in nature. For example, bridge age is a quantitative indicator that can be used to assess a bridge's sensitivity. Historical exposure to flooding, conversely, is a qualitative indicator that can be used to assess exposure to climate change and extreme weather. An indicator is defined as those characteristics of an asset in relation to a) its exposure to climate stressors, b) its sensitivity to the changes in the climate stressors, and c) the capacity in which the system that carries this asset can adapt to the changing climate once a structure reaches its sensitivity threshold. Those indicators can be measured either quantitatively or qualitatively.

In vulnerability assessments, the three vulnerability components are weighted and then combined for each climate stressor to come up with the overall vulnerability of each asset. The following equation demonstrates how vulnerability of transportation assets was calculated in this Pilot Study.

Vulnerability = Exposure (i) + Sensitivity (i) + Adaptive Capacity (i)

Where the term "(i)" represents a percentage of vulnerability component weight, depending on expert input and stakeholder judgment.

VAST Analysis Methodology

The VAST analysis was used to compare and qualify the extent in which structures within the Climate Change Impact Zone are vulnerable to climate stressors. The assessment consists of six different steps:

- Step 1- Select Climate Stressors and Asset Types within the study area
- Step 2- Enter Specific Asset Data
- Step 3- Define Indicators
- Step 4- Collect Climate Data related to selected indicators
- Step 5- Adjust Scoring
- Step 6- Review Results

Figure 2-6 illustrates the relationship and process flow between the six assessments steps listed above.

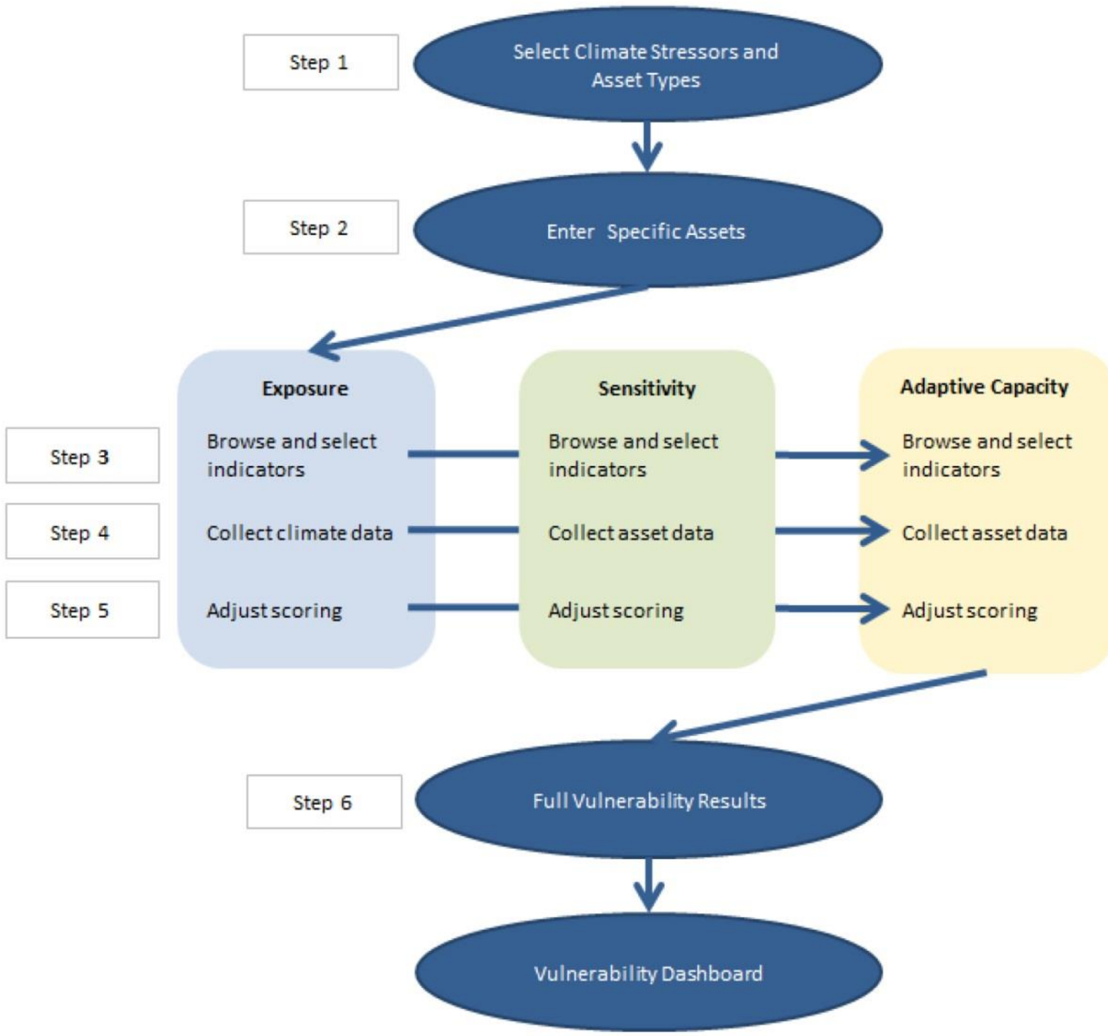


Figure 2-6. Diagram Showing Each VAST Step
Data source: (USDOT, 2014)

VAST Step 1: Select Climate Stressors and Asset Types

Climate Stressors:

In the context of this vulnerability assessment, a climate stressor refers to the water related changes in climate that would impact transportation infrastructure. As described in Chapter 3, three climate stressors, or variables, were identified to have a significant impact on SHA's transportation infrastructure and drainage assets as a result of flooding due to projected changes in climate. The three defined climate stressors are as follows:

- **Sea Level Change**: The rate of sea level rise and land subsidence is projected to increase in Maryland's coast during the next century. Any increases to sea level will cause permanent inundation in coastal areas, which would adversely impact SHA's transportation assets in Maryland.

- **Storm Surge**: Climate change is expected to increase the vulnerability of SHA's coastal transportation assets to storm surge, defined as the rise in water level from weather events such as hurricanes, tropical storms and nor'easters. Coupled with sea level rise, subsequent storm surges will lead to larger inland flood risks.
- **Precipitation Changes**: Average annual precipitation is projected to increase in some parts of Maryland, while other parts will not experience any considerable changes. However, climate change is projected to cause an increase in the frequency and intensity of extreme precipitation events in all regions of Maryland. These changes would impact transportation assets through the increased risk of flooding and erosion.

Asset Types

SHA held several meetings with planning, maintenance, and engineering personnel in February 2014 to identify asset types to be included in the assessment. These meetings reviewed only existing assets within state highway system. Due to this Pilot Study's focus on water related changes in climate, SHA identified three different types of drainage assets to be assessed:

- Bridges and large culverts that act as bridges
- Roadway segments at lower elevations
- Small culverts/drainage conveyances

Other transportation assets that are within SHAs jurisdiction but were not assessed in the Pilot Study include:

- Maintenance and operation facilities
- Storm water management facilities and structures
- Signs, traffic signals, lightning, ITS and roadside assets
- Bicycle and pedestrian facilities

These assets will be examined for potential vulnerability to climate change in future, more site specific assessments.

VAST Step 2: Enter Data on Specific Assets Within the Climate Change Impact Zone:

To identify the assets included in the vulnerability assessment, the Climate Change Impact Zone was developed. Assets that were out of the Climate Change Impact Zone were excluded from the VAST analysis. Assets within the Climate Change Impact Zone were identified and their data was collected from various resources and entered into VAST for analysis. Each asset was given a unique identification number specific to this Pilot Study. This identification number was linked to the 9 digit SHA Identification number for that specific asset. Other relevant data related to the asset identification and location were inputted into VAST including asset name, type, coordinates, location, and features crossed. To provide a relative scale of the number of transportation assets evaluated, the number of bridges, culverts and roadways within the Climate Change Impact Zone for Anne Arundel and Somerset Counties are shown in

Table 2-3.

Table 2-3. Number of Evaluated Assets for Each Pilot County

Asset	Anne Arundel County		Somerset County	
	Number of Assets	Evaluated in VAST	Number of Assets	Evaluated in VAST
Number of bridges including large culverts that act as bridges	517	150	86	72

VAST Step 3: Select Indicators

During the second engineering workshop a multidisciplinary group of SHA planners and engineers completed an exercise where they rated a list of VAST vulnerability indicators. The initial list was derived from the indicator library developed for VAST analysis of Phase II Gulf Coast Study (U.S. DOT 2011). The results of the exercise were used to identify the exposure, sensitivity, and adaptive capacity indicators most applicable to the State of Maryland and the highway system.

To establish ranks for the vulnerability indicators, each of the workshop participants were asked to assign a number corresponding to the indicator's relative importance. A ranking of 1 indicated a low significance, a ranking of 2 indicated a medium significance, and a ranking of 3 indicated a high significance indicator. The number assignments were first applied to bridges and very large culverts, as these assets aligned well with the Phase II Gulf Coast Study indicator library. Participants were then asked to suggest and rank other indicators that could help identify the vulnerability of small culverts/drainage conveyances. At the end of the exercise, input from all participants was collected and the results were averaged. Indicators with the highest average scores were selected as the high significance indicators to be used in the vulnerability assessment for the Pilot Study. The results of this exercise helped refine and define VAST to better reflect Maryland specific climate conditions, as well as the characteristics and data available that pertained to SHA's assets. The output, which was a predefined indicator list, was the first step in designing a long-term vulnerability assessment tool that is tailored to Maryland climate and SHA's needs and assets, which can then be replicated for future vulnerability assessments for other SHA transportation assets.

The exercise also helped define constraints for conducting subsequent analyses, which served to create a boundary for analysis that limited the collection of extraneous or insignificant data that will not have significant impacts on assessment results. Results of the engineering workshop indicator ranking exercise are demonstrated in Table 2-4.

After results were finalized, another ranking was made to display the availability of data related to selected indicators. If data for a significant indicator was available, the indicator was inserted into VAST and included in the analysis. If data was not available, could not be accessed from external sources, or was hard to create or tabulate for this study, the indicator was excluded from VAST. Second tier indicators, or the medium significance indicators, were used to replace those Tier I indicators that lacked data.

Table 2-5 explains the rationale behind each indicator.

Table 2-5 provides a list of indicator data gaps that included all non-available data was established for this assessment. The indicator data gap is an important element of the exercise because it identifies the missing data required to perform a comprehensive and accurate vulnerability assessment.

The outcome of the indicator data gap will be incorporated into the agency's decision making process where more coordinated resources and efforts will be dedicated to address those gaps. The results of this exercise will also help SHA refine data collection methods, as well as improve the geo-spatial tools to facilitate transformation of field data from flood related incidents and disruptions into a format compatible with the needs of other departments across the agency.

Table 2-4. Results of Ranking Indicators during Workshop #2

Exposue Indicators

High Significance	Medium Significance	Low Significance
Sea Level Change		
Sea Level Change Inundation Depth (AV)	Proximity to Coast (AV)	USGS Coastal Vulnerability Index (NAV)
Elevation of Asset (AV)		
Storm Surge		
Modeled Surge inundation Depth (AV)	Presence of protective structures (NAV)	Presence in FEMA coastal flood zone (AV)
Elevation of Asset (AV)	Proximity to Coast (AV)	USGS Coastal Vulnerability Index (NAV)
Precipitation Changes		
Change in Peak Discharge (NAV)	Asset Clearance (AV)	Location in FEMA 100 year flood zone (AV)
Change in Flow Velocity (NAV)	Change in number of consecutive days with precipitation (NAV)	Change in total annual precipitation (AV)
Change in discharge volume (Q) (NAV)	Change in rain amount associated with 100 year 24-hour storm (NAV)	Location in FEMA 500 year flood zone (AV)
Location in 10 year floodplain (NAV)	Location in 25 year floodplain (NAV)	Change in total seasonal precipitation (AV)

Sensitivity Indicators (Bridges, Culverts, and Roadways)

High Significance	Medium Significance	Low Significance
Sea Level Rise		
Past experience with tides SLR (AV)	Flood protection (NAV)	Navigational Clearance of Bridge (NAV)
Approach elevation (AV)	Nearby areas exposed to SLR (NAV)	Soil type (NAV)
Asset Clearance (AV)	Scour Rating (AV)	Bridge Age (AV)

Storm Surge		
Past experience with storm surge (AV)	Condition of bridge superstructure (AV)	Navigational Clearance of Bridge (NAV)
Scour rating (AV)	Culvert condition (AV)	Condition of bridge deck (AV)
Condition of bridge substructure (AV)	Movable Bridge (NAV)	Bridge Age (AV)
Asset Clearance (AV)	Approach Elevation (AV)	Weight of bridge deck (NAV)
Flood protection (NAV)	Height of bridge deck (NAV)	Number of longitudinal girders (NAV)
Precipitation Changes		
Past experience with precipitation (AV)	Culvert Condition (AV)	Proximity to the coast (AV)
Asset Clearance (AV)	Channel Condition (AV)	Bridge Age (AV)
Scour rating (AV)	Propensity for ponding (NAV)	
Frequency that water overtops the structure (NAV)	Percentage of impervious surface (NAV)	
Adaptive Capacity Indicators		
High Significance	**Medium Significance**	**Low Significance**
Replacement Cost (NAV)	Disruption duration (NAV)	Historical repair cost (NAV)
Detour length (AV)	Function Classification (AV)	
Average Daily Traffic (AV)	Evacuation Route (AV)	
Access to Critical Areas (NAV)		

AV: data is available and in a format compatible with analysis
NAV: data is not available, could not be accessed from external sources, or was hard to tabulate for this study. Obtaining the data requires resources and time beyond the scope of this study.

The final list of indicators selected for the vulnerability assessments are listed in

Table 2-5 below. A description and rationale for selecting the indicators are also provided for reference.

Table 2-5. Final List of Indicators Used for VAST

	Exposure
Indicator	**VAST Description or Rationale**
Location in FEMA 100-Year Flood Zone	Assets located in floodplains are more likely to be exposed to flooding from changes in precipitation. The flood zone return period depends on the assessment.
Asset Clearance	Elevation can serve as natural protection from increased precipitation, sea level change and storm surge. The higher an asset, the less exposed it may be to changes in climate stressors. Asset Clearance was incorporated into Modeled surge inundation depth for both sea level rise and storm surge.
Change in Total Annual Precipitation	Total annual precipitation impacts landscapes and vegetation and gives an indication of the projected increases in flow.
Modeled SLR Inundation Depth	Assets projected to be inundated by sea level rise are the most exposed to sea level rise.
Proximity to Coastline	Assets closer to the coast may be more likely to be exposed to sea level change and storm surge.
Modeled Surge Inundation Depth	The assets inundated under the most water, based on the model scenarios, are the most exposed to storm surge.
	Sensitivity
Indicator	**Description or Rationale**
Past Experience with Tides/SLR	Assets that have experienced flooding during extreme high tide events in the past are likely to be some of the first roads impacted by sea level rise.
Past Experience with Storm Surge	Asset segments that already experience storm surge impacts are more likely to experience damage if exposed again in the future.
Past Experience with precipitation	Assets that have experienced damage during historical heavy rain events are more likely to be damaged as precipitation increases in the future
Asset Clearance	Assets with less clearance above the waterway are more likely to be at risk for water reaching the bridge deck.
Scour Rating	Bridges that have already been identified as having problems with scour are more likely to be damaged when being flooded.
Culvert Condition	Culverts that are in poor condition are more likely to be damaged during heavy precipitation and storm surge events.
Condition of Bridge Substructure	Bridges that are in poor condition are more likely to be damaged during heavy precipitation and storm surge events.

	Sensitivity
Condition of Bridge Superstructure	Bridges that are in poor condition are more likely to be damaged during heavy precipitation and storm surge events.
Condition of Bridge Deck	Bridges that are in poor condition are more likely to be damaged during storm surge events.
Bridge Age	Some older bridges were built to outdated design standards, making them more vulnerable to the impacts of precipitation, sea level change, and storm surge.
	Adaptive Capacity
Indicator	**Description or Rationale**
FHWA Roadway Functional Classification	Function classification is the system in which roadways are grouped based on the character of services the roadways are intended to provide.
Evacuation Routes	Evacuation Routes were used as an indicator to the significance of the roadway in the system.
Detour Length	Overall increase in path length due to detours around flooded structures.
Annual Average Daily Traffic (AADT)	AADT is the volume of vehicle traffic of a road for a year divided by 365 days. It is a measurement of the road classification and the importance of that road for the surrounding areas.

VAST Step 4: Collect Asset Data

In order to provide SHA with a scientific assessment of assets that are vulnerable to the projected impacts of climate change, a thorough data collection effort was performed for each of the vulnerability indicators. As is often the case in climate change vulnerability assessment, complete datasets for all indicators were not available. Consequently, a combination of qualitative and quantitative data was used as necessary. Most selected indicators were from the high or medium significance indicators; however, low significance indicators were used in the precipitation analysis due to limited data availability.

Data from regional, state and federal sources, as well as SHA databases were collected, reviewed and attached to assets identified in this assessment. Output of various analysis including Hazus and SLOSH modeling, CMIP Climate Data Processing tool as well as GIS based data provided by Salisbury University were included in the assessment. Details on selected indicators for assets identified within the Climate Change Impact Zone and their integration into the VAST is described below:

Exposure Data: Location in the FEMA 100-year Flood Zone

FEMA's National Flood Hazard Layer maps depicting the extent of 1-percent-annual-chance floods (i.e. the 100-year floodplain) were translated into GIS datasets developed for the Pilot Study. Structures within the 100 year flood zone extents were identified as potential flood risk assets. This analysis was primarily used to identify inland bridges and large culverts vulnerable to climate stressors including precipitation.

Exposure Data: Projected percentage of change in Total Annual Precipitation for 2050 and 2100

Projected changes in runoff volume, peak discharge, or flow velocity were identified during the engineering analysis as the most significant indicators to demonstrate the exposure of an asset to the impacts of heavy precipitation. Changes in discharge volumes are typically calculated through hydrologic modeling of several variables that characterize a watershed including precipitation, drainage area, watershed slope, time of concentration, soil group types, and land use, along with other local features and conditions. Hydrological modeling to establish new discharge data or regression equations that incorporate changes in future precipitation were not performed for this Pilot Study as stated in Step 10, Conduct Site Specific Analysis for Vulnerable Locations at Risk (Tier III) of the Vulnerabilities and Adaptation Framework for the Pilot Study.

Percentage of change in total annual precipitation is Total Annual Precipitation an indicator that was ranked as "low significance" by the engineering working group. However, because of limited data available, it was incorporated in the analysis to identify a structure's vulnerability to changes in precipitation. It is important to note that the changes in total annual precipitation did not differ among the assessed structures, yet this indicator was incorporated within the VAST template to account for projected precipitation changes for future state level assessments.

The CMIP CDPT was used to project the changes in precipitation for the near term (2050) and long term (2100) scenarios. For the purpose of this study, high and medium emission scenarios were used as the baseline for precipitation projections. These emissions scenarios are consistent with observed global GHG emission trends, in that GHG emissions continue to rise on a global basis. However, the rate of that increase can vary (Netherlands Environmental Assessment Agency 2013). A1B (moderate emission) and A2 (high emission) scenarios were used from 8 different models for Anne Arundel and Somerset Counties, and the results of the CMIP analysis in the form of percentage of change in precipitation of 3.8% and 6% by the years 2050 and 2100 respectively, were inserted into VAST.

Exposure Data: Modeled Sea Level Change Inundation Depth

Salisbury University developed statewide water surface elevations for the 2050 and 2100 projected sea level change. Digital Elevation Models (DEMs) and the USACE model for sea level change projections were used to determine polygon areas and inundation depth at each asset location for years 2050 and 2100. Further description of the methodology used to calculate inundation depth can be found in Chapter 5Sections 1.4 and 2.4.

Exposure Data: Modeled Surge Inundation Depth

Hazus-MH models developed by Salisbury University were used for coastal flood modeling and to estimate inundation depth grids for the years 2050 and 2100. Further description of the methodology used to calculate inundation depth can be found in Chapter 5 Sections 1.4 and 2.4.

Exposure Data: Proximity to Coastline

The distances of each asset from the coastline was calculated using a Maryland Geological Survey shoreline map for tidewater Maryland and calculating the shortest linear distance of a certain asset to the coastline. The closer an asset is located to the coastline, the more it is considered vulnerable to the impacts of sea level change and storm surge. For the purpose of this assessment, the definition of Maryland's coastline included the Atlantic coast, tidal shores of the Chesapeake Bay, and the tidal portion of rivers.

Exposure/ Sensitivity Data: Asset Clearance

Spatial analyses were performed to identify the lowest elevation point on structure and their approaches, as well as the water height underneath the structure. A visual review of LiDAR-based imagery was used to determine each structure's lowest elevation point. Structural clearance was calculated by subtracting the water elevation, as indicated in the LiDAR-based imagery, under the structure from the elevation of the lowest point on the structure. Results were validated through a comparison of the structure height data obtained from the SHA Office of Structures Database, which grouped structure clearance in elevation categories of 0-10, 10-20, 20-30 and 30-40 feet.

Sensitivity Data: Past Experience with Precipitation, Tides/Sea Level Change and Storm Surge

Structures that have experienced damage during historic flood events are often considered more sensitive to flooding in the future. To expand upon this correlation, two datasets that included historical performance of structures were reviewed. The Coordinated Highways Action Response Team (CHART) closure data included relevant information such as the date of the closure and the type of weather closure incident (i.e. debris, weather, high water, or winter precipitation). The SHA Highway Hydraulic Division's (HHD) drainage complaints and investigations database included information on projects related to structural performance.

To augment the historical performance databases, a survey regarding historical flooding events related to sea level rise, storm surge, or heavy precipitation was developed for SHA maintenance staff. This survey included comprehensive information about bridge and large culvert assets in Anne Arundel and Somerset counties including: a detailed description of asset location, the waterway crossed, and high resolution maps for each county that showed the location and ID for each of the evaluated assets. The survey asked that the reviewer to score the assets based on their historical propensity for flooding due to the heavy precipitation, tidal sea level change, and storm surge. Based on their local knowledge, maintenance personnel gave a score on a scale from 1 to 4, with a rating of "4" for structures that experienced recurring flooding, and a score of "1" for structures that never experienced any past flooding.

Sensitivity Data: Scour Rating

Scouring ratings are produced by the SHA Office of Structures to describe the presence and impact of scour at bridges and culverts. The data used to generate scour ratings is collected through routine bridge inspection. Data regarding scour rating were inserted into VAST, and a guideline was used to translate scour ratings into severity of observed scour and subsequent potential asset vulnerability.

Sensitivity Data: Condition of Bridge Substructure and Superstructure and Deck

The SHA Office of Structures Data included description of the condition of various bridge and culvert components including the sub structure super structure, and bridge deck. Ratings of the condition of bridge components for both counties were inserted into VAST. The rating included five (5) categories and ranged between serious condition or highly vulnerable, to very good condition or least vulnerable.

Sensitivity Data: Large Culvert Condition

The SHA Office of Structures Data was also used to describe the conditions of large culverts. Ratings of the condition of culverts in both counties were inserted into VAST. Rating included five (5) categories and varied between serious condition or highly vulnerable, to very good condition or least vulnerable.

Sensitivity Data: Bridge Age

Bridge age was calculated by subtracting the year the asset was built or reconstructed from the year 2014, which was the year in which the analysis was performed. Data on when the asset was built or reconstructed was obtained from the SHA Office of Structures Database.

Adaptive Capacity Data: Evacuation Route

The process of identifying structures located on evacuation roads was done by visually analyzing structures within the Climate Change Impact Zone that were within an evacuation route shapefile provided by SHA Office of Structures.

Adaptive Capacity Data: FHWA Roadway Functional Classification

Functional classification is the system in which roadways are grouped based on the character of services the roadways are intended to provide. FHWA classifies roadways into three functional systems: arterial, collector and local. SHA mostly manages the arterial and collector roads in Maryland. Identifying the roadway functional class on which the structure is located was done programmatically by overlaying a functional class GIS shapefile with the shapefile that incorporates the structures located in the Climate Change Impact Zone and are assessed by VAST. The function class of the roadway on which the structure is located was used to identify the functional class for VAST structures.

Adaptive Capacity Data: Detour Length

Detour length in this analysis was defined as the overall increase in path length due to a detour around a flooded structure. The data was developed using a shapefile of a web sample code that allows user to place stops and barriers along networks and evaluate alternative routes. The following assumptions were followed to calculate the detour length: (a) route length without flooding and the length of detour, minus normal route length was captured, (b) if multiple flood locations were present, they were added, making structures more critical, as detour route would try to use adjacent flooded crossing, (c) downstream crossings of flooded structures were denied for alternative route but allowed upstream crossings, and (d) when no data on flood events for local roads were available, an alternative route was used for the detour. Assets with no available detours were considered most vulnerable to the impacts of sea level change and storm surge.

Adaptive Capacity Data: Average Annual Daily Traffic

SHA Office of Structures Database information on Average Annual Daily Traffic (AADT) was assessed for structures. AADT is defined as the average number of vehicle traffic passing over a bridge or a roadway segment in a 24 hour period, averaged over a year. If a roadway or bridge experiences high volume of daily traffic, then this is an indicator of the significance of this asset to the surrounding environment. Assets with a high AADT value are considered more vulnerable than assets with lower AADT values.

VAST Step 5: Adjust Indicator Scoring

Raw data collected for each vulnerability indicator in Step 4 were assigned to match each asset ID, then inserted into VAST. The following two types of scoring and weighting were performed on the data to be able to calculate and compare the vulnerability score for all assets:

1. Convert Data into Vulnerability Score

Data assigned to each indicator and asset was converted into scores on a scale of 1 to 4 based on the feedback from a multidisciplinary team of experts. If the asset data associated with a certain indicator was identified as having a significant impact on vulnerability, then the asset data received a score of 4. Asset data values that were identified as having no or low impact on vulnerability received a lower score. VAST provided the option of extracting the data values into VAST and tabulating them into ranges that corresponded with a suggested vulnerability score. Those ranges could be adjusted based on the feedback from the multidisciplinary team of experts.

2. Adjustment of Indicator Weight

The percentage of the value in which each indicator could contribute to the overall vulnerability component score was inserted in VAST based on the feedback from the multidisciplinary team of experts. These values for each vulnerability component was adjusted based on various discussions to identify the weight to which this indictor could contribute to the vulnerability component. If a specific indicator of a certain vulnerability components held higher significance, or was based on better data quality, then the weight of that indicator was increased while the weight of another indicator that is less significant or is based on a lower quality data is decreased. The total weight of percentages for each of the three vulnerability components must add to a 100% before being able to proceed.

VAST calculates the vulnerability score for each asset by adding the weighted averages of the three key components that dictate an asset's vulnerability: exposure, sensitivity and adaptive capacity. The overall weights of the vulnerability components could also be adjusted to give more weight to a certain component based on stakeholder input or to investigate various scenarios.

VAST Step 6: View Results

Results of the indicator based vulnerability screening include a diverse set of outputs that demonstrate the overall ranking of all assets by their vulnerability to each climate stressor. These results can work as a foundation and a stepping stone to understand the impact of climate change on transportation assets and their surrounding area. The results of the VAST analysis provide a general, high level indication of vulnerability and are not a final judgment on the required adaptation measures to be performed. Further detailed engineering analyses are recommended for those structures that are identified as highly vulnerable in VAST. Assessment results are summarized in Chapter 5 and tabular information is included in Appendix B. The assessment results are presented in the following format:

- **A Results Table** that displays the results of the vulnerability screening for each asset type and each climate stressor, with the ability to adjust the overall vulnerability components weights. VAST output included a "damage" column which presents the extent to which any asset is exposed to exposure to a certain climate stressor, and the sensitivity of that asset in relation to the climate stressor. The damage score doesn't include any data on adaptive capacity. The vulnerability column in the results table presents a combination of the three different vulnerability components. The weighted averages of the sum of the three vulnerability components (exposure, sensitivity and adaptive capacity) for each climate stressor and for both the 2050 and the 2100 scenario could be adjusted. The output table presents the damage and vulnerability, as well as a table giving an option to sort the results based on the required stressor, scenario, or vulnerability component.
- **A Vulnerability Assessment Summary Sheet or Dashboard** lists the top 10 vulnerable assets to each climate stressor for the 2050 and 2100 scenarios and provides a summary of the results for each Climate Stressor included in the assessment. The dashboard also includes a bar chart that compares the number of vulnerable, moderately vulnerable, and non-vulnerable assets in relation to each climate stressor.
- **Asset Score Query Sheet** is a summary of all data related to assets arranged by their ID. It presents all the data sources available for each asset in relation to each climate stressor. The sheet gives the individual score for each asset and a breakdown of the vulnerability score for each vulnerability component. These Asset Score Queries are valuable because they allow planners to compare information about more than one asset at a time.

The results of the assessment are a data-based asset vulnerability ranking of the most vulnerable structures based on historical data, projected climate conditions and impact scenarios, and applied expert judgment. The results for the two pilot counties are presented in Chapter 5 and will help decision makers integrate output into their decision making process to identify planning needs for construction of new assets versus implementing design or operation and maintenance changes to mitigate the impacts of climate change on existing assets. Results of the assessment were useful to help identify segments of transportation assets at risk to a specific type of climate change stressor, determine the potential consequence, and design adaptive measures that reduce a specific vulnerability that is related to a specific climate stressor to manageable levels. The assessment results also helped identify critical corridors throughout Anne Arundel and Somerset Counties without focusing on the details of each asset individually. This serves the purpose of prioritization, which is to look at transportation structures as a cohesive system rather than addressing individual components extracted from their surrounding environments.

2.2.5 Flood Inundation Modeling and Hazard Vulnerability Index (HVI)

Roadway vulnerability to sea level rise (SLR) and subsequent storm events were analyzed using Flood Inundation Modeling results and Hazard Vulnerability Index (HVI) risk calculations. Road segments at risk, meaning having any probabilistic flooding, to SLR were identified as permanent inundation roadways. The amount of inundation was not considered a significant factor for SLC as any permanent flooding on a roadway can lead to closures and problems such as scour. The permanent inundation determination was derived from mean sea level instead of a more conservative analysis that factors tidal effects. Including tidal effects would likely increase the amount of roadways vulnerable to inundation from SLC.

The HVI provides a comparative risk value for road segments to climate change variables including sea level rise and subsequent storm events. The equation for calculating the HVI risk value is comprised of three components, each with a distinct weighting factor to govern its influence to the overall risk value. The three components include the two road segment attributes of evacuation route designation and functional classification, as well as a hazard indicator assigned as the flood depth code for this study. The weighting factors were based on expertise in similar studies and refined through an iterative process.

The process for creating the HVI is as follows:

1. Create a Statewide Road Network with Appropriate Fields

Using the SHA Functional Classification dataset, the numerical Functional Classification was attached to each road segment. SHA follows the FHWA Functional Classification as referenced in Table 2-6. Road segments designated as an evacuation route were assigned a value of 1 for Evacuation Code. Road segments that were not designated as an evacuation route were assigned an Evacuation Code of 0.

Table 2-6. Federal Highway Administration (FHWA) and SHA Functional Classification of Roads
Data Source: (FHWA 2013)

Value	FHWA Functional Class	SHA Functional Class
1	Interstate	Interstate
2	Principal Arterial – Other Freeways and Expressways	Principal Arterial – Other Freeways and Expressways
3	Principal Arterial – Other	Principal Arterial – Other
4	Minor Arterial	Minor Arterial
5	Major & Minor Collector	Major Collector
6	Local	Minor Collector
7		Local

2. Split Roads based on the County Boundary

Because HVI generation is a computationally complex task, the entire state road network was divided into its component County designations.

3. Generate Flood Depth Polygons from Raster Data

Flood depth raster grids of Anne Arundel and Somerset Counties for 2050 and 2100 mean sea level (MSL) and subsequent storm events of 10, 25, 50, 100 and 500 year were converted to a polygon and overlain with the road network. During the raster to vector conversion, depth values are reclassified according to Table 2-7.

Table 2-7. Flood Depth Codes

Flood Depth (Feet)	Code
No Flood	0
0 – 0.5	1
0.5 - 1	2
1 - 2	3
>2	4

4. Overlay Flood Depth Polygons with Roads

The next step in the HVI process was to overlay each reclassified flood depth polygon with the road network. The result was a road network split at all flood depth polygon boundaries. Each road segment contained the corresponding flood depth classification, functional classification, and evacuation designation. Any ponding or moving water on roadways can lead to closures. Flood Depth Code 1 corresponds to loss of vehicle control and the potential for most passenger vehicles to stall. Flood Depth Code 2 indicates up to a foot of flooding, a catalyst for many vehicles to float. At 2 feet, Flood Depth 3 or greater, most vehicles can be carried away by rushing water (FEMA 2014).

Calculate HVI Risk Value

The following step was to calculate the HVI risk value. This formula considers road segment evacuation designation, functional classification, and modeled flood depths due to SLC and storm events.

The HVI formula is as follows:

Risk = ([Evacuation Code]*.5+1)*(([Flood Depth Code] + 0.01)/4)*(0.7/[Functional Classification])

5. Categorize Road Segments by Risk Value

For comparative purposes, the risk values were placed into the four categories shown in Table 2-8. Road segments with no probabilistic flooding (Flood Depth Code = 0) comprised the low category due to a limited flood risk to the road segments. The road attributes of functional classification and evacuation designation did not influence the categorization of road segments within the moderate category. The moderate category includes road segments that have a probabilistic flood depth of 0 to 2 feet (Flood Depth Codes 1-3) for functional classifications 2 through 7. Any probabilistic flooding (Flood Depth Codes 1-4) attributed to a functional classification 1 road segment resulted in a category of critical. This reflects the importance of the Interstates and potential impacts of even minor flooding to these road segments. For the high category, the maximum level of risk was defined as a road segment designated as an evacuation route with a probabilistic flooding depth of 0 to 2 feet. (Flood Depth Code = 1-3). If a road segment was designated as an evacuation route with a probabilistic flooding depth greater than 2 feet (Flood Depth Code = 4), it was placed in the Critical category. The road segment with the maximum risk value was an Interstate (Functional Classification = 1) designated as an evacuation route that had a probabilistic flood depth greater than 2 feet (Flood Depth Code = 4).

Table 2-8. Risk Categories

Risk		
Value	**Category**	**Description**
> 0.15	Critical	Lower Bound of Flood Depth Code of 4 and Evacuation Route for Any Roadway Lower Bound of Any Flooding to Functional Classification 1 Roadways (Interstates)
0.10 – 0.15	High	Lower Bound is Flood Depth Code of 4 for Any Roadway
0.01 – 0.10	Moderate	Flood Depth Code 1-3 for Functional Classifications 2-7
< 0.01	Low	No Probabilistic Flooding

Below is an example HVI evaluation for four representative road segments with the following attributes:

Table 2-9. Example Road Segment Attributes

	Evacuation Designation	Flood Depth Category	Functional Classification
Road Segment 1	1	0	1
Road Segment 2	0	3	6
Road Segment 3	0	4	5
Road Segment 4	1	2	2

In this scenario, Road Segment 1 has no probabilistic flooding (Flood Depth Code = 0); therefore, despite its evacuation route designation and high priority as an Interstate (Functional Classification = 1), the road is categorized as low risk. Road Segment 2 has significant flooding (Flood Depth Code = 3) and is a designated evacuation route; however, the lower priority of a Minor Collector (Functional Classification = 6) influences a risk categorization of moderate. Road Segment 3 is significantly flooded (Flood Depth Code = 4), but not an evacuation route. A functional classification value of 5 indicates that Road Segment 3 is of minor priority (Major Collector); however, the resultant risk value achieves a categorization of high due to the significant flooding of greater than 2 feet (Flood Depth Code = 4). Road Segment 4 has moderate flooding, and is a designated evacuation route with a higher functional classification of 2 (Principal Arterial – Other Freeways and Expressways). The calculated risk value of 0.26 for Road Segment 4 results in a critical risk category and demonstrates the elevated risk of a higher priority road segment with almost any depth of flooding.

The corresponding risk values for the four road segments are calculated as follows:

Road Segment 1:

$$risk = (1 * 0.5 + 1) * \left(\frac{(0 + 0.01)}{4}\right) * (\frac{0.7}{1})$$

$$risk = (1.5) * (0.0025) * (0.7)$$

$$risk = 0.0026$$

Road Segment 2:

$$risk = (0 * 0.5 + 1) * \left(\frac{(3 + 0.01)}{4}\right) * (\frac{0.7}{6})$$

$$risk = (1) * (0.7525) * (0.1167)$$

$$risk = 0.088$$

$$Category = \text{Moderate}$$

Road Segment 3:

$$risk = (0 * 0.5 + 1) * \left(\frac{(4 + 0.01)}{4}\right) * (\frac{0.7}{5})$$

$$risk = (1) * (1.0025) * (0.14)$$

$$risk = 0.14$$

$$Category = High$$

Road Segment 4:

$$risk = (1 * 0.5 + 1) * \left(\frac{(2 + 0.01)}{4}\right) * (\frac{0.7}{2})$$

$$risk = (1.5) * (0.5025) * (0.35)$$

$$risk = 0.26$$

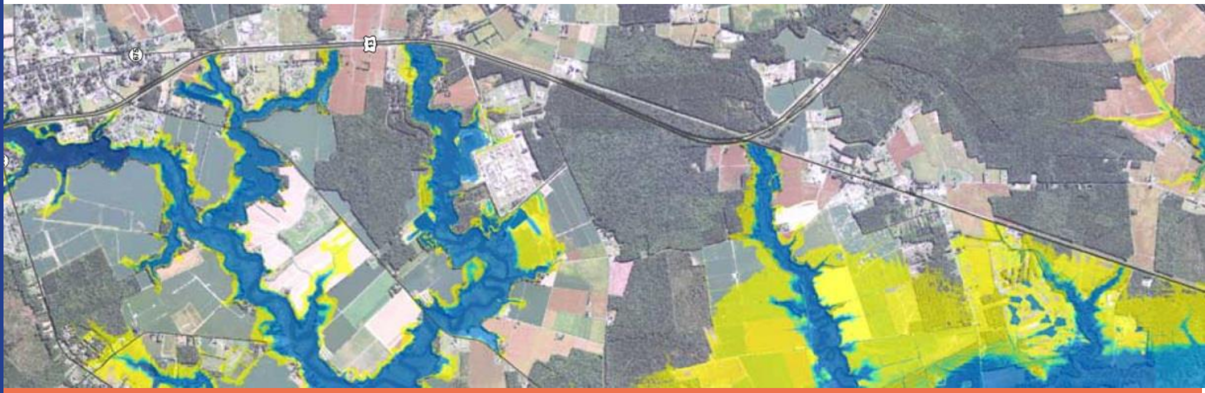
$$Category = Critical$$

The risk values and corresponding categories for the example Road Segments demonstrate the sensitivity inherent to the HVI. The *maximum* HVI risk value for a road without probabilistic flooding is 0.0026, regardless of the functional classification or evacuation route designation. In contrast, with a Flood Depth Code of 4 (greater than 2 feet of flooding) the *minimum* value of a road is 0.10025, the lower bound of the high risk category. The HVI equation demonstrates the importance of the flood depth code, but still allows the functional classification and evacuation code to provide some level of influence on the risk value.

2.2.6 Prioritization of Assets and Identify "Vulnerable Areas at Risk" for Site Specific Analysis

From the result of VAST and the HVI, SHA plotted the scores of each asset on a map in GIS for each pilot county. Consideration was given to the relative ranking of assets from VAST and HVI; and grouping of assets to identify "vulnerable areas at risk". Given the time allotted for this Pilot Study, SHA concluded its analysis for this Final Report at this stage. One of the next steps in SHA's adaptation planning efforts would be to use this data to conduct a scenario based approach (Tier III) to evaluate different alternatives including the no adaptation alternative and differing adaptation alternatives for these "vulnerable areas at risk". Alternatives could include engineering options, increased maintenance, changes to operations, or some combination of these different adaptation areas. Furthermore, cost/ benefits analysis would be conducted to further prioritize the areas at risk (see section on Cost-to-Benefits Tools in Chapter 4). The cost to benefits analysis would further refine the list of "vulnerable areas at risk" to be carried forward into Step 10 (Site Specific Analysis). For each vulnerable area at risk, a detailed feasible study would be conducted using detailed hydraulic and hydrology models of the watersheds, as-built or survey information, site visits by SHA, and detailed engineering analysis. In this analysis, SHA would explore site specific and detailed adaptation options to make the transportation infrastructure more resilient. In many instances, other factors outside of SHA's jurisdiction could drive the success of adaptation measure. As such SHA would coordinate with local jurisdictions to help to develop a holistic approach. For instance, increasing a culvert size or bridge opening is not effective if a downstream local bridge restricts the flow of the waterway. The real value of the feasibility studies will be the alternative analysis and preparation of different cost estimates for each potential adaptation solution to establish a knowledge base on the relative costs of adaptation and what is the appropriate level of investments given the transportation system scenario.

Chapter 3
Climate Variables for Maryland's Regions



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3 Climate Variables for Maryland's Regions

3.1 Overview of Climate Change Science

Maryland Past and Current Climate

Maryland's climate has been relatively stable for the approximately 6,000 years following stabilization from the last Ice Age (Boesch, D F 2008). Maryland has a temperate climate and experiences four distinct seasons. The average temperature in Maryland is 55.1 degrees Fahrenheit, with summer temperatures in the mid to upper 80s and winter temperatures in the low to mid 20s (Maryland State Archives 2013). Temperature varies slightly throughout the state due to elevation and coastal exposure. In general, temperatures are higher in low lying coastal plain areas, such as the Chesapeake Bay and Eastern Shore communities, and temperatures are comparatively lower in the higher elevation mountain regions to the west.

On average, Maryland receives approximately 41 inches of precipitation each year (Maryland State Archives 2013). Maryland has relatively little seasonal distribution of precipitation (Boesch, D F 2008); however, July and August see peak storm activity with thunderstorms every five days on average (Maryland State Archives 2013). The state receives roughly 21 inches of snowfall each year; however, this average is highly variable depending on geography. For example, on average, the Eastern Shore receives only 10 inches while Garret County in Western Maryland receives 50.1 inches (Maryland State Archives 2013).

Maryland experiences hurricanes, tornadoes and droughts. Hurricanes rarely track directly through the state and a major hurricane (Category 3 or higher) has never directly hit the shore. Despite this, storm effects including increased precipitation, high winds, and flash flooding from nearby hurricanes commonly occur in August and September. Maryland averages three reported tornadoes each year, typically during spring and summer storm events (Maryland State Archives 2013). Maryland does not regularly experience extended droughts. When dry spells occur, the average duration is approximately 15 days (Boesch, D F 2008).

Historic tide gauge records in Maryland coastal waters show that sea levels have risen by one foot over the past 100 years, which is twice the global average over the same period (Boesch, D F 2008). The combination of sea level rise and land subsidence is expected to net a relative sea level change along Maryland's coast on the order of several feet by 2100 (Boesch, D F 2008), (Boesch, et al. 2013), (MDNR 2000). The impact of rising sea levels will exacerbate hazards caused by waves, storm surges, wetland loss, and saltwater intrusion (EPA 2009). Temperatures are expected to rise several degrees, particularly during summertime (Boesch, D F 2008). Precipitation is expected to become more variable and harder to forecast. In general, precipitation is expected to increase during the winter and summer months. Changes in the activity of tropical (*e.g.*, hurricanes) and extratropical (*e.g.*, northeasters) storm systems are difficult to predict, but many studies indicate that intensity of extreme events will likely increase (Boesch, D F 2008).

In order to identify appropriate climate variables for the purposes of the Pilot Study, a comprehensive literature review focusing on climate variables that drive transportation network impacts was completed. The objective of the literature review was to identify climate change variables with relevance to transportation infrastructure vulnerability and to compile available projections for the Maryland region.

The literature review included the following sources:

- FHWA Vulnerability Assessment guidance documents (FHWA 2010), (FHWA 2011), (FHWA 2012).
- FHWA-funded pilot studies in North Jersey (New Jersey Transportation Authority 2011), Oahu (Oahu Metropolitan Planning Organization 2011), San Francisco (Commission 2011) (SFBCDC, 2011), Hampton Roads (Virginia Department of Transportation 2011), Washington State (Transportation 2011), and the Gulf Coast (U.S DOT 2008).
- State of Maryland sponsored publications, reports, and projections (Boesch, D F 2008), (Griffen, Halligan and Johnson 2008), (Boesch, et al. 2013), (Boicourt and Johnson 2010).
- Federal Emergency Management Agency (FEMA) sponsored study on the potential impacts of climate change on the National Flood Insurance Program (NFIP) (FEMA 2013).
- Intergovernmental Panel on Climate Change (IPCC) guidance for policy makers (IPCC 2007).
- U.S. DOT Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool (U.S. DOT 2014).

<u>Overarching Climate Change Research</u>

Over the past century, global average temperature has risen rapidly and glacial melting has increased. The American Meteorological Society issued its official statement on climate change on August 20, 2012, stating "It is clear from extensive scientific research that the dominant cause of the rapid change in climate of the past half-century is human-induced increases in the amount of greenhouse gases". In 2007, the Intergovernmental Panel on Climate Change (IPCC) concluded that warming of the earth is undeniable, supported by "increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level" (IPCC 2007). The IPCC has projected that continued or accelerated global warming will continue throughout the twenty first century and beyond (IPCC 2007). This is expected to have a variety of impacts to climate conditions in Maryland over the next century.

The *IPCC Fifth Assessment Report* (AR5) was released in 2014 and was preceded by the release of the findings of Working Group I (WG I); the Physical Science Basis, in September of 2013. The AR5 built upon contributions of WG I and the *2007 IPCC Fourth Assessment Report*, and incorporated new findings and scientific evidence from independent research, as well as improved climate models (IPCC 2013).

AR5 considered new evidence and observations to conclude with high confidence that climate change is occurring. The assessment recited findings from previous IPCC reports that warming of the climate system is unequivocal, and that evidence from scientific research proves that the atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of GHGs have risen (IPCC 2013). WG I stated that changes in climate events and accompanying extreme weather have been observed around the globe since the 1950s. Table 3-1 summarizes the recent observed changes in extreme weather and climate events for climate stressors related to this Pilot Study, as well as the projected changes for both the early (2016-2035) and late (2081-2100) 21st century.

Table 3-1. Observed Changes in Extreme Weather and Climate Events
Data Source: (IPCC 2013)

Phenomenon and direction of trend	Assessment that changes occurred (typically since 1950)	Likelihood of further changes Early 21st Century	Likelihood of further changes Late 21st Century
Heavy precipitation events. Increase in the frequency, intensity and /or amount of heavy precipitation	Likely more land areas with increases than decreases	Likely over many land areas	Very likely over most of the mid-latitude land masses
Increases in intense tropical cyclone activity	Virtually certain in North Atlantic since 1970	Low confidence	More likely than not in the North Atlantic
Increased incidence and/or magnitude of extreme high sea level	Likely (since 1970)	Likely	Very Likely

In their climate models used for the AR5, IPCC WG I applied a new set of scenarios called the Representative Concentration Pathways (RCPs) to project future global and regional climate change. A summary of the most significant projected changes in climate conditions, which will have substantial impacts on Maryland's climate, are presented as follows:

Temperature Projections

- Global surface temperature change for the end of the 21st century is likely to exceed 1.5°C (2.7°F) relative to 1850 to 1900 (IPCC 2013).
- It is virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase (IPCC 2013).

Water Cycle Projections

- Changes in the global water cycle in response to the warming over the 21st century will not be uniform. The contrast in precipitation between wet and dry regions and between wet and dry seasons will increase (IPCC 2013).
- Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense by the end of the century, as global mean surface temperatures increases (IPCC 2013).

Sea Level Projections

- The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia (IPCC 2013).

- Global mean sea level will continue to rise during the 21st century. Under all RCPs scenarios, the rate of sea level rise will very likely exceed that observed during 1971 to 2010 due to increased ocean warming and increased loss of mass from glaciers and ice sheets (IPCC 2013).

The IPCC Working Group II concluded in the 2014 *Impacts, Adaptation and Vulnerability Summary for Policy Makers* (IPCC, 2014) that the main drivers for climate related impacts in North America are Sea Level Rise, Damaging Cyclones, and Extreme Precipitation. The report projected with high confidence that the key risks of those climatic drivers include urban floods in riverine and coastal areas, including property and infrastructure damage; supply chain, ecosystem and social system disruption; public health impacts; and water quality impairment (IPCC 2014).

A detailed review of the practice of climate change projection and modeling is beyond the scope of this report; however, it is important to understand some of the underlying philosophy and assumptions in order to place future projections of climate in the proper perspective. Climate change projections are derived from general circulation models (GCM) run by various climate modeling groups participating in the IPCC. GCM are computer-based models that are used to understand the climate systems. They are the most advanced tools available to simulate how the global climate system will respond to the increased GHGs in our atmosphere (Boicourt and Johnson 2010). They use quantitative analysis to simulate interactions between different climate forcing agents and use emission scenarios to provide a trajectory of how the global climate could change, and then project the ranges of changes in climate related parameters including mean sea level and global temperatures. GCM results are based on large grids; therefore regional results can be obtained by downscaling GCM output through nesting of a Regional Climate Model (RCM) that is intended for smaller grids sizes associated with local regions.

In general, the impact on different climate variables can be predicted with varying degrees of confidence. For example, temperature change is projected with higher confidence than precipitation (Boesch, D F 2008). Also, due to the spatial and temporal resolution of these models, it is much easier to quantify long-term averages than to predict short-term events, such as hurricanes or snowstorms. Finally, is easier to project climate variables in the near future with more confidence than in the distant future.

It is notable that climate change modeling represents a significant departure from historical modeling approaches in which statistical analysis of past events are used to predict the future. The need for climate change modeling stems from the fact that with climate change, the concept of stationarity is lost. Stationarity is the phenomenon of natural systems fluctuating within an unchanging envelope of variability, and has been a fundamental assumption in traditional engineering design in many applications, including structural codes and water resources management. With historic datasets, the statistical parameters of mean and standard deviation do not change with time, but with climate change there is no more stationarity. Therefore, historical data alone will not describe or account for an entire range of operating conditions and expanded risks associated with that larger range of variation. With the application of climate models, “deltas” or changes in certain climate parameters can be generated and these “deltas” are then applied to the baseline (historical observed) datasets to determine a projection of the future climate for use in vulnerability assessments. The use of climate projections in combination with an assessment of recent trends in severe events can provide climate information that can be applied in vulnerability assessments of infrastructure and processes.

A recent Maryland Climate Change strategy report, *Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change, Phase II: Building Societal, Economic and ecological Resilience,* noted that "past methods for assessing flood probabilities based on historical records are not adequately accounting for future change" (Boicourt and Johnson 2010). Indeed, FHWA guidance for vulnerability assessments notes that "prevailing or typical historical climate conditions are unlikely to be representative of the future climate conditions" (FHWA 2011). As such, there is fundamental uncertainty with any climate model projection. As research advances, computing capabilities grow and modeling capabilities/algorithms improve, future climate projections will not only become more accurate but will likely be more readily generated for regions of interest in future vulnerability and adaptation assessments.

3.2 Rationale for Dismissing Certain Climate Variables

During the identification process, several climate variables were determined to be of minor significance to the Pilot Study's geographic region or infrastructure asset under assessment, or were beyond the scope of this study. Permafrost thaw is an example from the FHWA guidance (FHWA 2012) which would have no applicability in Maryland. Additionally, there are other variables which might be relevant, such as wind, relative humidity and solar radiation (FHWA 2011) that are not significant to the infrastructures assets, or reliable projections for these variables are not available. The key quantifiable impacts to SHA infrastructure will generally be limited to those variables that increase the potential for episodic flooding, permanent inundation and high water velocity, or wave action in the vicinity of floodplain crossings and coastal highways.

In order to merit consideration, a key climate stressor must:

- be relevant to the geography and climate of Maryland,
- be relevant to SHA's transportation infrastructure,
- have supporting scientific data,
- be feasible for analysis through use of historical records, and
- have available climate models capable of generating projections for the specific climate variable.

After detailed review, it was determined that three variables meet these criteria: sea level change, storm surge, and increases in precipitation intensity.

3.2.1 Sea Level Change

Given Maryland's coastal exposure and the considerable area within the Chesapeake Bay and Potomac River estuary, sea level change is already a prime concern for transportation infrastructure located within coastal areas. Historic island abandonment due to sea level change in the past century is well documented for Chesapeake Bay communities such as Holland Island (Arenstam Gibbons and Nicholls 2006). Thermal expansions of ocean and glacier mass loss due to melting are the dominant contributors to global sea level rise (Boesch, et al. 2013). Relative sea level change is the combined effect of vertical land movement (subsidence) and global sea level rise. Coastal areas in Maryland have historically experienced a subsidence of approximately 1.7 millimeters each year (Boesch, et al. 2013). Climate change over the next century is expected to increase the rate of sea level change, and there are several recent, well documented projections of what magnitude of change Maryland communities can expect.

In 1995, a United States Fish and Wildlife Service (USFWS) report broadly projected a 2-3 foot rise in sea levels in Maryland over the years 1995-2100 **(Leatherman, et al. 1995)**. In 2008, the Scientific and Technical Working Group (STWG) of the *MCCC* provided detailed sea-level change estimates based on downscaling results from the IPCC Fourth Assessment general circulation model **(Boesch, D F 2008)**. These estimates included assumptions on various future emission scenarios (lower and higher) and used a land subsidence rate in Maryland consistent with that observed in the 20th century. The 2008 projections, predict that Maryland may experience a relative sea level change by 2100 of 2.7 feet and 3.4 feet (see Figure 3-1) under the lower and higher IPCC emission scenarios, respectively. However, the IPCC model has been criticized as being too conservative due to the fact that ice flow dynamics are not included in the analysis **(Boesch, D F 2008)**.

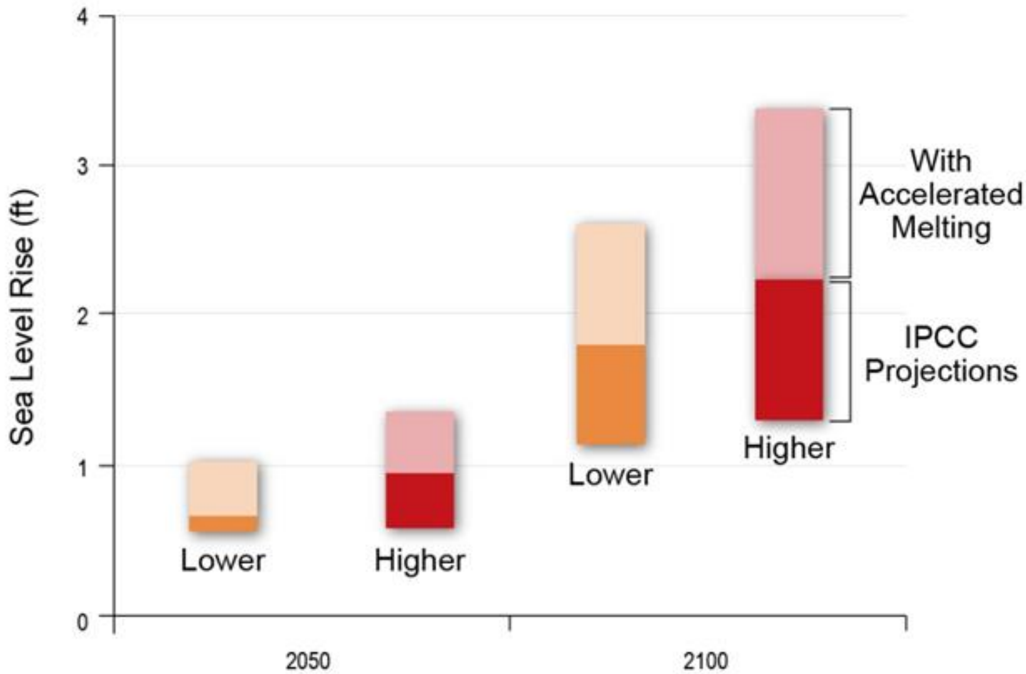

Figure 3-1. Projected Relative Sea Level Rise in Maryland during the 21st Century under the Higher and Lower Emission Scenarios

Data Source: (Boesch, D F 2008)

In 2013, the STWG convened again to update Maryland's sea level rise projections with a new approach (Boesch, et al. 2013). These results are provided in terms of best, low and high projections at sea-level rise for Maryland for 2050 and 2010 (Boesch, et al. 2013) and are summarized in Table 3-2. Sea Level Rise Projections below.

Table 3-2. Sea Level Rise Projections
Data Source: (Boesch, et al. 2013)

Maryland Relative Sea Level Rise	Sea Level Rise (ft)
2050 best	1.4
2050 low	0.9
2050 high	2.1
2100 best	3.7
2100 low	2.1
2100 high	5.7

In order to establish a more accurate projection for sea level change and develop GIS mapping that can be used in project planning, SHA established an agreement with Salisbury University to develop downscaled sea level change data for each Maryland County using the latest LiDAR information as described in Chapter 2. Table 3-3 presents the projected sea level change values for a selection of Maryland tidal stations. These values were developed by utilizing the US Army Corps of Engineers guidance (USACE 2013) and utilized in the Pilot Study to determine sea level change. Tidal Stations for each coastal County were identified based on proximity and conditions. Anne Arundel County's tidal range is projected to be 2.08 MSL for 2050 and 5.70 for 2100 (2.79 MHHW for 2050 and 6.41 MHHW for 2100) and Somerset county is projected to be 2.11 MSL for 2050 and 5.78 MSL for 2100 (3.13 MHHW for 2050 and 6.80 MHHW for 2100). Detailed inundation mapping for sea level change for each pilot county is provided in Chapter 5.

Table 3-3. Sea Level Change Values
Data Source: (Salisbury University)

County	Tidal Station	2050 MSL	2050 MHHW	2100 MSL	2100 MHHW
Anne Arundel	Annapolis	2.08	2.79	5.70	6.41
Baltimore	Baltimore	2.01	2.87	5.59	6.45
Baltimore City	Baltimore	2.01	2.87	5.59	6.45
Calvert	Solomons Island	2.10	2.82	5.76	6.48
Caroline	Cambridge	2.11	3.13	5.78	6.80
Cecil	Chesapeake City	1.98	3.63	5.56	7.21
Charles	Washington DC	2.21	3.83	5.78	7.40

County	Tidal Station	2050 MSL	2050 MHHW	2100 MSL	2100 MHHW
Dorchester	Cambridge	2.11	3.13	5.78	6.80
Harford	Baltimore	2.01	2.87	5.59	6.45
Kent	Annapolis	2.08	2.79	5.70	6.41
Prince George's	Washington DC	2.21	3.83	5.78	7.40
Queen Anne's	Annapolis	2.08	2.79	5.70	6.41
Somerset	Cambridge	2.11	3.13	5.78	6.80
St. Mary's	Solomons Island	2.10	2.82	5.76	6.48
Talbot	Cambridge	2.11	3.13	5.78	6.80
Wicomico	Cambridge	2.11	3.13	5.78	6.80
Worcester	Ocean City	2.06	3.25	5.86	7.05

3.2.2 Storm Surge

Storm surge is an abnormal rise of water generated by a storm, over and above the predicted astronomical tide. It is typically caused by tropical storms such as hurricanes and is occasionally attributed to winter storms including Nor'easters. Sixteen of Maryland's twenty-four counties are at risk from storm surge, as they are located along the Atlantic Ocean or Chesapeake Bay coasts. According to the National Hurricane Center, only two hurricanes have made landfall in Maryland since 1900 (National Weather Service n.d.). This statistic can be misleading though as direct impacts, including damaging storm surge from several hurricanes have affected Maryland when these hurricanes did not reach a landfall. SURGEDAT, a database of historical storm surge measurements, lists a storm surge value of 4.33 feet for Hurricane Sandy in 2012 and a storm tide (storm surge plus normal, astronomical tide) value of 3.01 feet for Hurricane Irene, both in Ocean City. These recent measurements are two of the highest storm surges on record in Maryland (Southern Climate Impacts Planning Program n.d.), and these values are consistent with a trend of hurricanes achieving maximum strength at higher latitudes (Kossin, Emanuel and Vecchi 2014).

Another contributing factor to increased storm surge potential in Maryland is the rise of sea level. Coastal areas experiencing sea level rise would see greater effects from storm surge and inland areas typically immune from storm surge effects could become more vulnerable. Coastal bathymetry, a significant factor in storm surge magnitudes, could also be altered due to sea level rise and contribute to storm surge impacts. Vegetation and infrastructure closer to the land-sea interface could be affected, resulting in increased debris fields resulting from storm surge.

As described in the methodology section in Chapter 5, Salisbury University analyzed riverine flood depth grids considering newly developed sea level change data and to prepare inundation mapping. Detailed inundation mapping for the 100-year storm event for each pilot county is provided in Chapter 5.

3.2.3 Precipitation Patterns

Yearly precipitation in Maryland is highly variable from year to year. Projections can capture long-term average changes in precipitation, as well as anticipated changes in seasonal variability, but it is difficult to quantify changes on a smaller scale with global circulation models alone.

The 2008 STWG report offers some broad projections based on global circulation models (Boesch, D F 2008). Generally, rainfall in the winter will increase over time as much as 13% by 2090. Winter snow volume is expected to decrease by 50% in 2100. Changes are not anticipated in the spring and fall seasons, however summer rainfall volume is expected to increase. Figure 3-2 shows the STWG projection for Maryland's precipitation.

Regional changes in precipitation data are also available from a 2010 FHWA report **(FHWA 2010)**, and those precipitation projections generally agree with the STWG precipitation projections. Maryland is difficult to project accurately as it lies on the border between the "northeast" and "southeast" regions of the U.S. which is the dividing line for regional projections. Greater increases are anticipated in the northeast. Projections for both the northeast and southeast are included in Table 3-4 and Table 3-5.

Seasonal precipitation percent changes are shown over three future time horizons: near term (2010-2029), mid-century (2045-2059) and end century (2080-2098) relative to 1961-1979. The range presented in the tables are from low and high emission scenarios, numbers in parentheses are negative (*e.g.*, (2) equals -2).

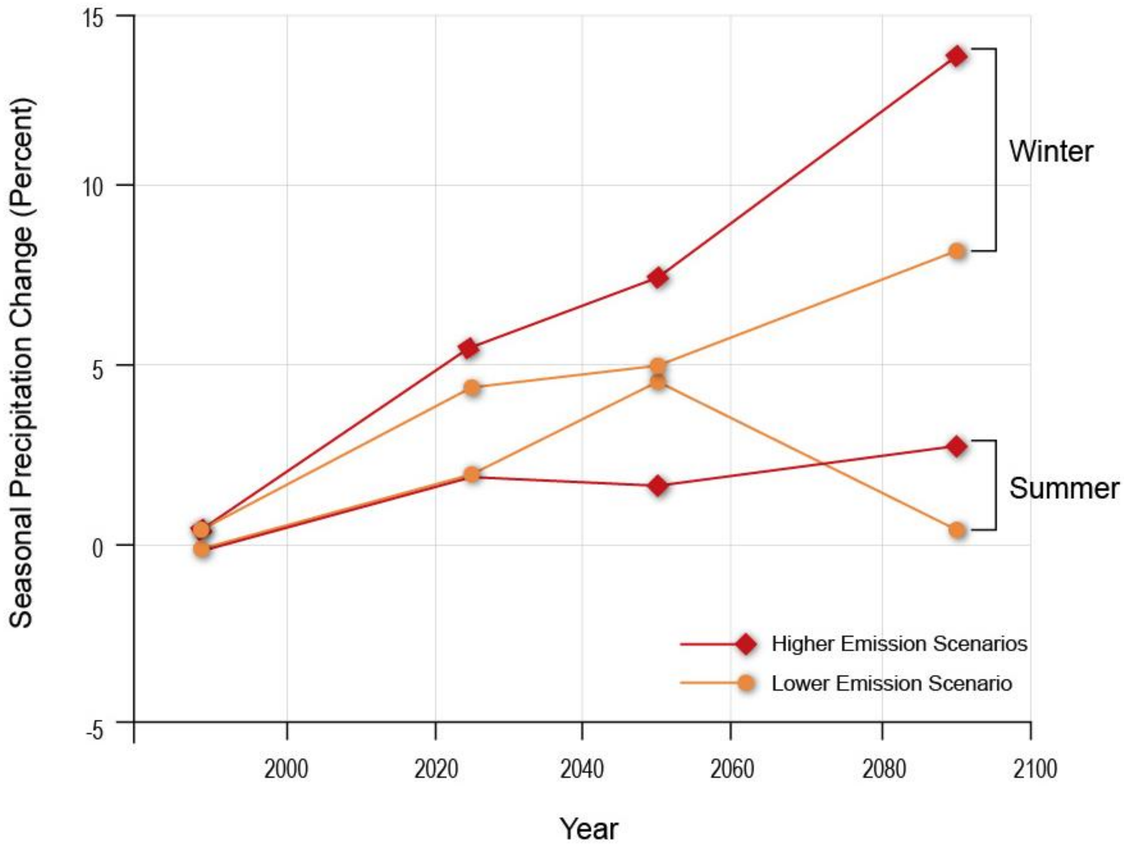

Figure 3-2. Anticipated Seasonal Precipitation Change

Data Source: (Boesch, D F 2008)

Table 3-4. Projected Changes in Precipitation (Low to High Emissions Scenario) for the Northeast Region over the near term (2010-2029), mid-century (2045-2059) and end century (2080-2098) relative to 1961-1979
Data Source: (FHWA 2010)

Northeast (Δ Precipitation)		Near-term (%)	Mid-century (%)	End-of-century (%)
Winter	Mean	6	8 – 11	11 – 17
	Likely	2-11	2 – 18	4 – 27
	Very Likely	(2) – 15	(4) – 26	(4) – 36
Spring	Mean	3	5 – 6	9 – 11
	Likely	(2) – 7	0 – 12	1 – 21
	Very Likely	(7) – 12	(5) – 17	(9) - 31
Summer	Mean	2	1 – 2	(1) – 2
	Likely	(1) – 6	(6) – 7	(12) – 11
	Very Likely	(5) – 10	(12) – 14	(24) – 23
Fall	Mean	1 – 2	3	3 – 4
	Likely	(4) – 6	(3) – 9	(5) - 13
	Very Likely	(10) – 11	(9) – 16	(15) – 23

Table 3-5. Projected Changes in Precipitation for the Southeast Region over the near term (2010-2029), mid-century (2045-2059) and end century (2080-2098) relative to 1961-1979
Data Source: (FHWA 2010)

Southeast (Δ Precipitation)		Near-term (%)	Mid-century (%)	End-of-century (%)
Winter	Mean	(1) – 0	(2) – 1	(3) – 0
	Likely	(6) – 5	(8) – 9	(15) – 10
	Very Likely	(11) – 9	(15) – 16	(28) – 22
Spring	Mean	(2) – 0	1 – 2	(7) –11
	Likely	(7) – 4	(5) – 8	(20) – 7
	Very Likely	(12) – 8	(11) – 14	(32) – 18
Summer	Mean	0	(2) – 0	(8) – 0
	Likely	(8) – 8	(14) – 10	(29) – 14
	Very Likely	(16) – 16	(26) – 23	(50) – 35
Fall	Mean	1 – 2	(2) – (1)	2 – 3
	Likely	(4) – 7	(9) – 5	(9) - 16
	Very Likely	(10) – 12	(16) – 12	(21) – 28

3.2.4 Temperature

Despite the fact that temperature was not one of the key climate stressors considered for the Pilot Study, it is important to present data on Maryland's temperature projections since all key climate stressors are related to and impacted by increases in temperature. Temperature is expected to increase in Maryland; however, the magnitude of this increase is largely dependent on the rate of emission loadings in the future. A 2010 state vulnerability assessment (Boicourt and Johnson 2010) used projections for temperature changes based on two emissions paths: a higher emissions scenario that assumes continued growth in global emissions throughout the century, and a lower emission scenario that assumes slower global growth, with a peak at mid-century, and a 40% decline compared to present levels by the end of the century (Boesch, D F 2008). The assessment found that:

- Under a low emissions scenario, the number of days in a given year exceeding 90 degrees Fahrenheit may double from 30 to 60 days over the next century.
- Under a high emissions scenario, nearly all summer days would exceed 90 degrees Fahrenheit (90 days).
- Winter temperatures are expected to warm between 0.8 and 2 degrees Fahrenheit under low and high emissions scenarios.

Table 3-6 provides a summary of the projected changes in temperatures for the NE region.

Table 3-6. Projected Changes in Temperature for the Northeast Region over the near term (2010-2029), mid-century (2045-2059) and end century (2080-2098) relative to 1961-1979
Data Source: (FHWA 2010)

Northeast (Δ Temperature)		Near-term (°F)	Mid-century (°F)	End-of-century (°F)
Annual	Mean	2.5	3.8 – 4.8	5.4 – 9.0
	Likely	1.9 – 3.2	2.8 – 5.8	4.2 – 10.8
	Very Likely	1.3 – 3.8	1.9 – 6.8	3.0 – 12.5
Winter	Mean	2.8 – 3.0	4.0 – 5.4	5.9 – 9.3
	Likely	1.8 – 3.8	2.9 – 6.6	4.7 – 11.0
	Very Likely	0.9 – 4.7	1.8 – 7.9	3.5 – 12.8
Spring	Mean	2.0 – 2.2	3.5 – 4.1	5.0 – 8.1
	Likely	1.2 – 3.0	2.2 – 5.5	3.6 – 10.0
	Very Likely	0.4 – 3.8	0.9 – 6.8	2.3 – 11.9
Summer	Mean	2.3 – 2.5	3.7 – 4.8	5.2 – 9.4
	Likely	1.8 – 3.1	2.8 – 5.8	3.9 – 11.8
	Very Likely	1.3 – 3.7	1.8 – 6.9	2.7 – 14.1
Fall	Mean	2.5 – 2.7	3.9 – 4.8	5.3 – 9.1
	Likely	1.9 – 3.3	2.8 – 5.6	3.9 – 10.8
	Very Likely	1.2 – 3.9	1.8 – 6.5	2.5 – 12.8

These projections are significantly more conservative than the 2008 projections of the STWG. The STWG projects a 4.8 degree increase in summer and a 4 degree increase in winter over the next century under a low emissions scenario, and a 9 degree summer and 7 degree winter increase under a high emissions scenario (Boesch, D F 2008). The 2008 assessment is in agreement with the 2010 projection with regards to the frequency of 90 degree days.

The 2010 FHWA report also includes regional temperature projections for the southeast region, the results generally are very close to the STWG projections. These results are included in Table 3-7 from low and high emission scenarios.

Table 3-7. Projected Changes in Temperature for the Southeast Region over the near term (2010-2029), mid-century (2045-2059) and end century (2080-2098) relative to 1961-1979
Data Source: (FHWA 2010)

Northeast (Δ Temperature)		Near-term (°F)	Mid-century (°F)	End-of-century (°F)
Annual	Mean	2.1 – 2.2	3.2 – 4.0	4.5 – 7.8
	Likely	1.7 – 2.7	2.4 – 4.8	3.4 – 9.4
	Very Likely	1.2 – 3.2	1.6 – 5.5	2.4 – 10.9
Winter	Mean	1.9 – 2.1	2.7 – 3.6	4.0 – 6.3
	Likely	1.1 – 2.8	1.6 – 4.5	2.8 – 7.9
	Very Likely	0.3 – 3.6	0.5 – 5.4	1.7 – 9.4
Spring	Mean	1.8 – 2.0	3.1 – 3.8	4.4 – 7.5
	Likely	1.3 – 2.7	2.2 – 4.6	3.2 – 9.1
	Very Likely	0.6 – 3.3	1.3 – 5.4	2.0 – 10.7
Summer	Mean	2.3 – 2.4	3.5 – 4.5	4.8 – 9.0
	Likely	1.5 – 3.0	2.5 – 5.6	3.5 – 11.2
	Very Likely	0.7 – 3.8	1.6 – 6.7	2.3 – 13.5
Fall	Mean	2.3	3.4 – 4.3	4.7 – 8.3
	Likely	1.8 – 2.9	2.6 – 4.9	3.5 – 9.8
	Very Likely	1.2 – 3.4	1.8 – 5.6	2.4 – 11.3

3.2.5 Storm Frequency and Intensity

Knutson et al. (2010) provide a comprehensive review of literature related to projected climate change impacts on the frequency and severity of tropical storm systems (*i.e.*, hurricanes and tropical storms). The model data was collated from various modeling groups and shows substantial variation. However, the general consensus is that in the northern Atlantic, tropical storm systems will see a mean increase in intensity of approximately 8% and a mean decrease in storm frequency of approximately 8%. There is greater confidence in the projections for storm intensity change (6% standard deviation) versus projections for storm frequency change (30% standard deviation).

To assess impacts resulting from increased precipitation and storm frequency, Salisbury University derived depth grids for estimated probabilistic 10-, 25-, 50-, 100-, and 500-year precipitation events for both 2050 and 2100, for all Maryland coastal counties. Inputs to the riverine flood model in Hazus are the detailed, LiDAR-derived DEM, flood elevation cross-sections (preferably imported from a recent dFIRM flood study), and the 100-year floodplain boundary. More detailed methods are presented in Chapter 2. Inundation maps for the two pilot counties are provided in Chapter 5.

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Chapter 4

General Evaluation of Asset Vulnerability, Adaptation, and Prioritization

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4 General Assessment of Asset Vulnerability, Adaptation, and Prioritization

Before making detailed recommendations on which assets are vulnerable and at risk, a review of the existing literature was conducted, including other pilot studies, to assess the applied understanding of the causes and mechanisms of transportation specific asset failures/vulnerabilities and the corresponding adaptation measures intended to maximize resiliency. This chapter presents the results of the asset vulnerability evaluation to each of the climate stressors. The information in this chapter, along with the table of vulnerabilities and potential adaptation measures provided in Appendix A**,** will provide a general tool box from which to draw from when considering options on how to make assets more resilient to climate change.

4.1 General Vulnerabilities and Failures by Asset

Figure 4-1. Typical Roadway Damage in Maryland
Photo Sources: (FEMA/Jun 2011)

Transportation systems are generally designed to withstand conditions anticipated by local climate and weather patterns. Transportation engineers use historic climate records when designing transportation systems. Due to climate change, historic climate data alone can no longer be used to predict future impacts to transportation systems. Climate change is projected to increase the frequency and intensity of extreme weather events (EPA n.d.). Sea level rise will increase storm surge impacts in coastal areas causing more damage. These changes could increase the risk of delays, disruptions, damage, and failure of transportation systems. Some transportation infrastructure, currently being designed and built, is expected to be in service for 70 years or longer; therefore, it is important to recognize how future climate might affect these investments during their service life (EPA n.d.). Roadway segment failure from a severe weather event is presented in Figure 4-1.

This Pilot Study focuses on three asset types: (1) bridges/small structures, (2) roadways, and (3) small culverts/drainage conveyances. A description of the vulnerabilities and risks follow in this chapter.

4.1.1 Bridges/Small Structures

Of the three asset types, bridges and small structures have the most available quantitative data because of the FHWA reporting requirements for bridges as part of the National Bridge Inventory. Bridges can be affected by changes in sea level, storm surge, and increased runoff due to changes in precipitation. Sea level change may impact additional bridges by pushing water further inland thereby creating tidal effects in areas where there was previously no tidal influence. Representative impacts to bridges and small structures from the three climate stressors include:

- Raising tailwater elevations due to increases in sea level may impact bridges by causing more frequent inundation.
- Sea level change has the potential to increase the volume of water and tidal flows causing additional scour that could potentially undermine bridge foundations.
- More frequent saltwater intrusion could cause bridge elements to corrode over time.
- Water flowing over roadway approaches to bridges could cause erosion of the road approach embankments and damage to the roadway surface.
- Storm surges may also cause bridge superstructures to become buoyant beyond what they were designed for. Timber bridges are at particularly high risk for this type of impact.
- Movable bridge mechanical systems and utilities are at risk of flood damage due to sea level change and storm surge.
- Riverine flooding associated with severe or flash rain events may cause scour and the undermining of foundations.
- Floating debris may accumulate during storm events causing increased flooding, damage and scour.
- Increased precipitation can lead to embankment /side slope erosion and possible slope failure.

Figure 4-2. Example of Floating Debris Lodged in a Bridge during 2006 Flood Event at Seneca Creek in Germantown, MD
Photo Source: (FEMA/Skolnik 2006)

An understanding of bridge vulnerability is very dependent on detailed knowledge about the individual structures. A number of variables increase or decrease the vulnerability of the structure in addition to the known physical location of the structure. The physical location indicates the structures exposure risk to rising sea level, storm surge, or riverine flooding. Other unknown factors that greatly impact the bridge's vulnerability include: height of the bridge span, age of the structure, the current condition of the structure, scour rating, etc. Site specific information about the flooding history of the structure, scour history, channel lateral migration and vertical degradation, geology, foundation material and how the structure responded in the past is vital to accurately assess the future responses of the structure to increased climate stressors. Figure 4-2 shows a photograph of a flood event in 2006 and how floating debris can become lodged into the bridge affecting the flow and capacity of the opening to convey water. This debris adds additional force and stress to the bridge structure. Figure 4-3 shows examples of the potential vulnerabilities for specific bridge components, resulting from severe weather events.

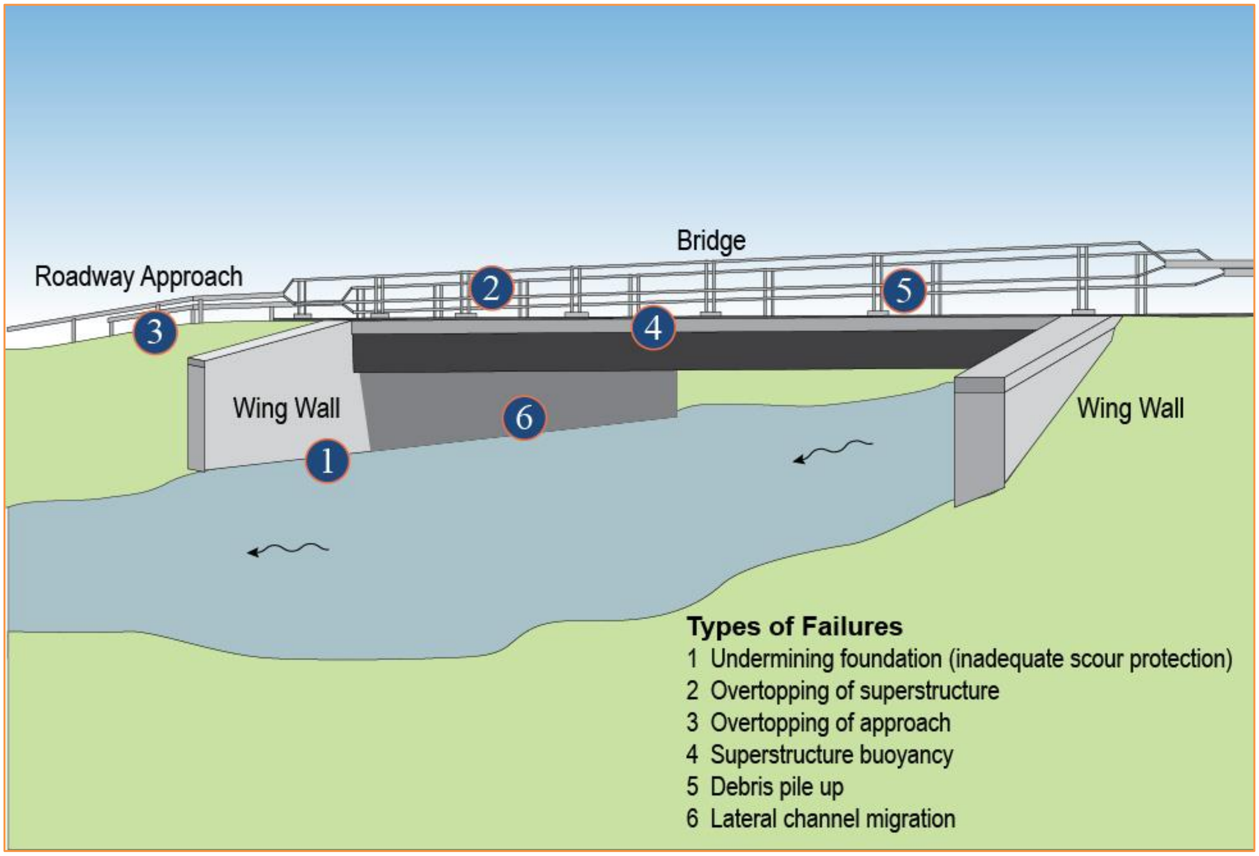


Figure 4-3. Types of Climate Induced Stressors that could lead to Failure during Extreme Weather Events

4.1.2 Roadways

Roadways and associated infrastructure in coastal areas are particularly sensitive to more frequent and permanent flooding from sea level change and storm surges. Approximately 60,000 miles of roadways in coastal zones in the United States are currently exposed to flooding from coastal storms and high waves (EPA n.d.). In addition, major highways in coastal areas serve as evacuation routes. Evacuation routes must be protected from flooding and damage so they can be used in case of emergencies. Climate change could also concentrate rainfall into more intense storms. Heavy rains may result in flooding, which could threaten public safety, disrupt traffic, delay construction activities, and weaken or wash out the soil and culverts that support roads, tunnels, and bridges (EPA n.d.). Exposure to floods also reduces the life expectancy of highways and roads because of the stress of water may damage infrastructure and reduce expected service life, requiring more frequent maintenance, repairs, and reconstruction. Overtopping or bank failure would also have an impact on roadway operations.

Figure 4-4. Example of roadside erosion along a MD road.
Photo Source: SHA, 2014

Assessing the vulnerability of a roadway segment presents different challenges than bridges or small conveyances. One of the challenges arises when transportation asset does not have surface water nearby. Climate change or severe weather can affect the roadway due to unseen impacts that may occur over time. As an example, sea level change can cause a rise in the water table, which in turn may affect the sub-base of pavement structure. Increased water in the sub-base can cause the weakening of the roadbed and pavement thereby reducing pavement life. Another challenge is assessing vulnerability related to inundation of roadways. Roadways that have been temporarily inundated do not always require replacement. There needs to be a review of the pavement history to help with the evaluations. Pavement design and historical information such as age, maintenance (*i.e.*, patching, overlays, etc.), and traffic volumes are important to the assessment. If some of the information is not available it is possible to supplement with data for similar roadways.

Assessing vulnerability of the roadways drainage systems is interdependent to the potential risk to the roadway and effective operations. Properly maintained closed system should not present a problem, but if there are cracks, misalignment of joints or clogs in the drainage pipes water could be forced outside the inlets or through pipes cracks and cause problems, like piping, erosion and even pipe collapse during increased intensified precipitation events.

4.1.3 Small Culverts/Drainage Conveyances

Small drainage assets including small culverts, storm drains, drainage swales, drainage ditches, stormwater management (SWM) facilities (i.e. Ponds), and environmental site design (ESD)/low impact development (LID) best management practices (BMPs) will likely be impacted by the climate stressors. Sea level change and/or higher storm surge in coastal areas could adversely impact the hydraulic function of the small drainage assets and their ability to provide stormwater management treatment benefits due to either inundation or increased tailwater. Increases in the intensity and volume of precipitation could impact small drainage assets in either coastal or upland areas by causing overtopping of structures, excessive ponding or increased erosion. Additional impacts could include loss of vegetation or increases in the groundwater elevation (infiltration and ESD BMPs require a minimum clearance above the groundwater in order to function properly).

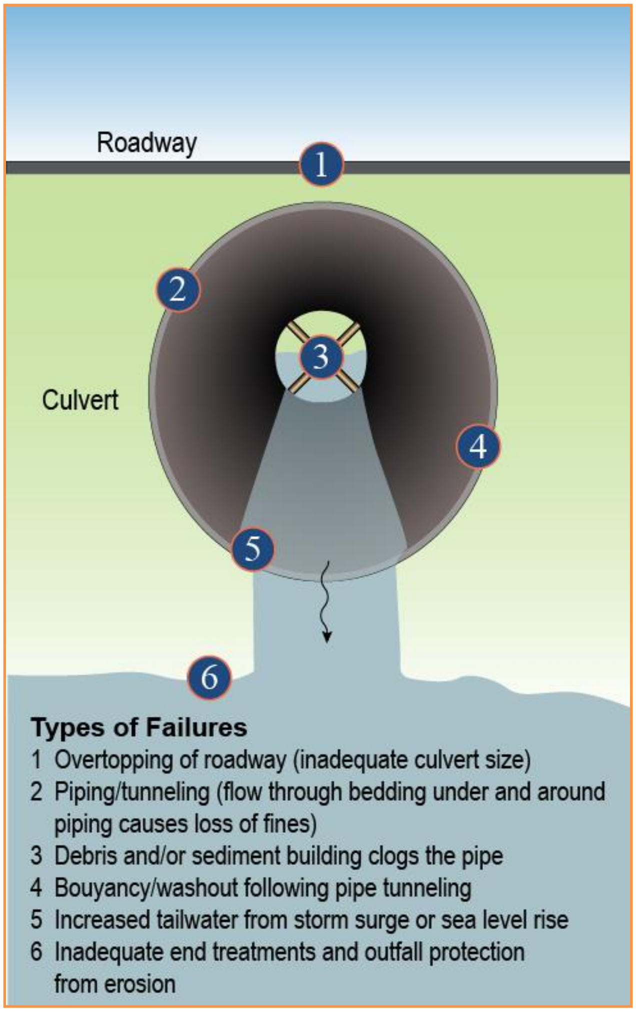


Figure 4-5. Typical Conditions that lead to Failures for Roadway Culverts

Each small drainage asset has its own unique characteristics, which makes large scale screening techniques impractical. Evaluation of a particular asset would require information about the drainage area, impervious area, non-impervious area, time of concentration to asset, dimensions of the asset, slope of the asset, and capacity of the asset. The same information might also be necessary for nearby assets that could have hydraulic impacts on the asset in question.

Identification of small drainage assets impacted by climate change is therefore limited to those assets that are in or adjacent to segments of impacted roadway. If a roadway is impacted by climate change it is assumed that all drainage and SWM facilities associated with that segment of roadway could also be impacted. It should be noted that nearby segments of roadway that lie just above the impact may experience impacts to the drainage and SWM assets due to increases in tailwater.

Figure 4-5 illustrates types of culvert failures and a table provided in Appendix A provides a more detailed list of vulnerabilities and failures with corresponding adaptation measure.

4.2 Adaptive Capacity of Infrastructure

Adaptive capacity is the ability of a system to adjust to climate change in order to decrease potential damages, to take advantage of opportunities, or to cope with the consequences (FHWA 2012). A transportation system can have stronger adaptive capacity if it has alternate routes or modes. For instance, if a roadway segment is blocked due to flooding, the accessibility of parallel routes or alternative modes can continue to enable travel between destinations. Another relevant factor is how easily and quickly service can be restored to a segment or asset following a climate-related disruption. Other key considerations for evaluating adaptive capacity include (FHWA 2012):

- Is the system already able to accommodate changes in climate?
- Are there barriers to a system's ability to accommodate changes in climate?

- Is the system already stressed in ways that will limit the ability to accommodate changes in climate?
- Is the rate of projected climate change likely to be faster than the adaptability of the system?
- Are there efforts already underway to address impacts of climate change related to the system?

Conducting a vulnerability assessment will aid transportation decision-makers in prioritizing actions and determining how to improve the adaptive capacity of the system. As part of the ranking used for VAST, adaptive capacity indicators were reviewed and ranked to help SHA prioritize the assets most vulnerable or at a higher risk.

4.3 General Adaptation Strategies and Actions

The overarching goal of the climate change adaptation strategy is to continue to cost-effectively maintain the safety and serviceability of Maryland's highway system as the state's climate changes (SHA/MDTA Adaptation Strategy, 2013).

Climate change adaptation addresses the vulnerability of natural and human systems to climate change and focuses on a reduction of damage resulting from those changes (GAO 2013). Adaptation efforts reduce the vulnerability of systems that have some risk of experiencing an extreme event or long-term change in conditions. The *SHA/MDTA Climate Change Adaptation Strategy* (SHA and MDTA 2013) provides broad mitigation measures intended to primarily protect state roadways, but also has implications for all modal administrations. These measures have been identified as practical operations, maintenance, and administrative actions that respond to and limit damage from extreme weather events that are already occurring and may worsen over time. The Pilot Study considers and helps to accomplish a number of the action items proposed in the strategy including but not limited to:

1. Create an internal climate change adaptation task force to guide the climate change assessment process
2. Identify sources of probabilistic climate projections for key infrastructure design parameters through the year 2100
3. Recommend SHA/MDTA climate projections (climate models, downscaling technique, & emissions scenarios) to use
4. Identify the key climate threats to the transportation system through the year 2100 and their expected onset dates
5. Identify critical thresholds where asset functionality and safety will be jeopardized and enter into asset management system
6. Conduct high-level system wide risk analysis of the climate threats to SHA assets; begin with one county pilot analysis
7. Conduct detailed asset-specific vulnerability analyses for the most critical and unsafe high-risk assets
8. Develop a menu of possible adaptation solutions for common climate threats

9. Utilize best available data to identify future project needs due to climate change
10. Incorporate adaptations into new project siting and designs when necessary

Another consideration in SHA's approach to climate change adaptation is the recent passing of House Bill 615 (HB 615), the *Coast Smart Council* and the *Coast Smart Construction Siting and Design Guidelines* dated January 31, 2014 developed by the DNR. HB 615 establishes the Coast Smart Council housed within the DNR. Key points from HB 615 include:

- The Council will be responsible for developing "Coast Smart" siting and design criteria related to sea level rise and coastal flood impacts on capital projects.
- "Coast Smart" is defined as a construction practice in which preliminary planning, siting, design, construction, operation and maintenance, and repair of a structure avoids or minimizes future impacts associated with coastal flooding and sea level rise.
- Beginning July 1, 2015, if a state capital project includes construction of a structure or reconstruction of a structure with substantial damage, the structure must be constructed or reconstructed in compliance with the site and design criteria.
- "Structure" is defined as a walled or roofed building, a manufactured home, or a gas or liquid storage tank that is principally above ground (not applicable to bridges at this time).
- A requirement of the HB 615 is that capital projects within a Special Flood Hazard as defined by the National Flood Insurance Program be constructed so that the lowest floor elevation of each structure is built at an elevation of at least 2 feet above the base flood elevation (2 feet of freeboard).
- Special Flood Hazard as defined by FEMA is subject to at least a 1% chance of flooding in any given year and is designed in Flood Studies or on Flood Insurance Rate Maps (FIRMs) as Zone A, AE, AH, AO, AI-30, A99, VE or V1-30.

The *Coast Smart Construction Site and Design Guidelines* apply to construction of new state structures (buildings), the reconstruction of substantially damaged state structures, and/or other new major infrastructure projects. These structures should not be constructed, to the fullest extent practicable, within areas likely to be inundated by sea level rise within the next 50-years. New state "critical or essential facilities" should not be located within Special Flood Hazard Areas designated under the National Flood Insurance Program (NFIP) and should be protected from damage and loss of access as a result of a 500-year flood magnitude. There is an exemption for existing transportation assets, among other exemptions including critical facilities such as highway accesses and other essential transportation infrastructure. In the *Coast Smart* document infrastructure refers to roads and bridges.

One adaptation measure proposed in the siting and design criteria is a two (2) foot freeboard requirement. All new state structures (buildings) and the reconstruction or rehabilitation of substantially damaged state structures located in Special Flood Hazard Areas are required to be constructed with a minimum of two (2) feet of freeboard above the 100-year base flood elevation, as defined by the NFIP. Users should take note that the regulatory floodplain maps along the Maryland shoreline are currently being revised by Federal Emergency Management Agency (FEMA). State structures serving transportation purposes that are not water dependent or dependent on integral infrastructure are to be constructed with a minimum of two (2) feet of freeboard above the 100-year base flood elevation, as defined by the NFIP. State agencies should employ *Coast Smart* practices when constructing all new state structures, reconstructing or rehabilitating substantially damaged state structures, or making other major infrastructure improvements in Maryland's coastal zone, such as roads, bridges, sewer and water systems, drainage systems and essential public utilities. Similar measures should be applied to non-state structure or infrastructure projects if partially or fully funded by state agencies; and to non-state projects located on state-owned lands. The guidance goes on to state that state agencies should take the necessary steps to incorporate the recommended *Coast Smart* practices into all appropriate architecture, engineering, construction and design manuals, state planning programs, regulatory programs, permitting and review processes, disaster planning and response, capital budgeting, and state grant and loan programs. State agencies should develop or amend an agency specific implementation plan which should include the status and next steps toward incorporation of the *Coast Smart Siting and Design Guidelines* into applicable state policy and programs; the identification of appropriate categorical exceptions; and cost, size, and use application thresholds. This Pilot Study will assist SHA in each of these next steps.

4.4 Adaptation Measures

One of the main goals of the Pilot Study and an action item outlined in SHA/MDTA 2013 Climate Change Adaptation Strategy was to develop a menu of possible adaptation solutions for common climate threats. One of the outcomes of the SHA Pilot Study was that applicable system-wide adaptation solutions do not exist because of the many interdependencies driving vulnerability. However, it was agreed that a general list of potential adaptation practices is a good tool as a starting point for practioners for review and consideration of potential risk reduction measures. The list of climate change addaptation options for SHA's transportation infrastructure in terms of potential design solutions, maintenance and operational measures is presented in Appendix A. The table also lists applicable design criteria and standards specific to SHA. To prepare this summary, available literature was reviewed to assess adaptation practices applied by other jurisdictions in response to climate change. As stated in numerous publications reviewed for this Pilot Study, information on adaptation practices and engineering solutions is limited but growing. Part of this growing knowledge is the professional judgment and experience of experts in the field of transportation design and hazard mitigation, and this professional knowledge supplemented the results of this study based upon their applicable experience. As SHA conducts more detailed adaptation studies, it is anticipated that this list of adaptation measures will be expanded upon and will become more detailed . Some of the recommendations are provided in Chapter 6 of this report.

The development of adaptation measures is heavily dependent on the climate stressor, asset characteristics, inter-related infrastructure (such as multiple culverts conveying water), and the surrounding environment. In many cases, infrastructure owned by others could have a large influence on the success of an adaptation measure. Similarly, implementation of an adaptation measure could result in impacts to other assets if a holistic watershed approach is not taken. For instance, increasing culvert size or raising a bridge above the projected sea level rise for 2100 could result in the downstream area becoming more susceptible to flooding. One overarching lesson learned from the vulnerability and adaptation workshop conducted is there is no "one size fits all" solution and detailed analysis with hydraulic modeling is needed in most cases to prescribe adaptation measures with a high level of confidences for bridges, roadways, and small drainage conveyances.

4.5 Vulnerability and Adaptation Workshop and Case Scenarios

To evaluate the Pilot Study tools and methods being employed and to gain technical input into the process, two engineering/planning workshops were held with staff from different Offices and Divisions of SHA as well as FHWA and MDTA. The following is a summary of Workshop #1, held on April 10, 2014 focused on vulnerability assessment and adaptation measures. Workshop #2, held on May 15, 2014 concentrated on assessing risk and prioritizing assets vulnerable to the different climate stressors in Maryland and is discussed later in this chapter. In each workshop, real scenarios were presented to brainstorm ideas and identify concerns specific to Maryland's highway transportation asset planning, design, policy, and operation.

The intent of the vulnerability and adaptation workshop was to present the Pilot Study to a multi-disciplinary team from different SHA Offices and Divisions and to solicit their comments and expertise. At the onset of the workshop, a presentation was given on climate change and the SHA Pilot Study, which highlighted the need for adaptation.

Many of the documents discussed in this report were introduced to the audience including, but not limited to: *The Maryland Climate Action Plan*, The *MCCC Phase II Strategy for Reducing Vulnerability to Climate Change*, and *the Coast Smart Siting and Design Guidelines*. The Pilot Studies objectives (See Chapter 1), and defined key terms for the workshop (*i.e.*, vulnerability and adaptive capacity) were outlined for the workshop participants. Also, data collection methods, the key climate variables for Maryland, examples of asset failures, and known adaptation measures were presented.

Figure 4-6. Photograph from Workshop #1 held on April 10, 2014.

Following the overview of the Pilot Study, a group exercise was conducted to assess vulnerability and explore adaptation measures for three scenarios. The working groups had 75 minutes to discuss the projects, look over the background material, and discuss ideas on vulnerability and adaptation. For each scenario, groups were asked to answer six questions.

- What assets are vulnerable to a given climate variable?
- What are the vulnerabilities and potential failures?
- What can SHA do to make the assets more resilient (i.e., adaptation measures)?
- What are the obstacles SHA would face during implementation of the adaptation measure (planning, policy, regulatory, or operations hurdles)?

- Are there other considerations (related assets)?
- What additional information is needed to inform this process?

At the end of the working group session, each working group presented their results to the larger group. This exercise was used to help populate and refine the table of vulnerabilities and adaptation measures in Appendix A. Each scenario and the general results follow.

Scenario #1 – MD 222 Drainage Project

The MD 222 drainage project is located in Port Deposit, Cecil County, MD. Storm drainage improvements are required for a 1.33 mile stretch along the main section of town. The roadway is periodically flooded by the Susquehanna River, but in general is not within the FEMA 100-year floodplain. A railroad embankment for Norfolk and Southern Railroad is located in between the river and the road; it acts as a partial levee. The river is tidally influenced and may be within the Chesapeake Bay Critical Area.

SHA is in the planning preliminary design stages of a drainage improvement project for this roadway. The drainage area is approximately 65 acres. The focus of the project is on improving storm drainage, which would include installing check valves on outfalls to stop backflow from rising river levels. Storm surges, from the Susquehanna, could cause increases in storm drain hydraulic grade line (HGL). The plans do not include any new or redeveloped pavement.

Scenario #1 - Key Lessons Learned:

- Other infrastructure in the watershed can heavily influence adaptation design. In the case of MD 222, a large dam exists upstream from the project site, which regulates the release of stream flow from the Susquehanna based on the operations of the dam for hydro-power as well as protection during large rainfall events.
- The best adaptation solution might be to build an alternate route.
- Both natural and cultural resources play into adaptation

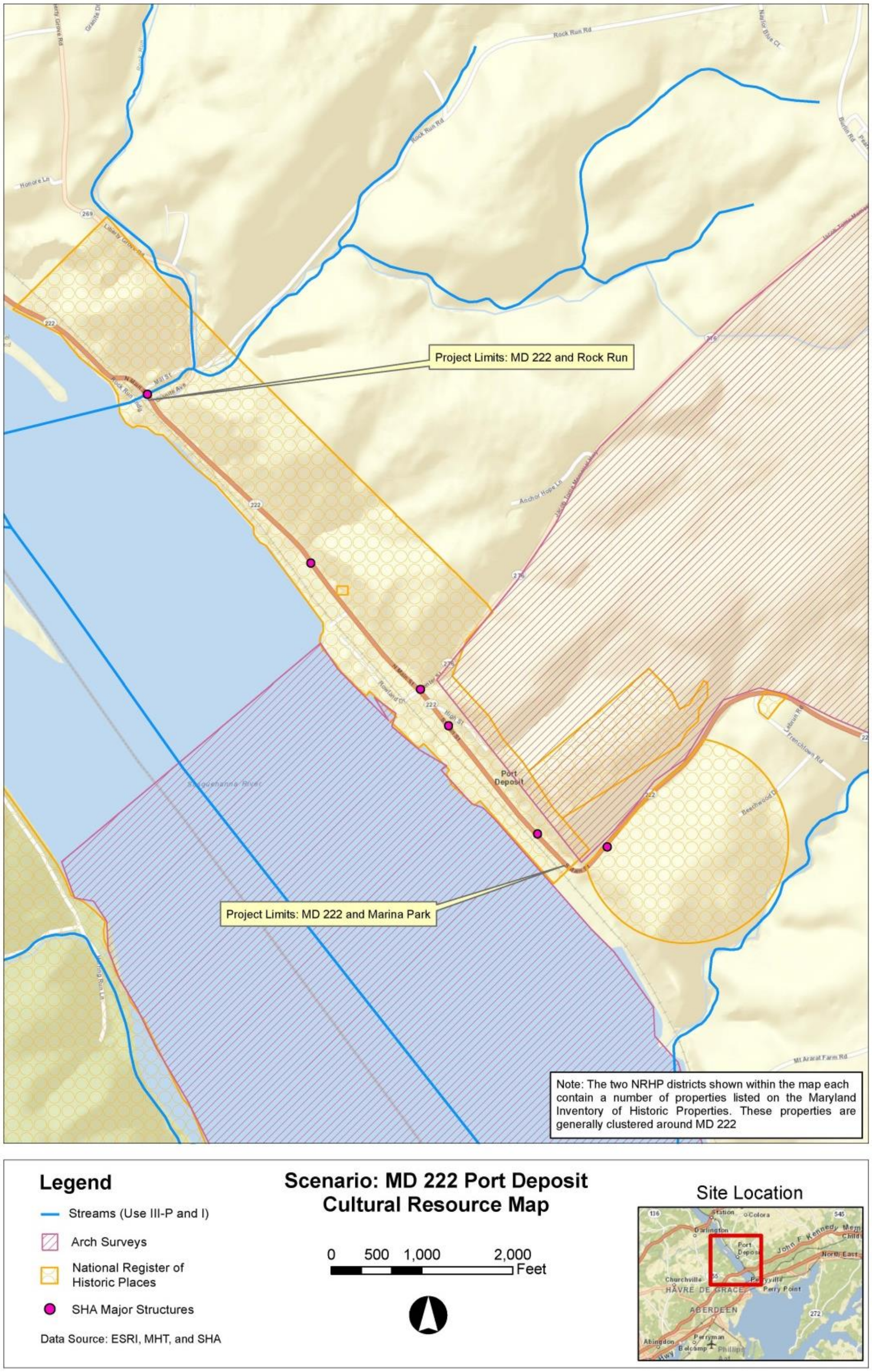


Figure 4-7. MD 222 Port Deposit Cultural Resources Map shown at Workshop #1

Scenario #2 – MD 717 Bridge

The second project is located in Upper Marlboro, Prince George's County, MD. The focus asset of this project is the MD 717 bridge over the Western Branch. The bridge, constructed in the 1900, is a single span bridge with an open grid deck on steel floor beams and steel girders. The structure carries two lanes of MD 717 and the bridge receives an average of 11,061 cars per day. There is riprap placed along the bridge abutments. The bridge and its approaches are within the FEMA 100-year floodplain. The bridge is overtopped by the ten (10) year storm event. In addition, the bridge has scour issues, and is improperly aligned with the Western Branch streambed. Buildings, upstream of the bridge, are located inside the 100 year floodplain. The existing 12-inch sanitary sewer is suspended on the side of the bridge and a multi-use trail parallels the roadway.

Scenario #2 - Key Lessons Learned:

- This project has an existing problem that will only be worsened by climate change. The lesson learned is in some instances there may not be a viable or feasible applied remedial action.
- Downstream "choke points" in the watershed contribute to the flooding issue.
- The criticality of the roadway is low, based on the fact that there are alternative routes available and the route carries low average daily traffic.
- In many cases, there are interrelated assets that are also affected. In Scenario 2, a multi-use bike path and utilities parallel the roadway and bridge. These adjacent features complicate decisions.

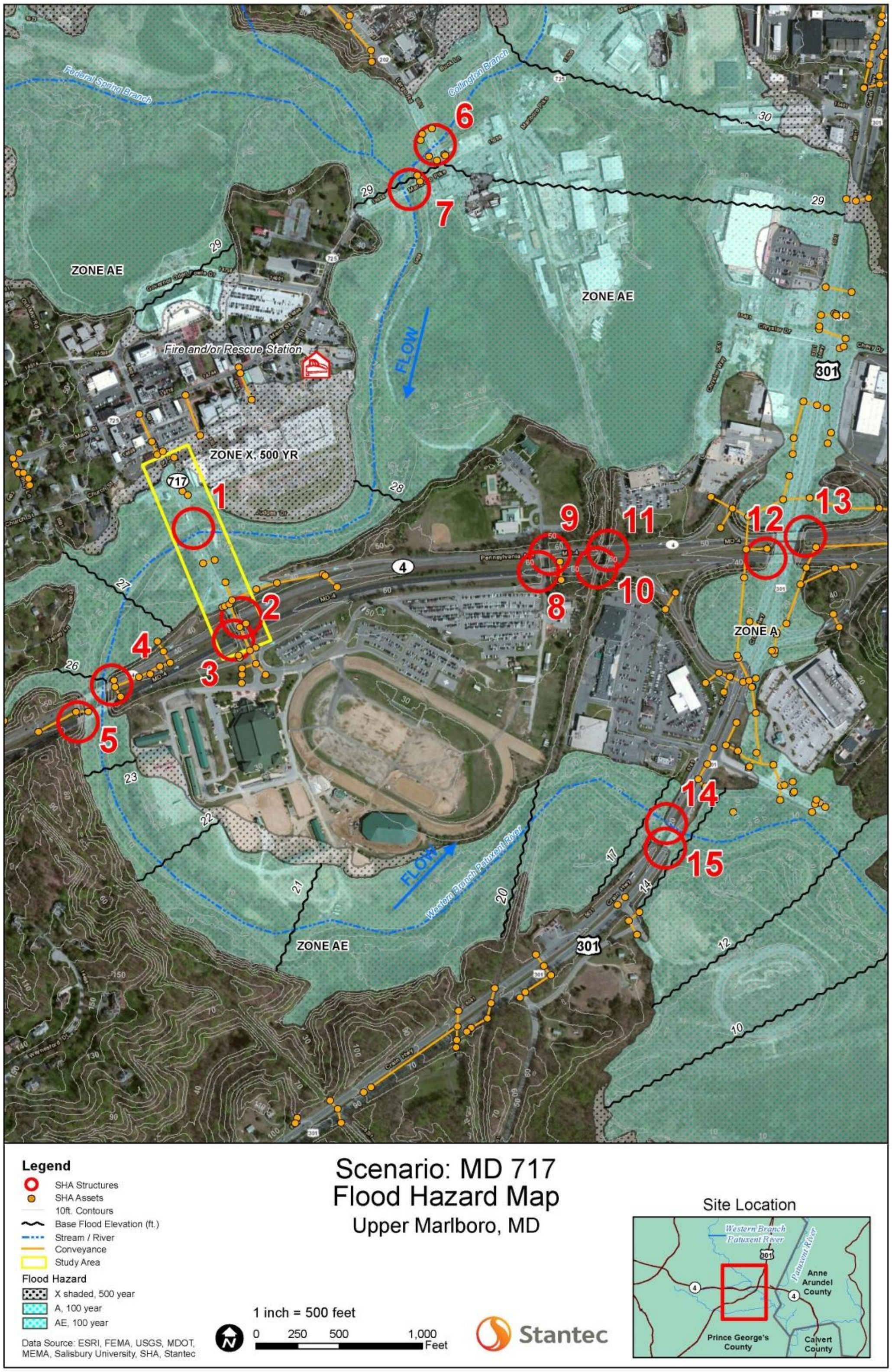


Figure 4-8. MD 717 Flood Hazard Map shown at Workshop #1

Scenario #3 – US 113 Bridge of Purnell Branch

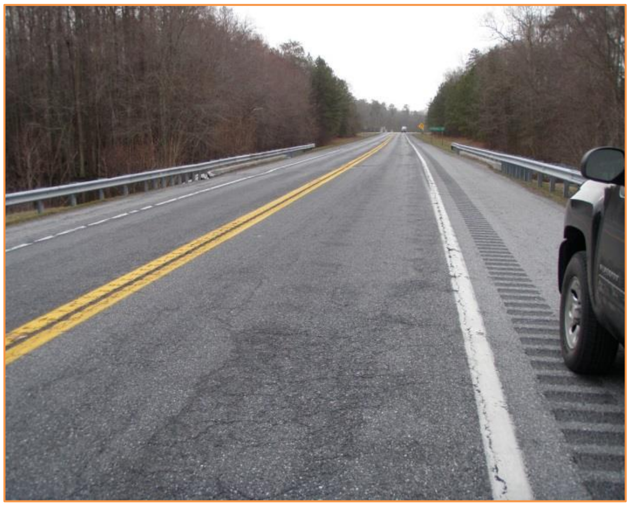


Figure 4-9. Road Surface of US 113
Photo Source: SHA, 2014

The final project is located in Snow Hill, Worcester County, MD. The focus asset of this project is the US 113 bridge over the Purnell Branch. The bridge was constructed in 1975. The river flows westerly into the Pocomoke River. The bridge previously experienced scour, but newly installed riprap provides additional protection. A 2004 hydrology and hydraulics report stated that because the area is extremely flat, the large drainage area of 12.9 square miles produces a small 100-year discharge of only 1,730 cubic feet per second (cfs). The 2004 report also stated that the 100-year storm does not overtop the bridge. It is also understood that predicted sea level change levels will not overtop the bridge; however, one of the approaches could be overtopped.

Scenario #3 - Key Lessons Learned:

- A watershed approach is needed. In the case of Scenario 3, multiple upstream and downstream structures and the effects of tailwater from sea level rise will influence the effectiveness of adaptation solutions, such as raising the roadway approach that would be inundated by sea level rise under the 2100 scenario.
- Increased preventative storm maintenance is needed to prevent asset failures from occurring. The meeting participants discussed the use of contractor's on-call contracts for this type of work similar to arrangements made for snow removal to assist during storm events.
- Larger and more robust drainage systems may be a solution and the roadway subbase and pavement designs should be examined for their tolerance to inundation and/or a higher water table.

Workshop #1 Results/Lessons Learned:

The engineers identified the roadway, drainage system, sidewalks, signs, roadway amenities, other structures, and community service structures (*e.g.*, a firehouse) as vulnerable assets within the transportation facilities considered in these scenarios. The commonly identified threats were roadway inundation, bridge surface overtopping, drainage system failure, debris damage, and reduced community service capacity (*e.g.*, slower fire/rescue response and sanitary sewer failure). The groups had differing adaptive measures that were specific to their scenarios. A common challenge discussed was funding, which is often a limiting factor to any highway project. General results from the three scenarios follow.

Results from Workshop #1 Vulnerability and Adaptation

Vulnerable Assets Considered

- Drainage systems
- Roadways
- Sidewalks
- Signage & Roadway amenities
- Retaining Walls
- Bridges
- Nearby Historic Properties

Threats/Failures Encountered

- Road service and access to town due to overtopping
- Slow response for fire/rescue
- Loss of Road (*e.g.*, collapse)
- Structural damage from water
- Ponding
- Tailwater causing flooding or scour
- Down trees and floating debris
- Reduced culvert capacity

Adaptive Measures

- Drainage system upgrades
  - more and larger pipes (increase of capacity)
  - create detention and retention ponds or devices
  - storage or bypass system
  - flow diversion/ flow splitters
- Build a levee (MD 222 specific) with floodgates
- Improve roadway subbase drainage system
- Acquire more right of way
- Relocate community service buildings (*e.g.*, fire house)
- Add riprap to protect structures
- Build new bridges or raise the bridge
- More robust maintenance program

Challenges/Obstacles

- Ponding does not show up on Hydraulics and Hydrology reports
- Raising other structures in watershed not under SHA control (*e.g.*, the railroad)
- 50 Year Storm Design Capacity
- Requirements of environmental permits
- Coast Smart Council specific requirements
- Coordination with county and municipality
- Utilities
- Limited right of way
- In a Historic District
- Community Involvement/multiple stakeholders
- Railroad Coordination
- Constructability concerns
- Additional data collection needed
- Prioritization vs. Other Project(s)

Other Considerations

- Utilities in corridor
- Railroad and business impacts
- Access to emergency services
- Environmental considerations
- Topography/geology considerations

Data Needs

- Detailed topographic and right of way survey
- Assessment of railroad condition
- Existing roadway pavement structure
- Existing drainage system condition and capacity
- Utility & railroad plans (location & future improvements)
- Dam failure surge models
- Future roadway plans (from town)
- Property values
- Existing/remaining service life
- Utility network
- Emergency Routes
- Cost/Benefit

4.6 Prioritization

4.6.1 Prioritization of Assets

In developing a response to climate change, a major challenge is how does one prioritize as many assets as SHA owns and maintains? One of the first steps is to conduct screening level assessment of those assets that are exposed to the identified climate stressors. For the Pilot Study, the Climate Change Impact Zone was the initial step to eliminate those assets that will not be impacted by sea level change, storm surge, or increased precipitation intensity causing flooding. Next, VAST and HVI were applied in the Pilot Study as two tools to help score vulnerability and determine the criticality of SHA's assets exposed to climate change. Methodologies for the application of these tools are presented in Chapter 2. VAST was used to evaluate bridges and HVI for roadway segments and an additional desktop screening was conducted for small culverts and drainage conveyances.

Highly vulnerable assets are not always the assets that should be addressed, it is important to determine what assets are important for SHA to make more resilient for the greater good of the larger transportation system. Therefore, an effective prioritization process takes into account both the criticality and adaptive capacity of the asset. HVI and VAST incorporate indicators such as the FHWA highway functional classification (the class, or group, of roads that the road belongs to), roadway volumes, and evacuation routes. Other considerations when data is available could includereplacement costs and operational delays. The later information was not readily available for this Pilot Study, but would be considered for evaluating adaptation alternatives for "vulnerable areas at risk." This information would be included in the Tier III level (quantitative, site specific) analysis as well as a Cost to Benefit Analysis to further prioritize the most advantageous solution considering safety, cost, environmental impacts and long-term resiliency of the transportation assets under assessment.

4.6.2 Cost-to-Benefit Analysis/Considerations

A reliable transportation network is beneficial to the public and a vulnerable transport network represents a net cost to the public. Therefore, vulnerability is an important factor to be considered in a Cost-to-Benefit analysis. The purpose of a Cost-to-Benefit analysis is to weigh the cost of a proposed adaptation measures against the benefits gained from that adaptation (*i.e.*, avoided damages and costs incurred) as well as the cost of inaction. If project benefits exceed project costs, then the project increases the public's welfare. If the costs exceed the benefits, the public will experience a loss of welfare. In highway decision-making, Cost-to-Benefit analysis may be used to help determine the following (FHWA n.d.):

- Whether or not a project should be undertaken (*i.e.*, will the project's life-cycle benefits exceed its costs).
- When a project should be undertaken. For example, cost-to-benefit analysis may reveal that the project does not make sense financially now, but would be worth pursuing 10 years from now due to projected growth.

- Which among many competing alternatives and projects should be funded given a limited budget? For example, Cost-to-Benefit analysis can be used to select from among design alternatives that yield different benefits.

Tools are available to help conduct Cost-to-Benefit analyses. One of these tools is FEMA's Cost Benefit Analysis Tool. FEMA's Benefit Cost Analysis (BCA) program consists of guidelines, methodologies and software modules for a range of major natural hazards including flooding (Riverine and Coastal Zones A and V).

4.6.3 Cost of Inaction

Adaptation and response planning is essential to Maryland's ability to achieve sustainability (Griffen, Halligan and Johnson 2008). Inaction could result in a greater risk to transportation systems and important transportation links over time. Transportation planners and legislators must understand that the application of measures to mitigate climate change and sea level change impacts associated with erosion, flooding, and inundation of low-lying lands is imperative to sustainable management, as well as protection of Maryland's resources and communities. As part of the Tier III analysis, one of the alternatives that should be considered is the no-action alternative.

4.6.4 Risk and Prioritization - Engineering Workshop #2, May 15, 2014

On May 15, 2014, representatives from different SHA Offices and Divisions participated in the second engineering workshop of the Pilot Study. The objectives of this workshop were to introduce the attendees to the concept of risk assessment and asset prioritization, and use their expertise in ranking VAST indicators. After a brief welcome and introduction there was a recap of the first workshop. Next, VAST was briefly introduced and an exercise was started to poll the group's response to different vulnerability indicators. This exercise presented the attendees with a short list of exposure indicators, sensitivity indicators, and adaptive capacity indicators from the VAST.

Following the exercise, a small selection of the results from Salisbury University's study was presented to the group. The first data presented were overlays of the expected sea level change in 2050 and 2100 over a Digital Elevation Model (DEM), which was created using Somerset County LiDAR data. Using these data, the preliminary results and examples of a Climate Change Zone (CCZ) and Hazard Vulnerability Index (HVI) were explained. Next, observations were presented from the rain event on April 30, 2014, a small flash rain event that created small, but short term closures and one city road collapse. The rain event was a good example of how minor events can affect the infrastructure and the scale of effects expected from climate change and extreme events.

Following this presentation, Roger Rempel, Environmental Engineer from Stantec, gave a brief presentation on the techniques used to assess risk and prioritize assets from other countries. This presentation introduced the group to these concepts and detailed the focus of the second exercise. The second exercise split the group into three smaller groups, one for each of three scenarios. The scenarios were SHA assets selected from the two pilot counties, Anne Arundel and Somerset, and from areas affected by climate change stressors. The first scenario, focused on the segment of roads, culverts and bridges of MD 450 and US 50 crossing the South River in Anne Arundel County.

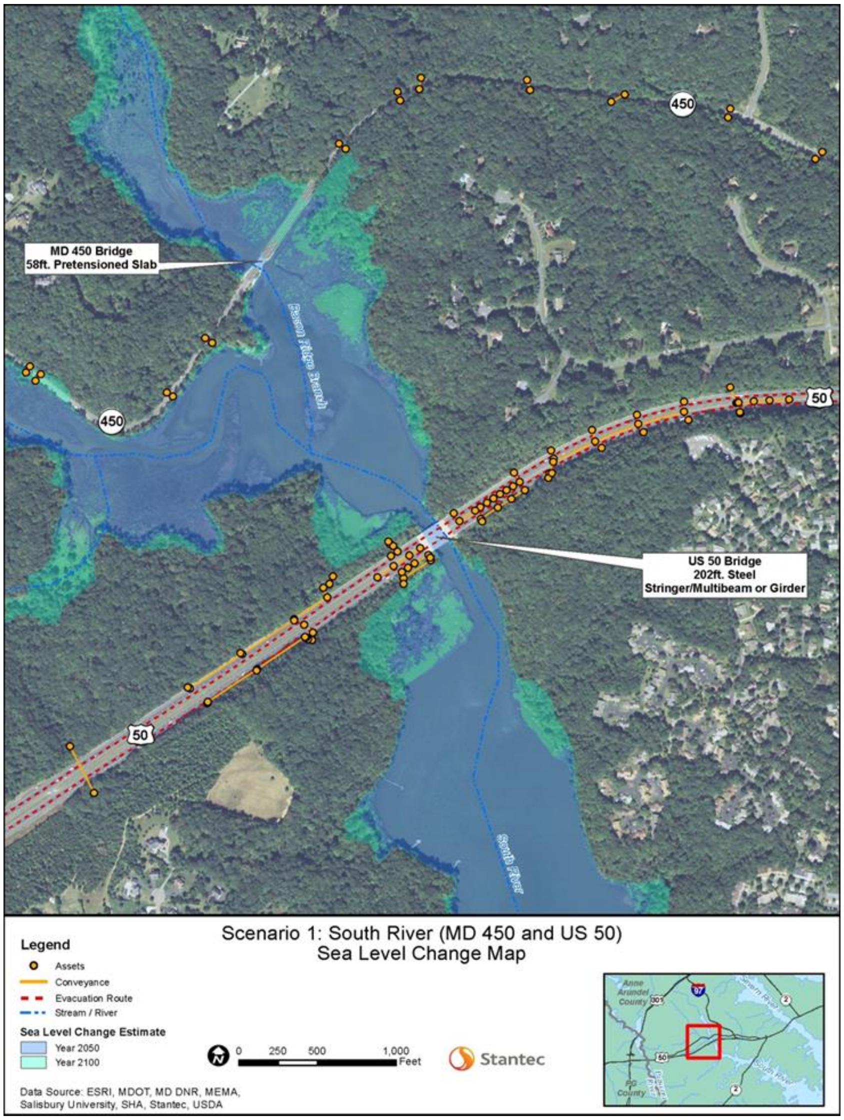


Figure 4-10. Scenario 1 - The South River

Scenario #1 - Key Lesson Learned:

- The risk assessment can become skewed if you place too much weight on functional classification or other adaptive capacity indicators, when the actual vulnerability of the infrastructure is very low. This information was used by the study group in assigning weights in VAST to sensitivity, exposure and adaptive capacity. This example highlights awareness of this issue because in the group exercise, priority would have been given to the US 50 bridge despite it being located well above the 100-year floodplain and sea level zones.

The second scenario focused on three bridges (MD 3, US 50, and Governors Bridge Road) crossing the Patuxent River.

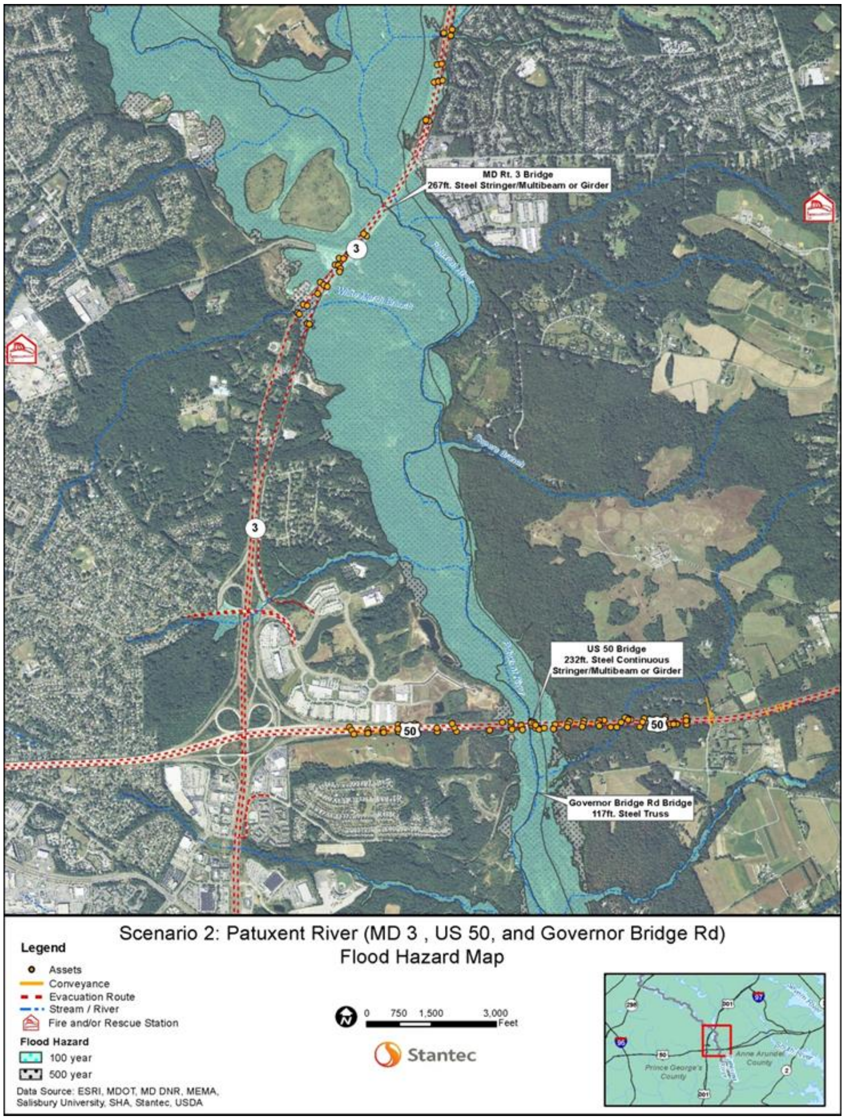


Figure 4-11. Scenario 2 - The Patuxent River

Scenario #2 - Key Lesson Learned:

- The general public knows that the Governor Road Bridge floods and this roadway is not critical to the transportation system.
- Another lesson learned is that in general the interstate system has been built to a standard that will withstand most extreme weather events and that secondary routes such as MD 3 are more vulnerable.

The third scenario, focused on a section of MD 413 in downtown Crisfield, Somerset County. The section of road does not have any bridges, but has an extensive drainage system and the profile of the road is only a couple of feet above MSL.

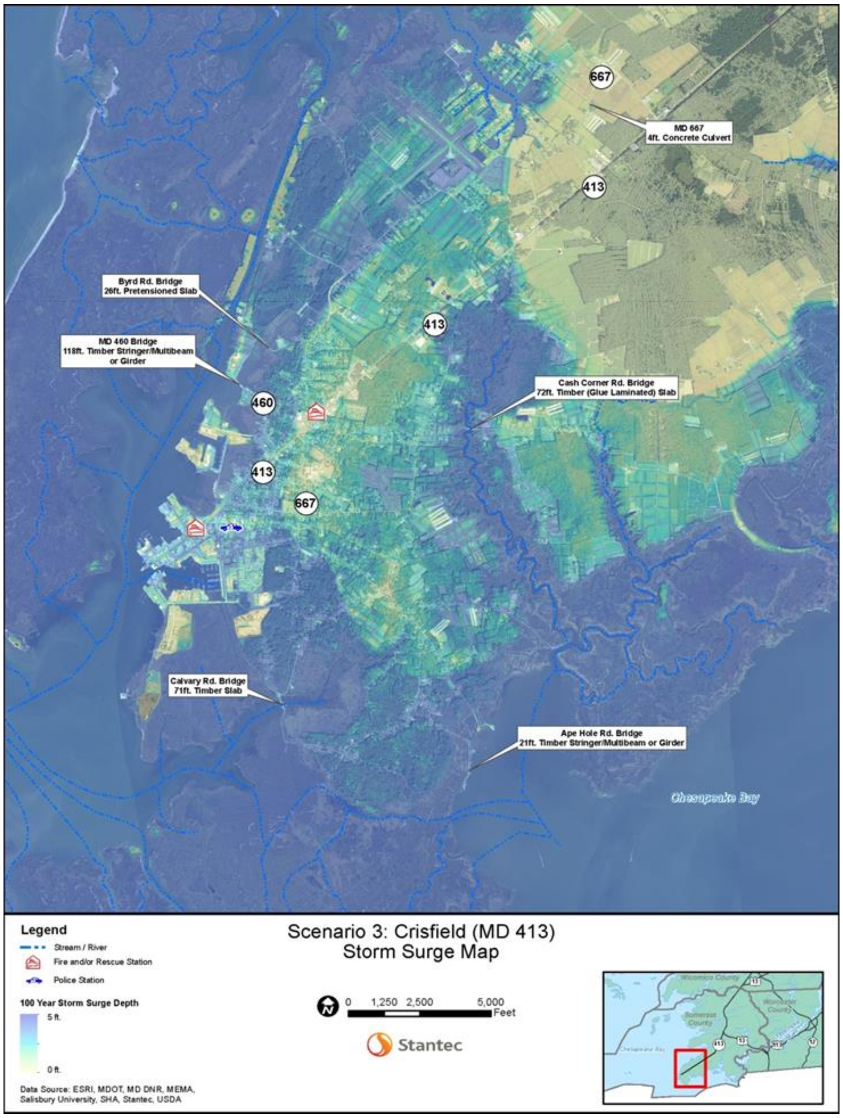


Figure 4-12. Scenario 3 - Crisfield, Maryland

Scenario #3 - Key Lesson Learned:

- In this scenario, SHA may need to keep access to the pockets of residential properties and businesses that remain prior to a point in time when the community will be forced to retreat inland or develop their own adaptive measures to sea level rise. In this case, increasing the roadway elevation seemed like the only feasible alternative since MD 413 is the main access to points along the Chesapeake Bay in Crisfield, but all the land on either side could be inundated.
- This scenario highlighted the importance of engaging community stakeholders to determine what minimum acceptable extent of service transportation assets need to be maintained once climate impacts begin to threaten the viability of those assets, particularly in a hazardous or repeatedly impacted location. Part of this consultation would involve determining the maximum level of transportation asset investment that could be sustained for the service area facing increasing damage and repeated impacts requiring restoration for its transportation infrastructure due to climate risks.

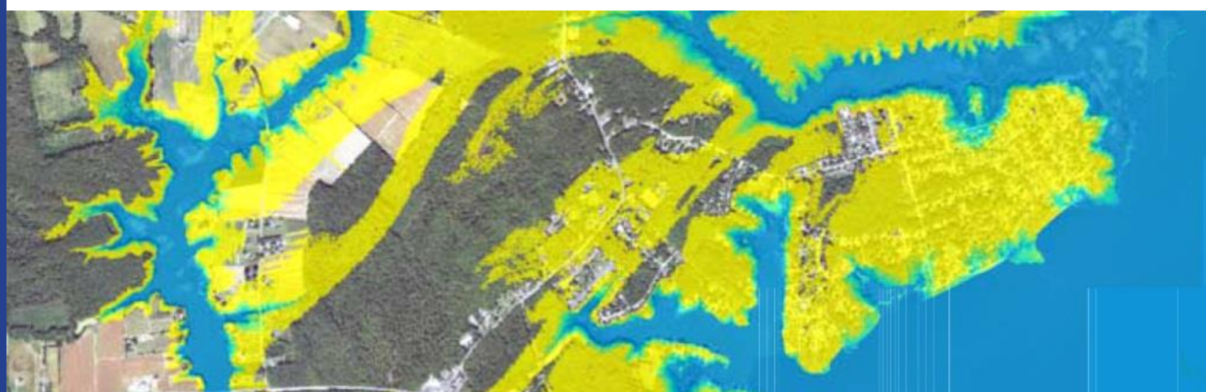
Each group was provided a packet of information about the scenario and maps showing the predicted changes in relation to the relevant climate change variables. The groups were also given a spreadsheet to fill out, which outlined the impact areas, the potential climate events and change factors. The group members were asked to first decide if a given climate change variable would affect an asset (*e.g.*, roadway). If the group decided that a climate change variable affected an asset, then they decided which impact areas would be affected. Next, the group assigned a value, one to five, for the severity of that asset failing from that climate variable. The product of multiplying the severity ranking with the probability ranking provides the risk factor. The risk factor then informs the user of how much additional study the asset requires.

Risk Threshold Level	Characteristics of Risk Level
Less than 5	**LOW RISK:** Can be maintained under review but expected that existing controls/approaches will be sufficient and no further action needed unless these become more severe. **NO ADDITIONAL STUDY REQUIRED AT THIS TIME**
5-10	**MEDIUM RISK**: Can be expected to form part of routine operations, but these items may require subsequent action, or maintained under review and reported on at senior management level. **MONITOR AND ASSESS NEED FOR FURTHER STUDY**
Greater than 10, Less than 20	**HIGH RISK:** The most severe level of risk that can be accepted as part of routine operations. Mitigation required in forward planning but assessment required specifying remedial measures. **MITIGATION REQUIRED, BUT OPTIONS AND IMPLEMENTATION REQUIRE FURTHER ANALYSIS**
20 or more	**EXTREME RISK:** defines and unacceptable event for SHA operations, facilities, personnel, contractors, and user-base. Responsible parties must take remedial action ASAP to mitigate as this condition as its occurrence will result in long-term loss of facilities, services, community confidence, and safety. **MITIGATE IMMEDIATELY – NO STUDY REQUIRED TO DETERMINE NEED FOR ACTION**

Figure 4-13. Risk Threshold Level Example from Workshop

The meeting concluded with each group sharing their results with the entire audience. There was a brief discussion on the commonalities among the scenarios.

Chapter 5 –
Detailed Vulnerability Assessment for Two Pilot Counties



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5 Detailed Vulnerability Assessment for Two Pilot Counties

This chapter presents the results of the detailed vulnerability assessment for the two pilot counties in Maryland: Anne Arundel and Somerset. More detailed information from VAST is provided in Appendix B. As outlined in the methodology section, Flood Inundation Modeling and HVI were used to evaluate the vulnerability of roadways while VAST was used to evaluate the vulnerability of structures. Roadway data included functional class, evacuation route designation, and flooding depth. For the HVI, the three available roadway data parameters were combined to compute a risk value for each road segment. Additionally, culverts and small drainage features located in the Climate Change Impact Zone were screened only in Tier I. A more detailed, culvert specific analysis utilizing detailed hydraulic information would enable further analysis of the vulnerability of these assets.

5.1 Anne Arundel County

5.1.1 Anne Arundel County Overview

Anne Arundel County is located within SHA District 5 in central Maryland, along the western shore of the Chesapeake Bay and according to the 2010 census, it has a population of 537,656 (US Census Bureau 2014). Anne Arundel County contains 9,274 road segments and 517 structures, 150 that are located in the Climate Change Impact Zone (SHA n.d.), in which 655 road segments and 104 structures are SHA assets. The county is 587.90 square miles in size, but only 70.25 percent (415.94 square miles) of that area is land (US Census Bureau 2014). The elevation of the county varies from a maximum height of 300 feet above sea level along the western border of the county to at sea level along the banks of the Chesapeake Bay (Salisbury University 2014). With 533 miles of shoreline, Anne Arundel County has a significant exposure to tidal and non-tidal waterways. The county seat and state capital of Annapolis includes areas vulnerable to flooding with “urban flooding” listed as the most typical. Undersized culverts, mainly in historical parts of the town are highlighted as a principal cause of urban flooding in Annapolis (City of Annapolis n.d.).

In the 2011 *Sea Level Rise Strategic Plan* for Anne Arundel County, there are several suggested general policy changes to account for changes to sea level and floodplains. A number of these could affect SHA planning and design, including establishing policy for the abandonment of public infrastructure in areas vulnerable to floods. The document suggests substantial lead times for public notice of abandonment allowing for input, as well as alternative measure considerations. Anne Arundel’s master plan states that for areas where flooding is already a known issue and future sea level rise could exacerbate the problem, short and long term mitigation alternatives should be studied. Furthermore, current design standards should be reviewed for potential operational and maintenance procedures that could reduce impacts from flooding (Anne Arundel County 2011).

A recent study published by the NOAA in June 2014 takes a detailed look at what it coined "nuisance flooding" throughout the United States. Nuisance flooding refers to daily rise in water level above the minor flooding threshold set locally by the NOAA National Weather Service. The report concluded that any level of sea level rise will further intensify nuisance flooding impacts and reduce the time between flood events. The results found that eight of the top ten cities that have seen a significant increase in nuisance flooding were along the Eastern Coast of the United States. Annapolis and Baltimore, MD saw the greatest increase overall in nuisance flooding with increases of 925 and 922 percent respectively, above the historical frequency averages (Sweet, et al. 2014).

The data used for the Flood Inundation Modeling, HVI and VAST assessments for roadways, drainage structures, and bridges in Anne Arundel County came from multiple sources including SHA GIS, Salisbury University, National Bridge Inventory and others. These data sources are discussed in greater detail in Chapter 2.

5.1.2 Anne Arundel County: Result of Hazus Modeling

As described in the methodology section, sea level change and storm surge data were modeled for each pilot county. The following maps show the results of this modeling. Figure 5-1 and Figure 5-2 show modeled mean sea level inundations for 2050 and 2100 due to sea level rise. The mean sea level values for 2050 and 2100 were calculated by combining the applied sea level rise values developed by the Army Corps of Engineers, with a vertical calibration, and a correction factor for glacial isostatic adjustment and land subsidence to sync tidal station observation with the 2015 project year. The average 2050 sea level inundation change from current mean sea level (MSL) for Anne Arundel County was 2.08 feet. The sea level change for 2100 in Anne Arundel was an increase of 5.70 feet above current MSL. The most impacted areas were along the shoreline and included the entire towns of Shady Side, Churchton, and Deale.

Figure 5-3 shows the mean higher high water (MHHW) inundation for 2050. MHHW is the average maximum daily high tide during the National Tidal Datum Epoch. MHHW inundation data for 2050 does not consider any storm events including storm surge, but does consider sea level change. MHHW values for 2050 and 2100 were calculated using the same numbers as the MSL, but a correction was carried out to convert the numbers from tidal station MSL to MHHW. The average sea level rise for 2050 MHHW in Anne Arundel was 2.79 feet above current MSL. The MHHW for 2100 sea level rise in Anne Arundel was 6.41 feet above current MSL. As in 2050, the coastal areas experience the most inundation, but in the 2100 scenario more coastal areas are predicted to experience inundation in excess of 3.6 feet. For the Flood Inundation Modeling, HVI and VAST analyses, the MSL values were used; however, MHHW values demonstrate that tidal effects could result in greater vulnerabilities to bridges, roadways and other assets.

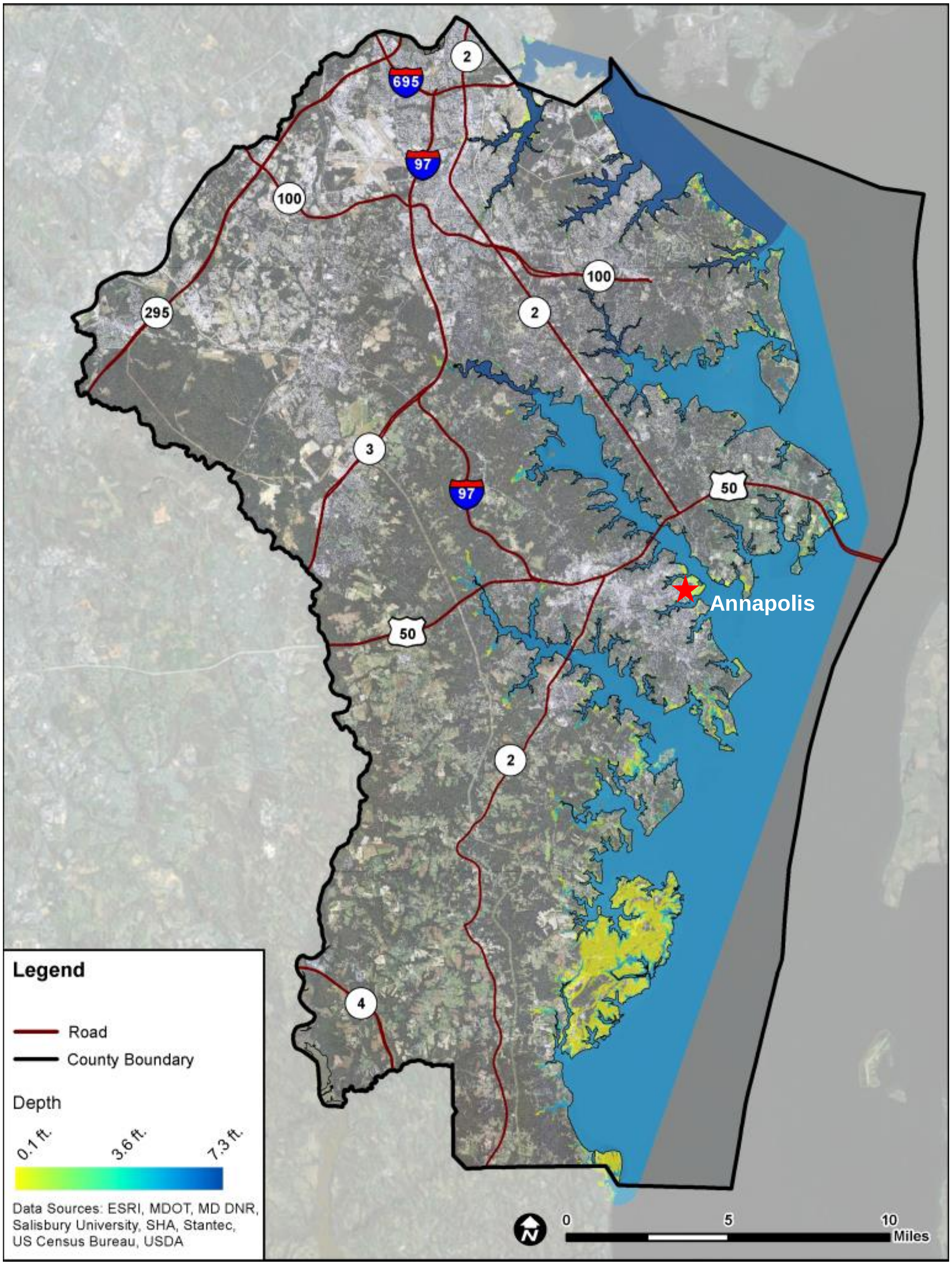


Figure 5-1. 2050 Sea Level Rise Inundation Levels in Anne Arundel County

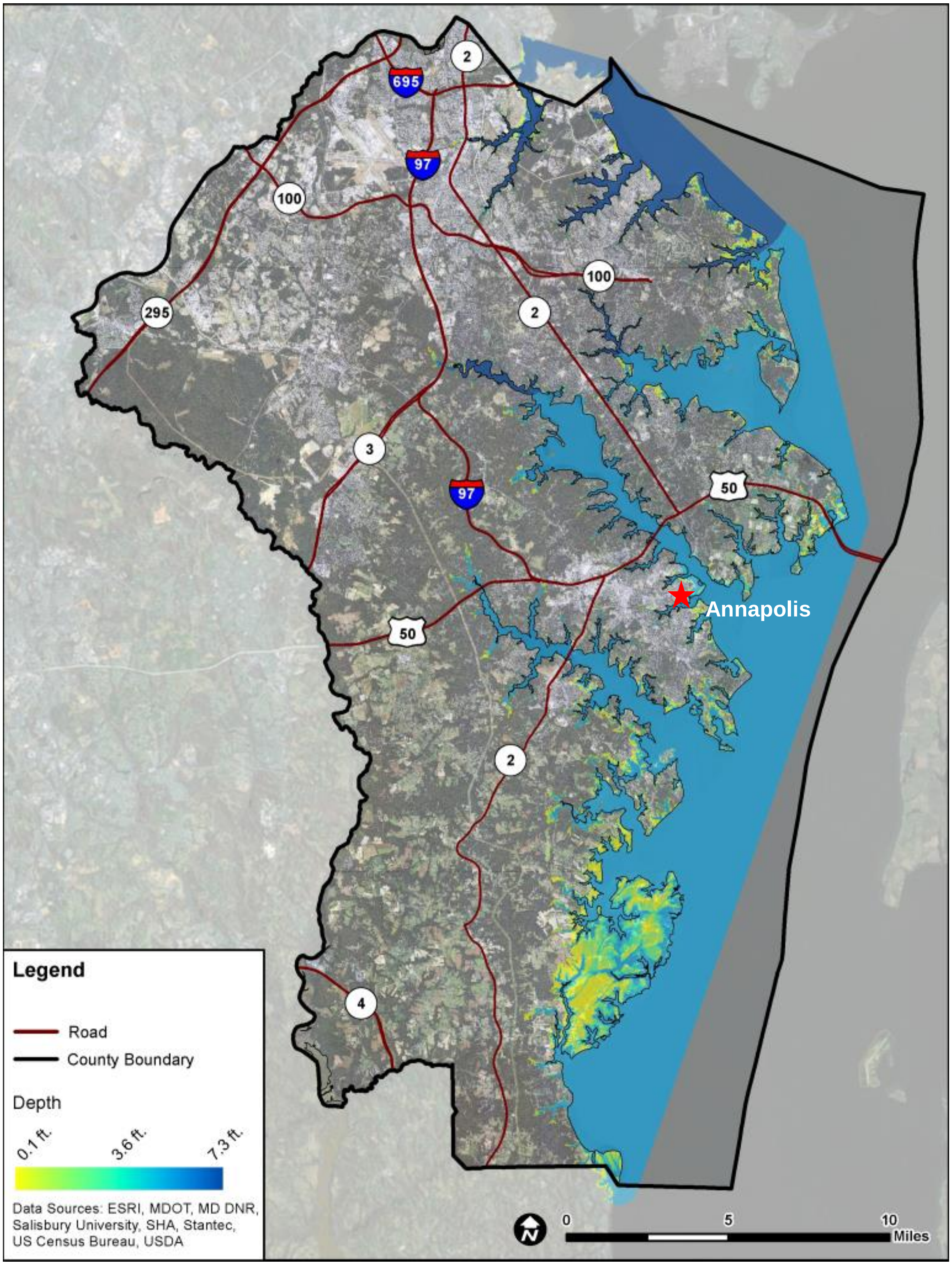


Figure 5-2. 2100 Sea Level Rise Inundation Levels in Anne Arundel County

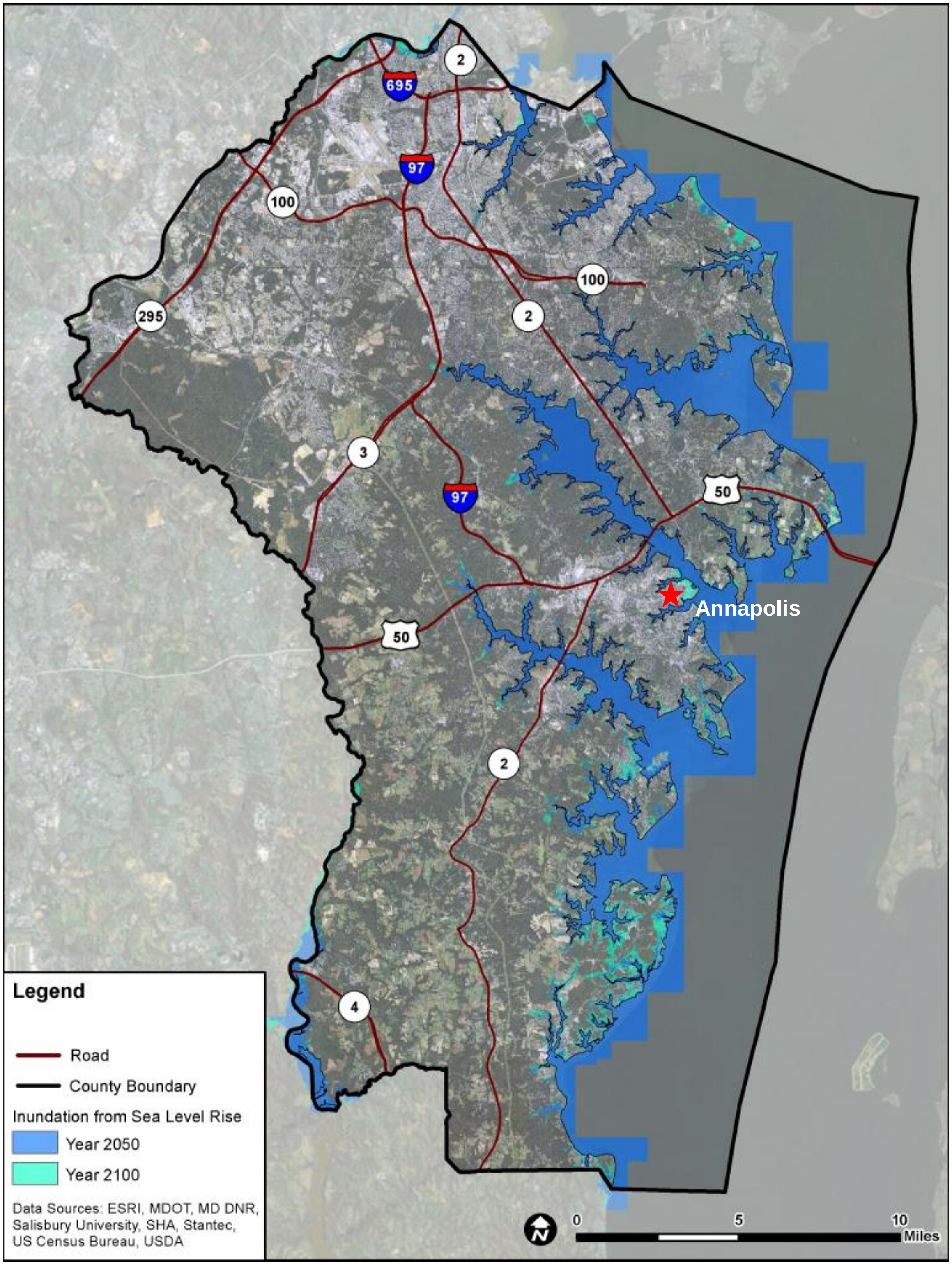


Figure 5-3. Mean Higher High Water for 2050 and 2100 Sea Level Rise in Anne Arundel County

5.1.3 Anne Arundel County: Result of Hazard Vulnerability Index (HVI)

SHA compiled an inventory of pertinent transportation assets within Anne Arundel County. These assets were identified during the Tier I analysis and were analyzed using Flood Inundation Modeling, HVI or VAST. The total number of bridges, small culverts and conveyances as well as the miles of SHA roadways present in Anne Arundel County is listed in Table 5-1 below.

Table 5-1. Anne Arundel Assets Evaluated in Flood Inundation Modeling, HVI or VAST

Assets	Anne Arundel
Bridges	104
Small Culverts and Conveyances	2017
Miles of Roadways	751.32

The flood inundation modeling identified road segments at risk to permanent inundation due to sea level rise. The HVI provided a risk value for road segments exposed to sea level rise and subsequent storm surge. This value was derived from three components, each with a distinct weighting factor, and included evacuation route designation, functional classification and a hazard indicator defined as flood depth code. Flood Inundation Modeling and HVI evaluated the functional classification 1-6 roadways within the Climate Change Impact Zone.

Figure 5-4 and Figure 5-5 depict Flood Inundation Modeling for the roadways impacted by mean sea level rise within Anne Arundel County, respectively in 2050 and 2100. The maps illustrate the roadways at risk for permanent inundation due to sea level rise impacts. Although individual road segments are modeled with varying depths of water the *At Risk* designation does not take flood depth into account. Constant inundation caused by sea level rise will result in harmful effects to roadways regardless of depth. Two county roadways, MD 423 and MD 740, were modeled to have permanent inundation in 2050 but no SHA roadways are projected to be inundated in 2050 due to sea level rise. In 2100, the number of roadways with modeled permanent inundation is significantly greater. Figure 5-6, Figure 5-7, and Figure 5-8 provide inset maps that further call out the specific roadway segments threatened by inundation due to sea level rise in 2100.

The SHA roads most impacted by mean sea level rise in 2100 within Anne Arundel County are presented in Table 5-2. There are no SHA roadways projected to be inundated in 2050. Several sections of MD 261 are expected to be permanently inundated in 2100. This roadway is a functional class 5 or a major collector. The sections of road identified as inundated are all located along Herring Bay and support a residential development called Herrington on the Bay. This road is not an evacuation route but is the major roadway along this section of the coast and a detour route so mitigation will need to be considered.

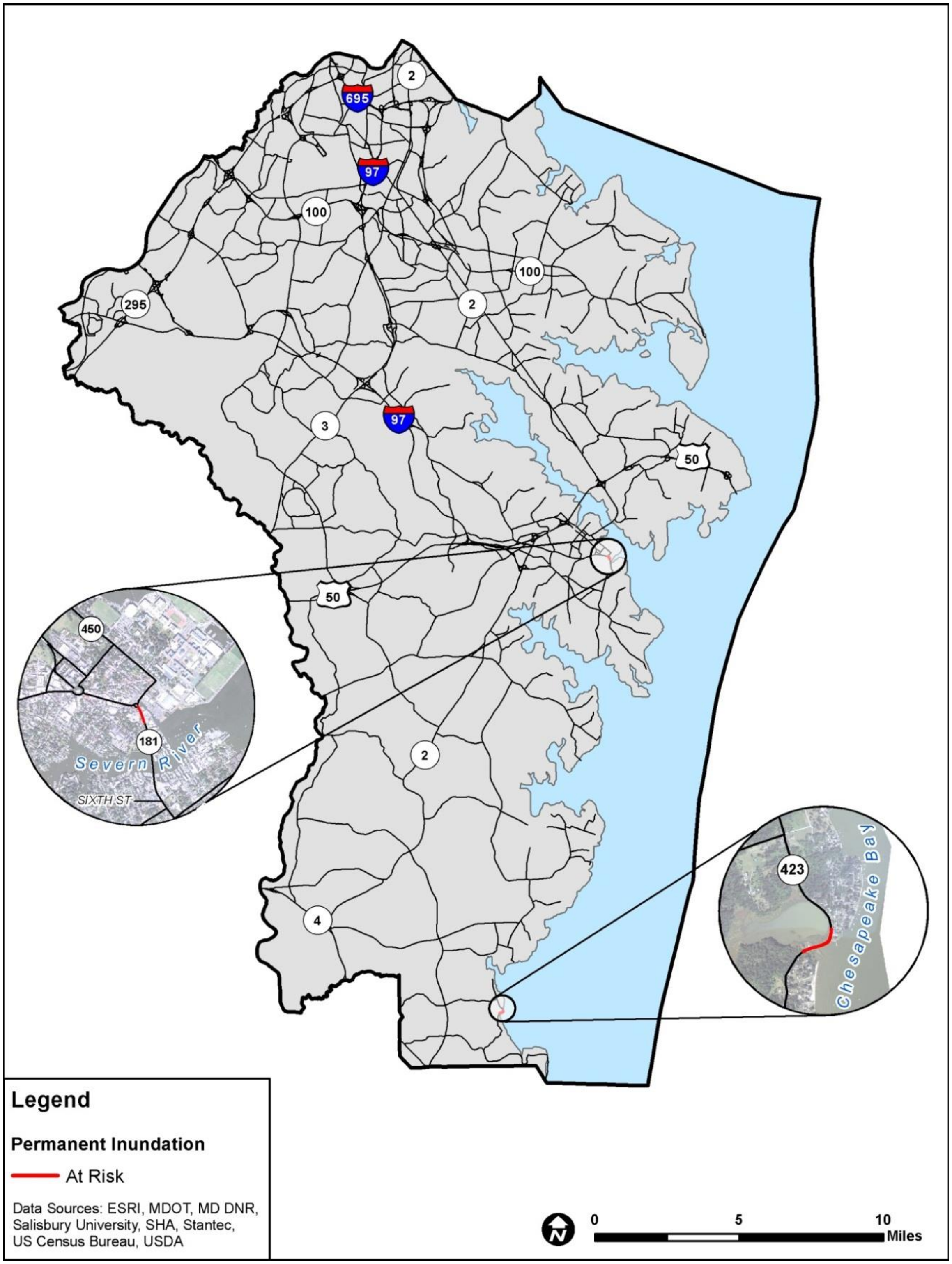


Figure 5-4. 2050 HVI Sea Level Rise Results for Roadways within Anne Arundel County

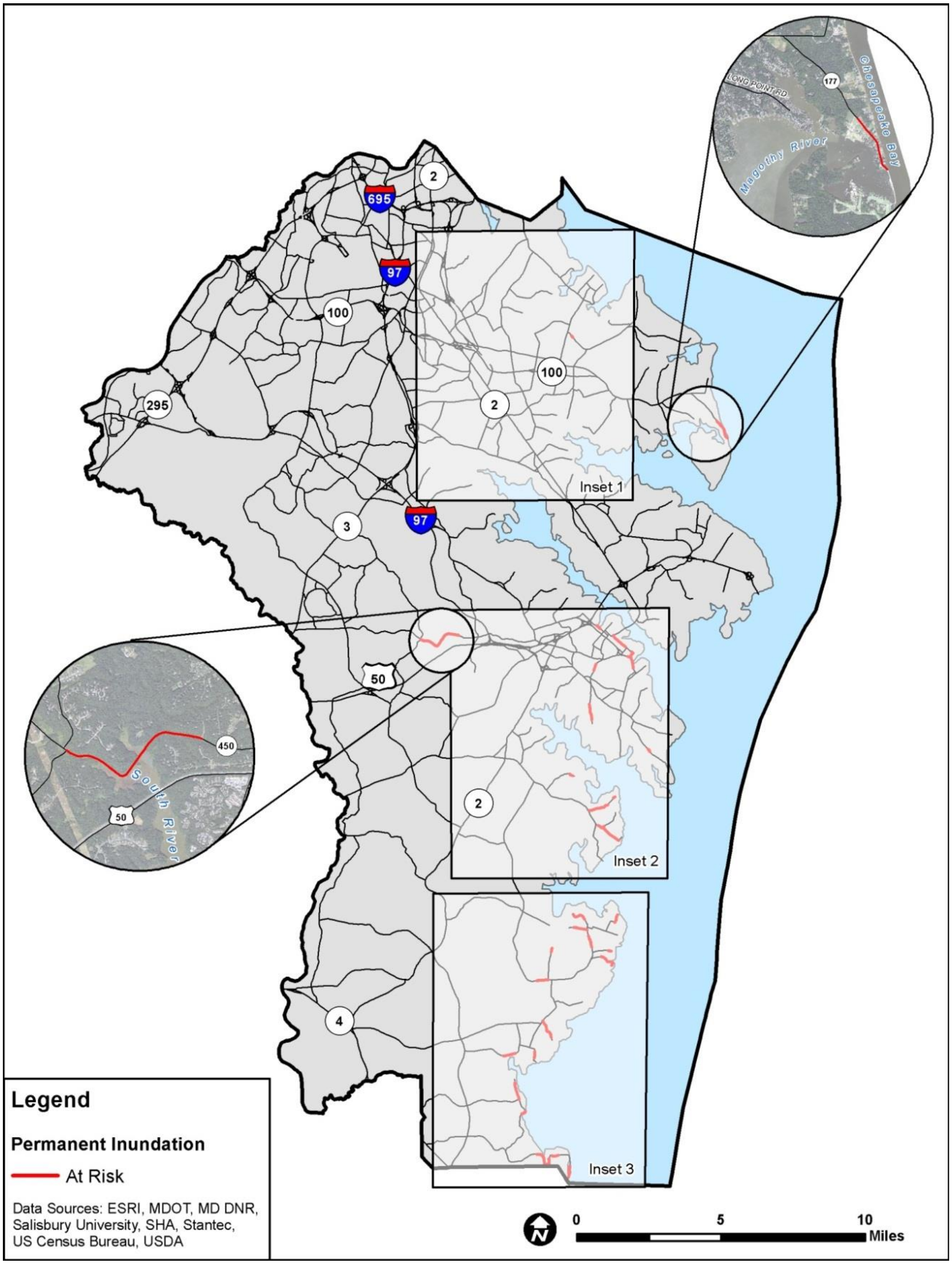


Figure 5-5. 2100 HVI Sea Level Rise Results for Roadways within Anne Arundel County

Figure 5-6. 2100 HVI Sea Level Rise Results Inset #1 Map

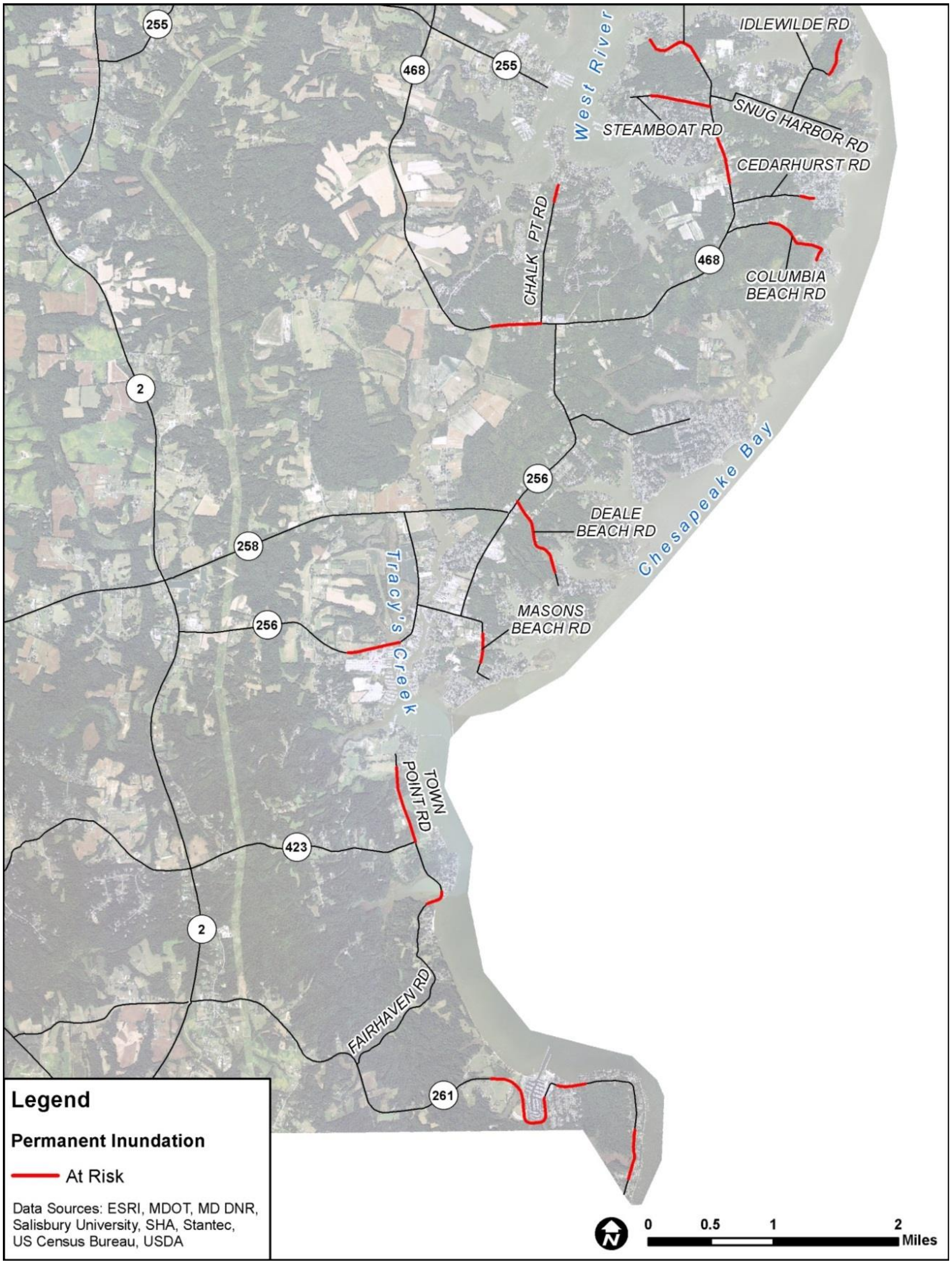


Figure 5-7. 2100 HVI Sea Level Rise Results Inset #2 Map

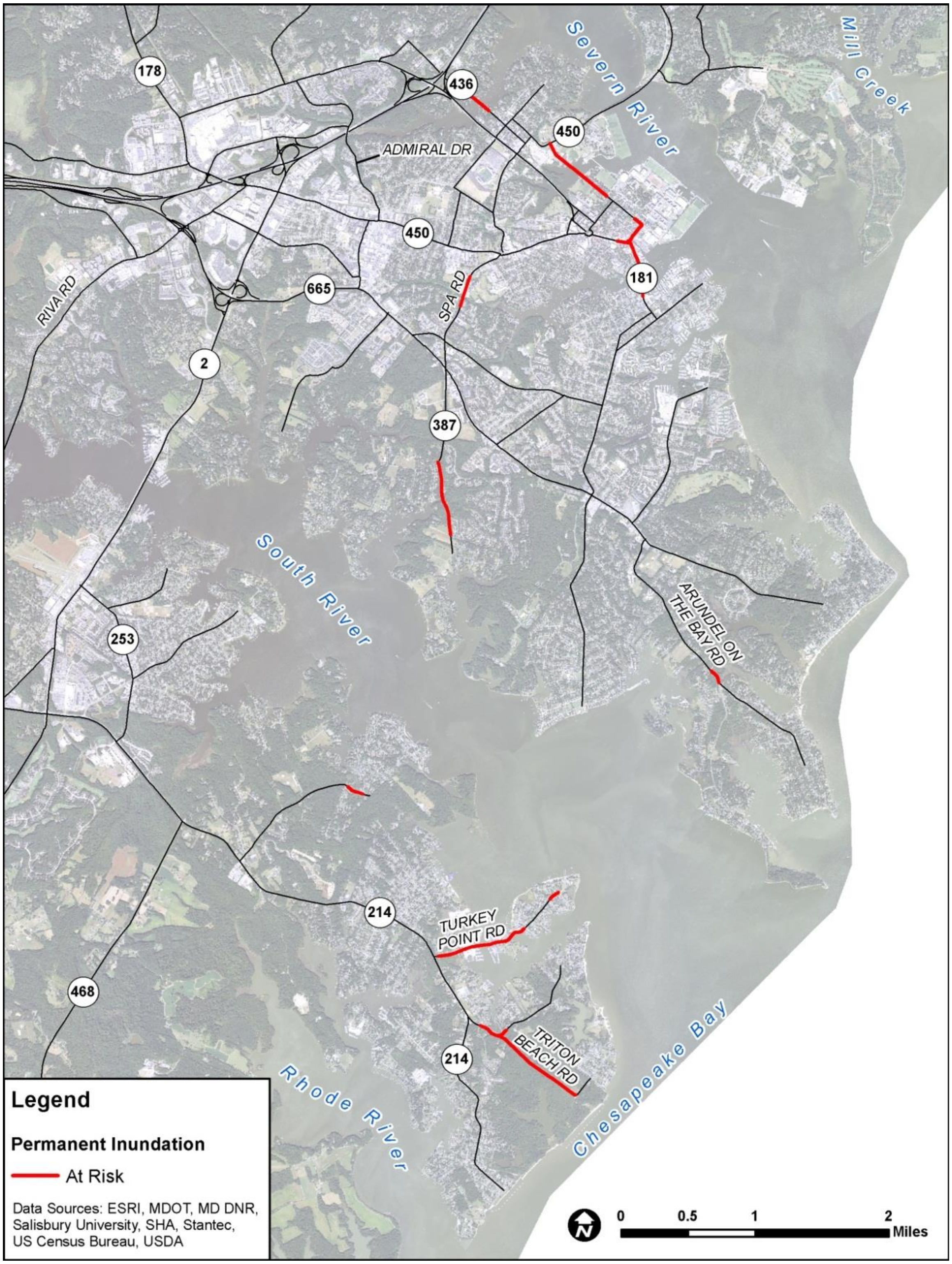


Figure 5-8. 2100 HVI Sea Level Rise Results Inset #3 Map

Table 5-2. 2100 Sea Level Rise Most Impacted Roadways

Route Number	Mileage of Roadway Permanent Inundation	Evacuation Route
MD261	0.51	No
MD468	0.14	No
MD423	0.14	No
MD450	0.11	No
MD177	0.02	No
MD256	0.02	No
MD387	0.02	No

For the HVI assessment, road segments with a functional classification of 1-6 were categorized into Critical, High, Moderate or Low risk. These categories are based on the risk value and are in reference to the modeled flooding risk associated with sea level rise and storm surge, as well as the functional classification and evacuation route designation for each roadway. The Federal Emergency Management Agency (FEMA) guidance on driving in flooded conditions influenced risk category delineations. This guide identifies depths of six inches, one foot, and two feet as critical depths. According to FEMA, six inches of water will reach the bottom of most passenger cars possibly causing loss of control and stalling, one foot will float many vehicles and two feet of flowing water can carry away most vehicles (FEMA 2014). The HVI storm surge data presents the results for the 100-year storm event as modeled in Hazus.

Figure 5-9, which presents the HVI for the roadways in Anne Arundel in 2050, depicts coastal roadways will be most impacted by storm surge. Inland sections of roads identified to be at risk are typically located within close proximity to a river or river crossing.

The HVI results for 2100 in Anne Arundel County are provided in Figure 5-1. A similar correlation to 2050 of at risk roadways in coastal areas is depicted as coastal areas are logically more at risk to storm surges than inland roadways. A significant portion of coastal roads within Anne Arundel County are considered to be in the Critical, High or Moderate risk categories by 2100.

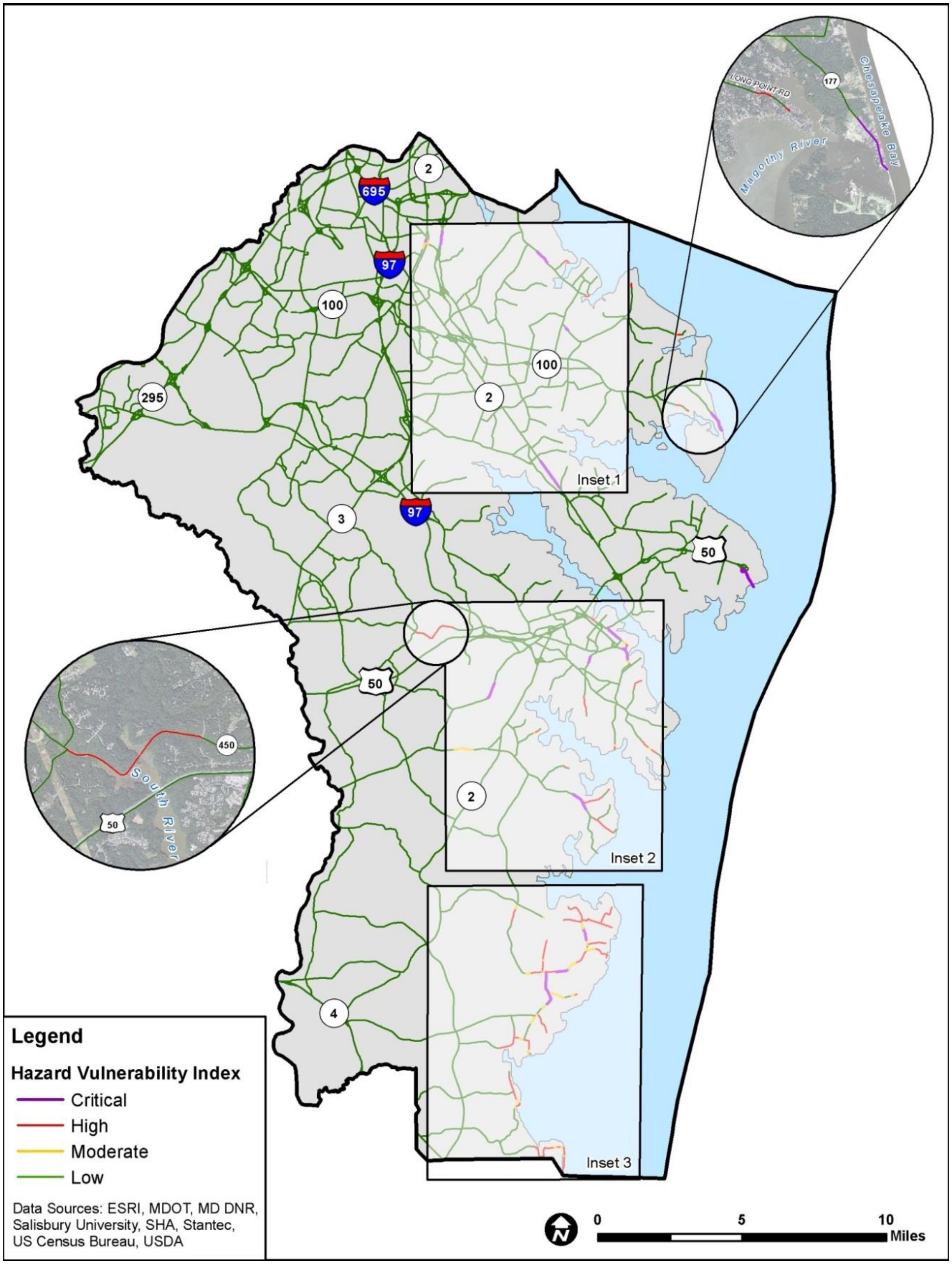


Figure 5-9. 2050 HVI Storm Surge Results for Roadways within Anne Arundel County

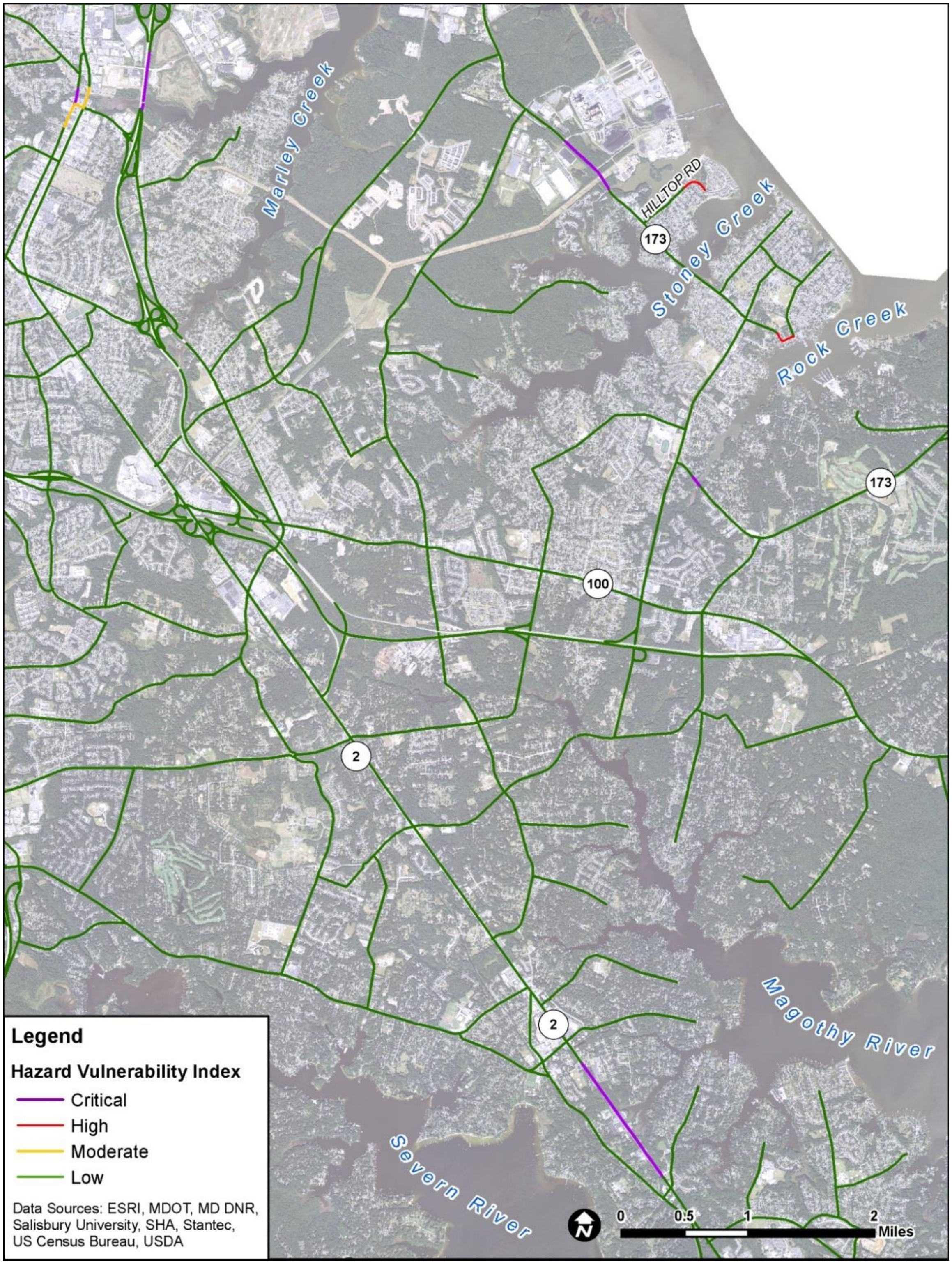


Figure 5-10. 2050 HVI Storm Surge Results Inset #1 Map

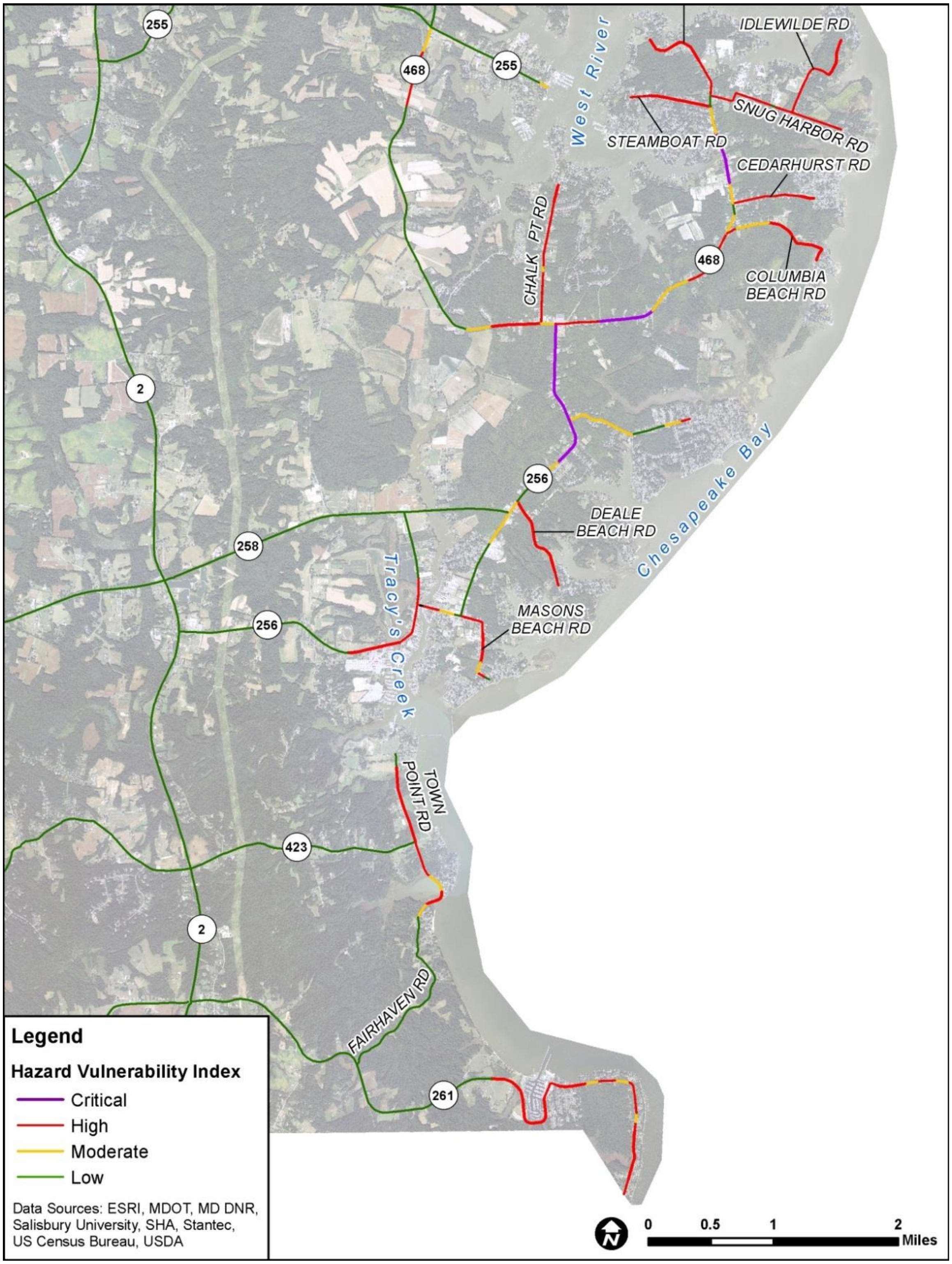


Figure 5-11. HVI 2050 Storm Surge Results Inset #2 Map

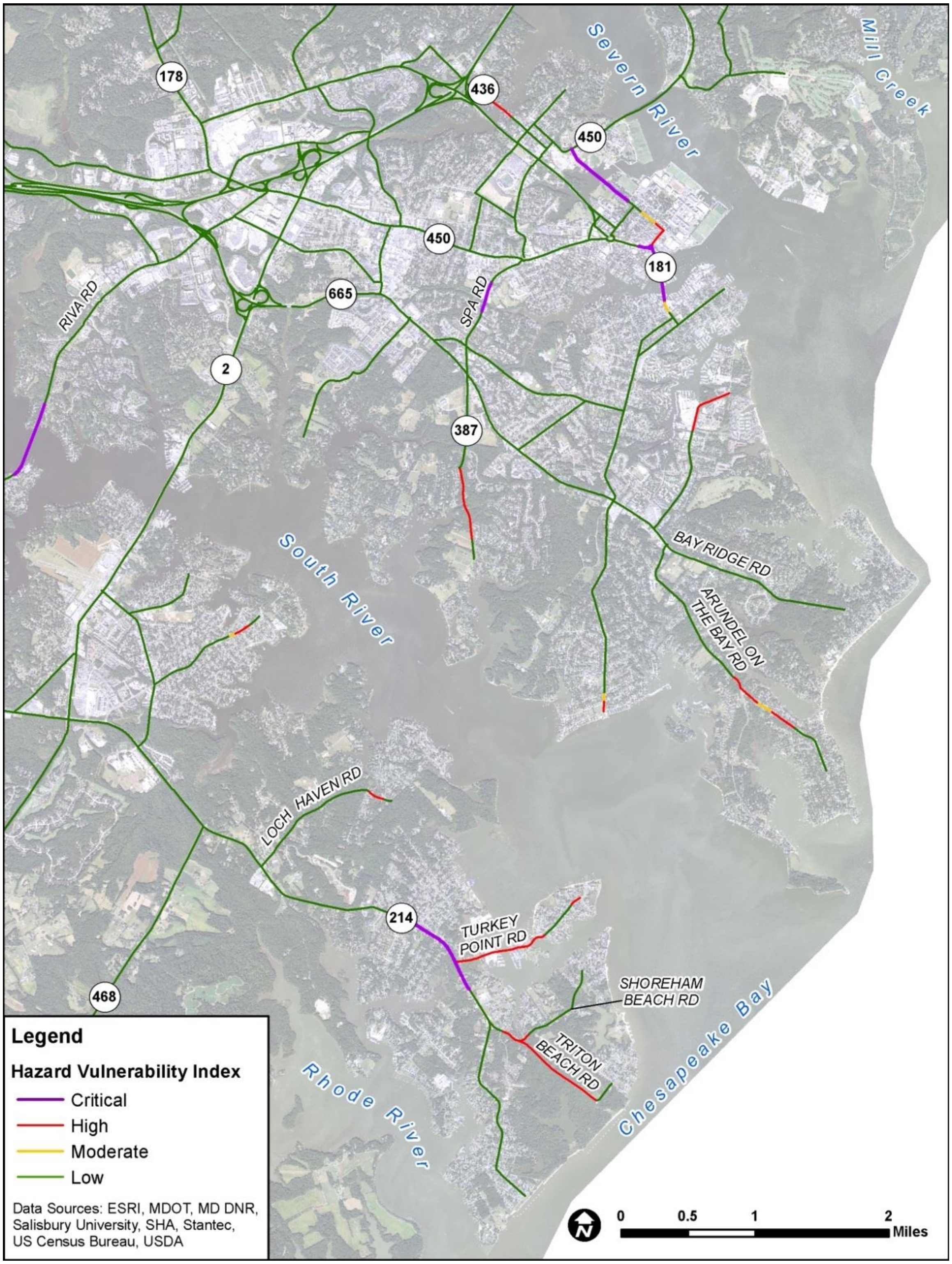


Figure 5-12. HVI 2050 Storm Surge Results Inset #3 Map

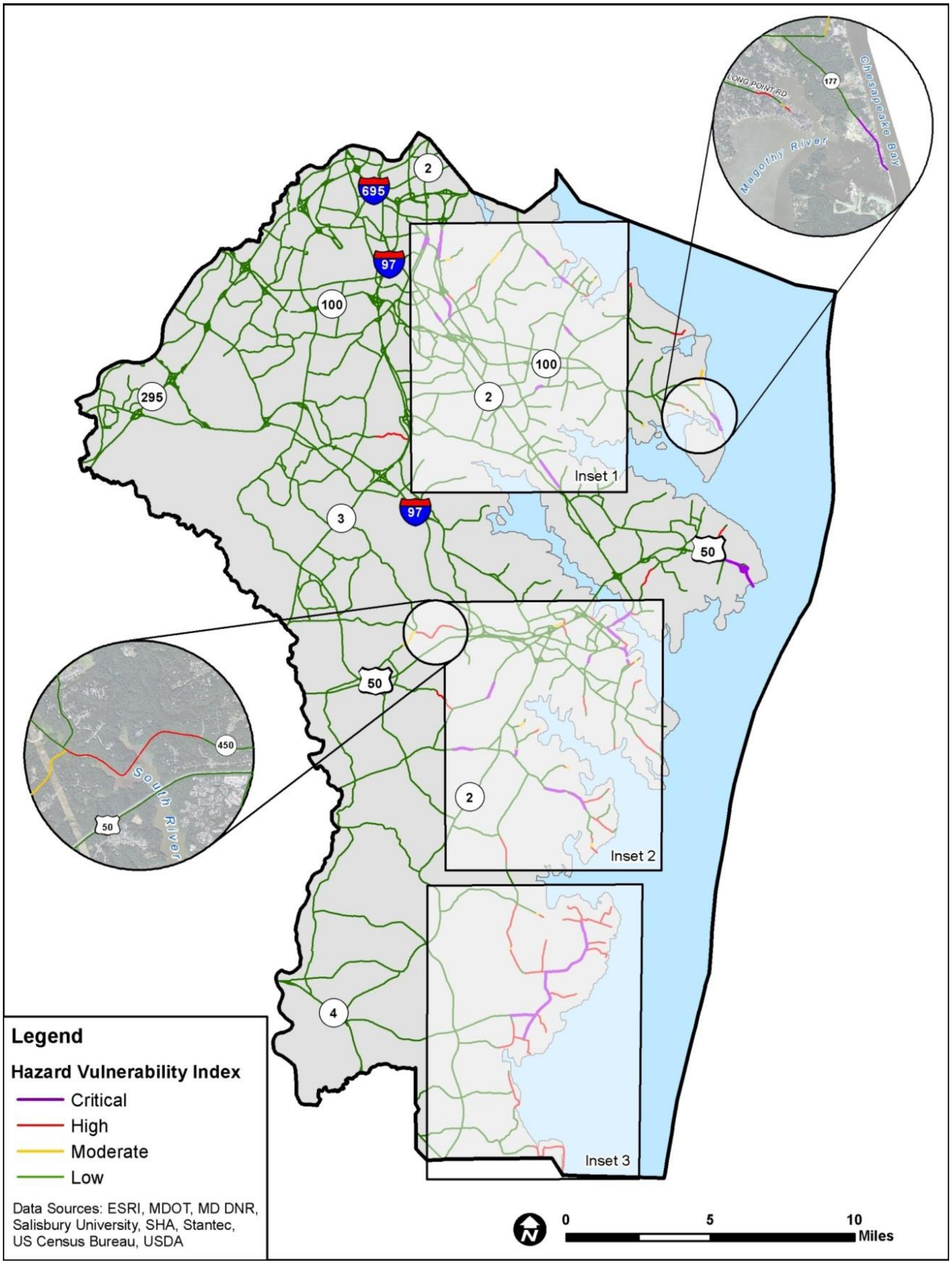


Figure 5-13. 2100 Storm Surge HVI Results for Roadways within Anne Arundel County

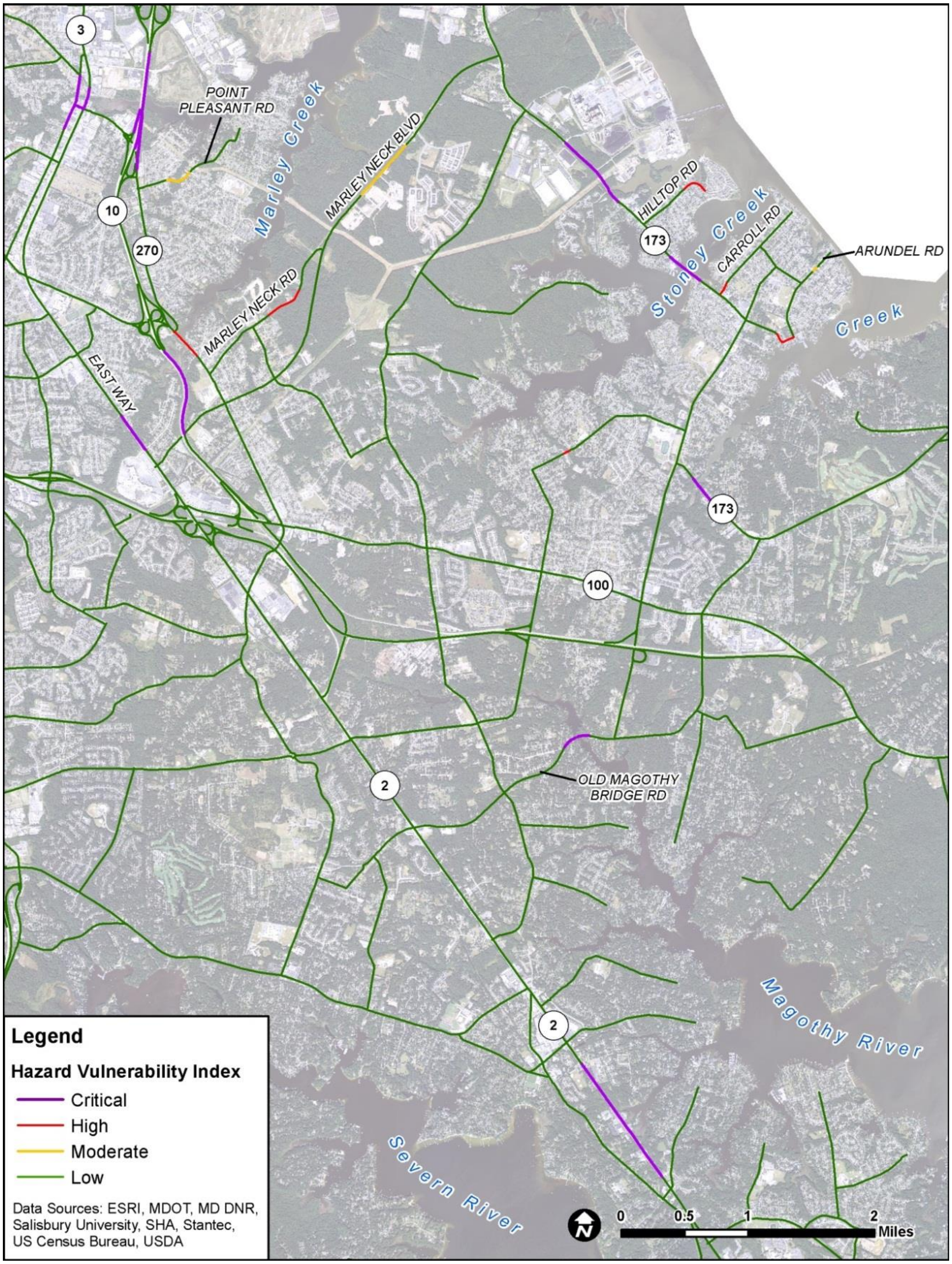


Figure 5-14. 2100 HVI Storm Surge Results Inset #1 Map

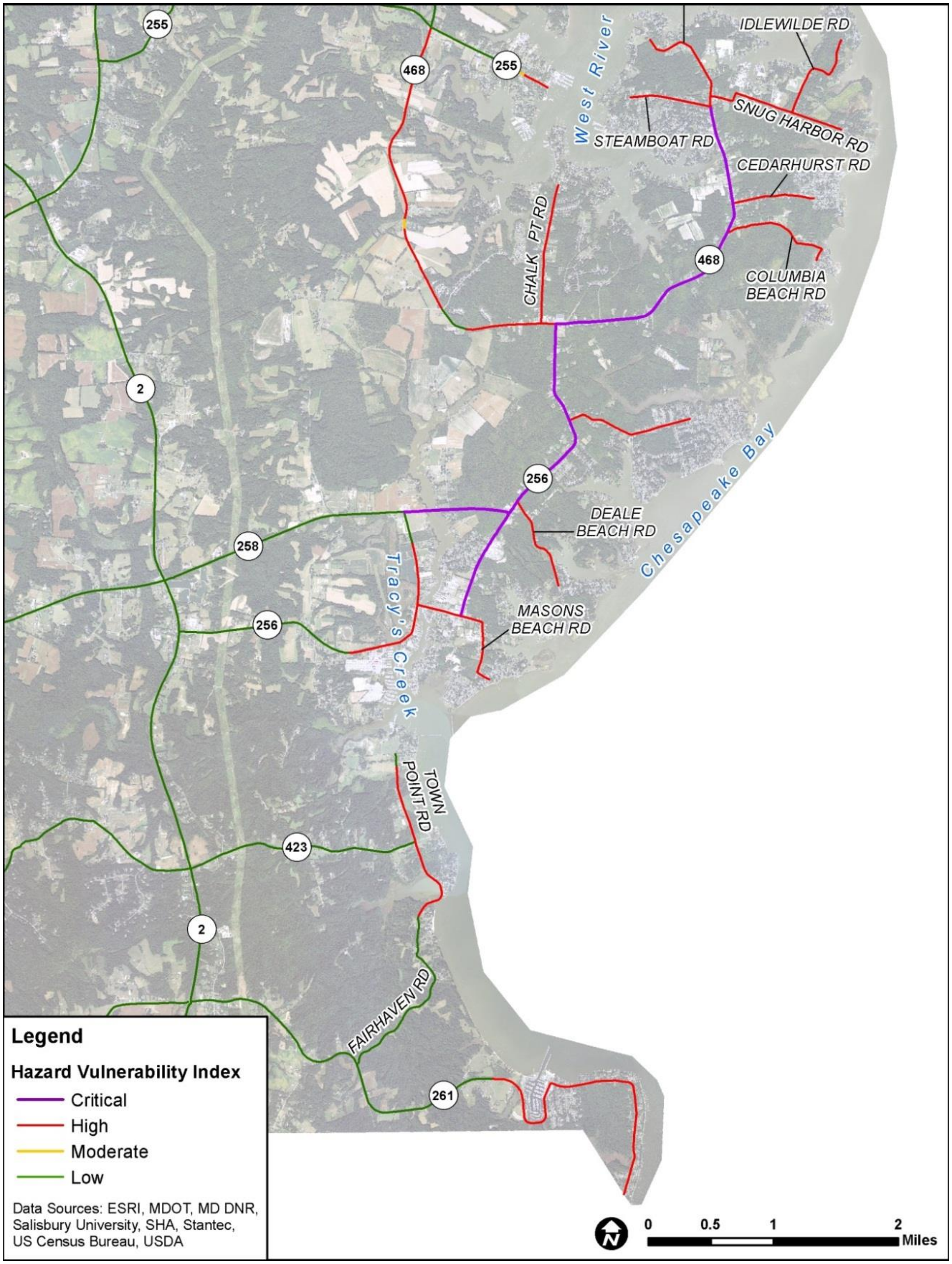


Figure 5-15. 2100 HVI Storm Surge Results Inset #2 Map

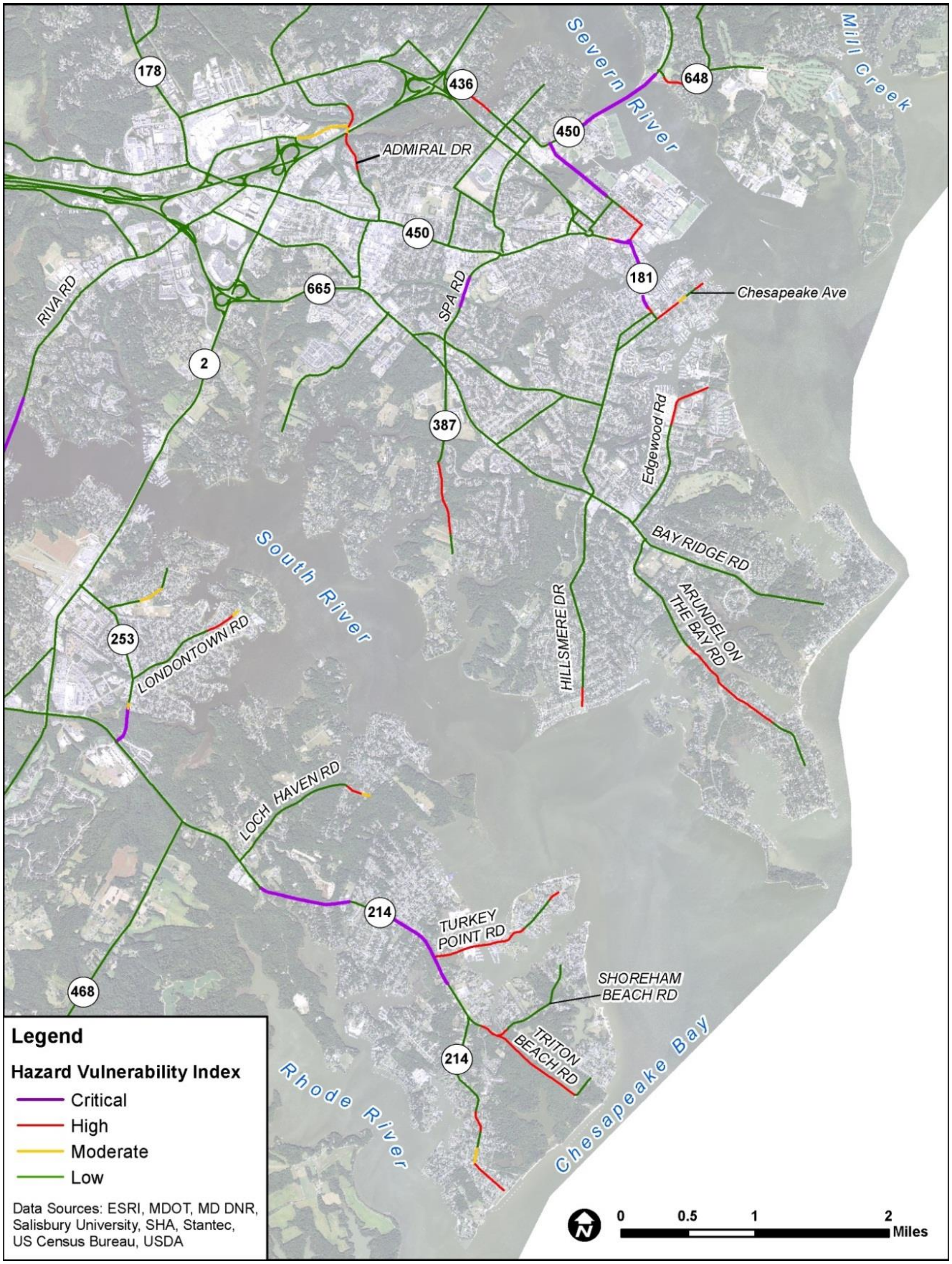


Figure 5-16. 2100 HVI Storm Surge Results Inset #3 Map

To highlight the roadways most at risk and to allow for a similar comparison with the VAST bridge analysis output, the roadways most at risk in 2050 and 2100 are presented in Table 5-3 and Table 5-4. The roadways are listed according to those with the most mileage within the Critical, then High risk categories. MD 468 includes the greatest amount of Critical risk roadway of 0.28 miles by 2050 with 0.48 and 1.19 miles at High and Moderate risk, respectively. MD 468 extends from Snug Harbor Road in Shady Side north to MD 212 in Edgewater. MD 468 is a functional class 4 roadway and is not identified as an evacuation route. Regardless, it is a significant roadway along the coastline and a detour and mitigation would need to be considered. In 2100 MD 256 has a Critical risk of being impacted by storm surge. MD 256 begins at an intersection with MD 2 (Solomons Island Road) at Tracy's Landing and extends to the eastern end of MD 258. A total of 2.76 miles of MD 256 were rated as Critical in the HVI analysis for 2100. MD 256 is a functional class 4 roadway and is not identified as an evacuation route. This roadway runs north/south and its feeder roads (Deale Beach Road and Masons Beach Road) run east/west carrying residents from the coastal areas; therefore, a detour or mitigation should be considered.

Table 5-3. HVI 2050 Storm Surge Most Impacted Roadways

Route Number	Mileage of Roadway			Evacuation Route
	Critical	High	Moderate	
MD468	0.28	0.48	1.19	No
MD450	0.14	0.32	0.13	No
MD256	0.13	0.45	0.54	No
US50	0.13	0.14	0.01	Yes
MD214	0.10	0.19	0.09	No
MD3	0.07	0.01	0.01	Yes
MD177	0.03	0.01	0.01	No
MD173	0.02	0.07	0.03	No
MD2	0.02	-	0.05	Yes
MD387	0.01	-	<0.01	No
MD261	-	1.20	0.52	No
MD423	-	0.24	0.17	No
MD270	-	-	0.02	No
MD255	-	-	0.01	No

Table 5-4. HVI 2100 Storm Surge Most Impacted Roadways

Route Number	Mileage of Roadway			Evacuation Route
	Critical	High	Moderate	
MD256	2.76	1.31	0.09	No
US50	1.15	0.06	0.07	Yes
MD2	0.38	-	0.03	Yes
MD450	0.19	0.63	0.04	No
MD173	0.12	0.10	0.03	No
MD3	0.14	0.01	0.01	Yes
MD10	0.08	-	0.10	No
MD214	0.84	0.18	0.16	No
MD177	0.06	0.01	0.01	No
MD253	0.04	0.02	0.02	No
MD270	0.03	0.01	0.01	No
MD258	0.02	0.16	0.11	No
MD387	0.01	<0.01	0.01	No
MD181	<0.01	-	-	No
MD261	-	2.41	0.11	No
MD179	-	0.03	0.01	No
MD648	-	0.02	0.01	No
MD436	-	0.01	0.09	No
MD255	-	-	0.04	No
MD423	-	-	0.02	No

5.1.4 Anne Arundel Results of VAST

As explained in detail in Chapter 2, VAST analyses were performed on bridges located within the Climate Change Impact Zone, in response to three identified climate stressors: sea level rise, precipitation changes and storm surge. Final VAST results were calculated by ranking and weighting data collected on indicators for the three vulnerability components of exposure, sensitivity and adaptive capacity. Exposure was defined in VAST as the degree to which the asset is exposed to climate variation of a certain climate stressor; sensitivity was defined as the structure's response to being exposed to a climate stressor; and adaptive capacity was defined as the ability of the system to cope with the results of the asset's damage.

Assets that fell within the Climate Change Impact Zone were given a unique ID that remained with the structure throughout the assessment. A total of 150 structures were identified as being within the Climate Change Impact Zone. A simple convention of "1" through "150" was given to the 150 structures assessed, and these asset IDs were consistent in the vulnerability results tables as well as the vulnerable structures map. VAST's unique asset IDs were linked with sufficient information about the structure to identify the exact asset location. Table 5-5 depicts the information associated with each of the assessed structures.

Table 5-5. Example of VAST Asset Features Including Location

Asset ID	Asset Name	NBI ID	Feature Crossed	Location
1	MD 423	20068001	Branch of Herring Bay	2.44 Mile East Of Md 2
4	MD 256	20126001	Traceys Creek	1.73 Mi W Of Md 258
5	MD 258	020018X01	Cabin Branch	0.84 Mile West Of Md 796a
6	MD 256	20127001	Rockhold Creek	0.94 Mi W Of Md 258
7	MD 258	020049X01	Lyons Creek	0.13 Mi W Of Md 2
8	MD 258	20087001	Tracys Creek	1.05 Mile East Of Md 2
10	MD 258	20079001	Rockhold Creek	0.62 Mile West Of Md 256
12	MD 4 EBR	160095001	Patuxent River	On Anne Arundel Co Line
13	MD 4 WB	160011001	Patuxent River	On Anne Arundel Co Line
15	MD 468	020017X01	Smith Creek	0.79 Mile South Of Md 255
17	MD 468	020016X01	Smith Creek	0.19 Mile South Of Md 255
19	MD 255	020024X01	Branch Of Lerch Creek	0.6 Mile West Of Md 468
21	MD 468	020013X01	South Fork Of Muddy Crk	0.55 M N Of Lansdale Road
22	MD 468	020012X01	Muddy Creek	0.69 M N Of Lansdale Rd
25	MD 468	020011X01	Williamson Branch	0.15 M S Of Collins Road
26	MD 468	020010X01	Bluejay Branch	0.07 M N Of Collins Road
27	MD 468	020009X01	North Fork of Muddy Crk	1.48mile South Of Md 214
29	MD 214	020008X01	Glebe Creek	0.26 Mile West Of Md 468
30	MD 214	020006X01	Beards Creek Marsh	0.35 M W Of Rolling Road
31	MD 2	20010001	South River	0.86mi N Of Md 253

Indictors for each vulnerability components were first selected and later data on all vulnerability components were collected and inserted in the VAST database. Using the exposure vulnerability component as an example, the VAST indicators included precipitation change, sea level rise and storm surge (see **Error! Reference source not found.**). These indicators were chosen from the preset list of indicators within the VAST Indicator Library or, as with the largest 3 day rainfall event indicator, were added due to availability of data and applicability to the Pilot Study conditions. All other indicators selected for the sensitivity and adaptive capacity components were also selected from the VAST Indicator Library or based on input from stakeholders during the second engineering workshop.

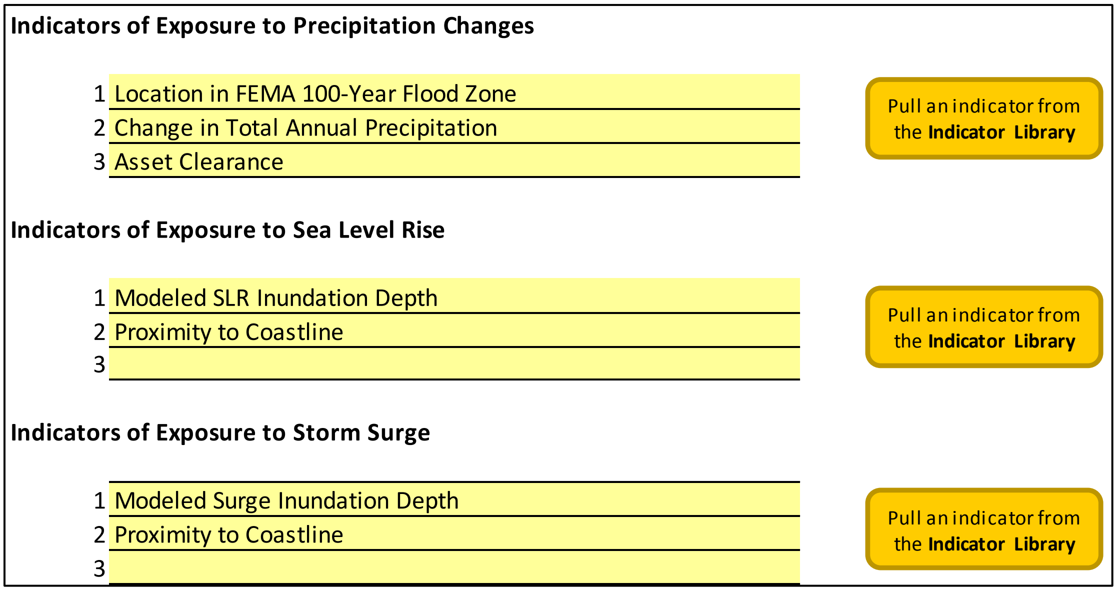


Figure 5-17. Example of VAST Indicator Weight Assignment s

Indicators, as depicted in **Error! Reference source not found.**, were selected because they provided data helpful in identifying the exposure level of the structure to a particular climate stressor. For example, the asset clearance is a measurement derived to provide the height of the bridge above the water. The approach elevation was used since this is typically the lowest point on the bridge and therefore a critical elevation of the bridge. The water elevation at the center point of the bridge, which was acquired from the 2050 and 2100 flood depth grids provided by Salisbury University, was subtracted from the approach elevation to calculate a conservative clearance value. If the depth grids did not extend to the bridge, the water elevation was derived from the LiDAR data. The LiDAR data was back checked against the Salisbury data when both were available and found to be consistently accurate.

Because the assessed area is relatively small, the change in total precipitation was a constant value across all assets within Anne Arundel County. Projected change in total precipitation, according to CMIP analysis, in Anne Arundel County was an increase of 3.8% in 2050 and 6% in 2100. Once the collected data was entered into VAST, it was divided into ranges based on the lower and higher value, then scores were assigned to correspond with the various ranges. The ranges were assigned based on a simple division by a factor of 4. These ranges could be altered once generated to reflect the actual data mean and applicable limits. All ranges were assigned scores from 1-4 (low-high vulnerability) to reflect the vulnerability corresponding with the data range. These scores could also be altered to accurately reflect the significance of a certain range of values. Table 5-6below provides an example of what the database entry, range and scoring looks like once completed.

Asset data on the sensitivity and adaptive capacity indicators were then inserted into tables where each column indicated a data field that was collected for each asset. Because this is a high-level planning scale vulnerability assessment, the indicators inserted in the document included high, medium and low resolution depending on data availability, however, for each indicator, a consistent data source and resolution was used. Table 5-6 demonstrates how the units, data source and data associated with each asset were inserted in VAST. Assets with no detours with adjacent flooding should be considered most vulnerable to the impacts of sea level change and storm surge.

Table 5-6. Example of VAST Units, Data Source and Data Associated with Each Asset

Asset ID	Asset Name Units (if applicable):	Past Experience with Precipitation	Bridge Age Years	Scour Rating	Proximity to the Coast Feet	Asset Clearance Feet	Past Experience with Tides/SLR	Condition of Bridge Substructure
1	MD 423	2	25	8L	3.72865	3.47768	1	7 Good Condition
4	MD 256	1	39	8L	145.218	9.12071	1	6 Satisfactory Condition
5	MD 258	1	50	0	19387.3	4.8112	1	6 Satisfactory Condition
6	MD 256	1	34	8L	89.3754	10.9252	1	6 Satisfactory Condition
7	MD 258	1	51	0	9946.14	13.4898	1	7 Good Condition
8	MD 258	1	51	8P	4984.61	2.5533	1	7 Good Condition
10	MD 258	1	6	8L	115.65	13.3858	1	6 Satisfactory Condition
12	MD 4 EBR	3	18	0	42873.6	5.982732	3	7 Good Condition
13	MD 4 WB	3	23	0	42873.6	5.983761	3	7 Good Condition
15	MD 468	1		0	2186.26	3.73502	1	4 Poor Condition
17	MD 468	1		0	2087.38	2.99577	1	4 Poor Condition
19	MD 255	3	20	0	4976.6	5.7878	3	7 Good Condition
21	MD 468	2	4	0	3157.56	7.00331	1	7 Good Condition
22	MD 468	2	55	0	3434.4	4.03519	1	6 Satisfactory Condition
25	MD 468	1	17	0	4760.06	1.5914	1	7 Good Condition
26	MD 468	1	55	0	4892.03	20.5735	1	6 Satisfactory Condition
27	MD 468	1	55	0	5440.54	5.9173	1	6 Satisfactory Condition
29	MD 214	1	68	0	1457.22	13.09407	1	6 Satisfactory Condition
30	MD 214	3	68	0	2519.41	3.292	3	6 Satisfactory Condition
31	MD 2	1	31	8L	728.65	28.6745	1	6 Satisfactory Condition
34	MD 665 EB	1	23	8L	714.292	11.98462	1	6 Satisfactory Condition
35	MD 665 WB	1	23	8L	727.553	18.31247	1	6 Satisfactory Condition

The indicators were weighted based on the percentage of value in which each indicator could contribute to the overall vulnerability component score. In the case where scores are available for all indicators, the overall score is the weighted average of all indicator scores. For example the formula to calculate the exposure score is:

$$Exposure\ Score = \sum_{i=1}^{n} E_i \times W_i$$

Where n is the total number of exposure indicators

When scores are not available for all the indicators, the weights for the remaining indicators are adjusted. The weight of the missing indicator is distributed among the remaining indicators based on their original weight. The resulting formula is used:

$$W_{new} = W_i + (W_X \times \frac{W_i}{W_O})$$

Where:
Wi is the original indicator weight
Wx is the sum of the original weights of all indicators with no data
Wo is the sum of the original weights of all indicators with data

The weight of the indicator for each of the indicators within the vulnerability component was manually adjusted to reflect the importance of that indictor or the reliability of that data source. The results are portrayed within the VAST program as a pie chart, depicted below in Figure 5-17.

Once the scoring and weighting of the indicators was completed for each vulnerability component and each climate stressor, the total score for each of the three components were combined for each climate stressor to come up with the overall vulnerability of each asset. A percentage or a weight was given to each vulnerability component based on the importance of that component in identifying the vulnerability of the structure. Higher weights were given to exposure and sensitivity components compared to adaptive capacity. Exposure to climate stressors is an integral element to identify whether a structure is vulnerable to a certain climate stressor. If an asset is not exposed to that climate stressor then it was not considered vulnerable even if it obtained high vulnerability scores for sensitivity and adaptive capacity. Results of the indicator screening were displayed within VAST to show the overall score that each structure obtained for each climate stressor.

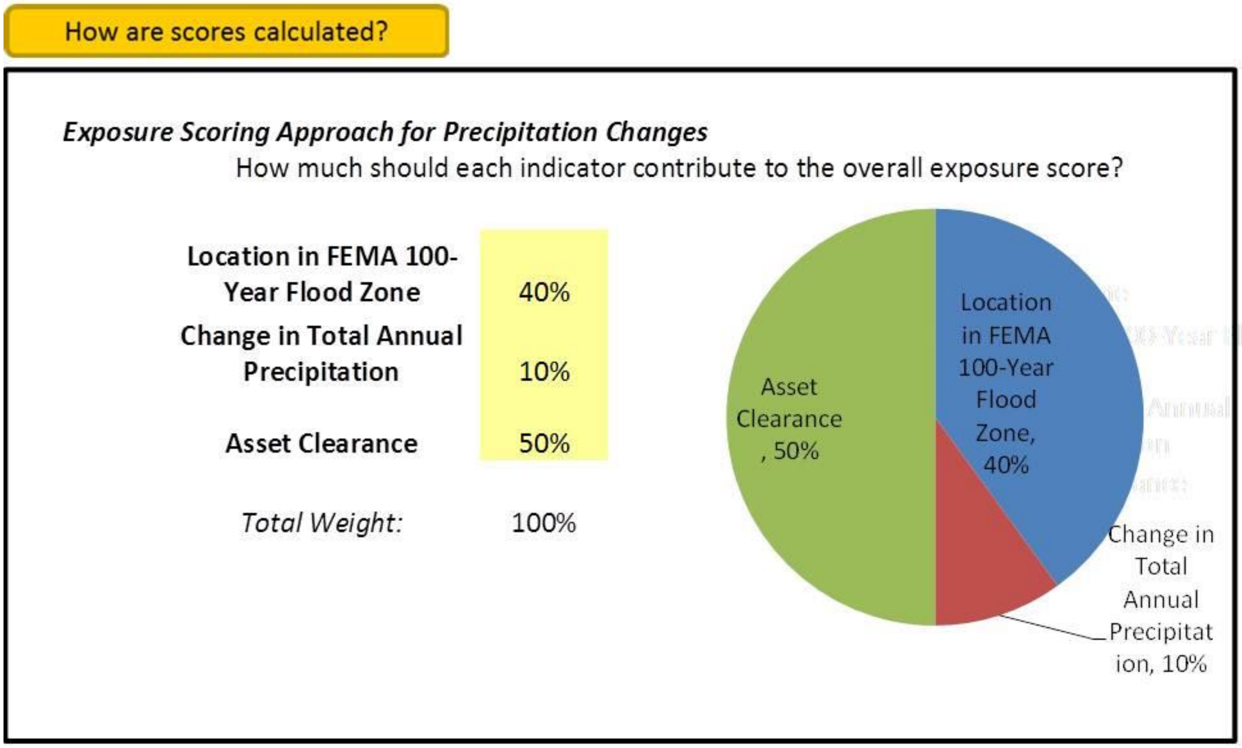


Figure 5-17. Example of VAST Indicator Weight Assignment

The VAST results table shows both the damage and vulnerability of each structure in response to the three identified climate stressors. Damage, which is defined in VAST as the extent to which an asset is exposed and sensitive to a climate stressor is only a function of exposure and sensitivity. The damage score demonstrates the possibility of an asset's failure, while the vulnerability score demonstrates how the system will function if a structure was damaged (see

Table 5-7). If a structure obtained a low damage score, then the structure was not considered vulnerable even if the adaptive capacity score was high.

Vulnerability component weights were adjusted so that damage contributed to 80% of the vulnerability score and adaptive capacity contributed to the remaining 20% of the vulnerability score.

Assets were ranked based on the overall vulnerability score calculated in VAST's result sheet. With an overall vulnerability score that could range from 1 to 4, structures that scored the highest were considered the most vulnerable, and structures that scored the lowest were considered safe and resilient against the climate stressor being assessed. Each asset received an independent score for each Climate Stressor included in this analysis; for example, assets that could be vulnerable to precipitation might prove to be resilient against sea level rise or storm surge, and vice versa.

Table 5-7. Example of Damage and Vulnerability Scores in VAST

		Precipitation Changes				Sea Level Rise			
		2050	2050	2100	2100	2050	2050	2100	2100
Asset ID	Asset Name	"Damage"	Vulnerability	"Damage"	Vulnerability	"Damage"	Vulnerability	"Damage"	Vulnerability
1	MD 423	2.8	2.6	2.8	2.6	2.4	2.3	2.9	2.6
4	MD 256	1.8	1.8	1.8	1.8	1.3	1.4	1.3	1.4
5	MD 258	1.9	1.9	1.9	1.9	1.4	1.5	1.4	1.5
6	MD 256	1.5	1.5	1.5	1.5	1.2	1.3	1.2	1.3
7	MD 258	1.4	1.5	1.4	1.5	1.1	1.2	1.1	1.2
8	MD 258	2.5	2.4	2.5	2.4	1.9	1.9	1.9	1.9
10	MD 258	1.5	1.6	1.5	1.6	1.2	1.4	1.2	1.4
12	MD 4 EBR	2.2	2.4	2.2	2.4	1.6	1.9	2.5	2.7
13	MD 4 WB	2.2	2.4	2.2	2.4	1.6	1.9	2.5	2.7
15	MD 468	2.4	2.3	2.4	2.3	1.5	1.6	1.5	1.6
17	MD 468	2.4	2.3	2.4	2.3	2.0	2.0	2.0	2.0
19	MD 255	2.2	2.1	2.2	2.1	1.6	1.6	1.6	1.6
21	MD 468	2.0	2.0	2.0	2.0	1.2	1.3	1.2	1.3
22	MD 468	2.7	2.6	2.7	2.6	1.5	1.6	1.5	1.6
25	MD 468	2.4	2.3	2.4	2.3	1.8	1.8	1.8	1.8
26	MD 468	1.4	1.5	1.4	1.5	1.2	1.3	1.2	1.3
27	MD 468	1.8	1.8	1.8	1.8	1.3	1.4	1.3	1.4
29	MD 214	0.9	1.1	0.9	1.1	1.2	1.3	1.2	1.3
30	MD 214	3.0	2.8	3.0	2.8	1.9	1.9	1.9	1.9
31	MD 2	1.4	1.9	1.4	1.9	1.2	1.7	1.2	1.7
34	MD 665 EB	1.4	1.7	1.4	1.7	1.2	1.5	1.2	1.5
35	MD 665 WB	1.4	1.7	1.4	1.7	1.2	1.5	1.2	1.5
37	MD 181(SIXTH ST)	1.9	1.9	1.9	1.9	1.4	1.5	1.8	1.9
39	MD 70	1.5	1.6	1.5	1.6	1.2	1.3	1.2	1.3
41	MD 450	1.8	1.9	1.8	1.9	1.3	1.4	2.6	2.5

The vulnerability score of structures in Anne Arundel County ranged from 1.0 to a score as high as 3.2 on the vulnerability scale. An example of a structure vulnerable to precipitation is Asset number 134 (MD 3) which is a large culvert located over Sawmill Creek and is located 0.06 miles north of MD 270. The Asset Score Query sheet below shows that the structure obtained a total score of 3.1 for vulnerability to precipitation changes. The ranking and weighting that led to identifying this asset as vulnerable can be attributed to both its exposure and sensitivity high scores. The asset got a high exposure score because it was located in the FEMA 100-year flood zone and the asset's clearance was only 2 feet above water. Sensitivity scores were high for Asset 134 where the asset received a score of 4 in one indicator that accounted to 50% of the sensitivity score which is previous experience with precipitation. SHA operations and maintenance staff indicated that the structure has experienced frequent historical flooding in the events of heavy precipitation. The overall sensitivity score for this asset was 3.3 on a scale of 4. The adaptive capacity was also high for this asset; this asset is considered an evacuation route and its average daily traffic exceeds 15,000 vehicles. Despite having a function class of 5, this asset scored 2.8 out of 4 in its adaptive capacity. By adding up the exposure, sensitivity and adaptive capacity scores, and weighing them based on the weights identified for each vulnerability component, the overall vulnerability score for asset 134 was 3.1 (Figure 5-18).

Figure 5-18. Structure 134 from Downstream Figure, Structure 134 is Vulnerable to Precipitation Changes, Sea Level Rise, and Storm Surge (VAST 2.6)
Photo Source: (Maryland Environmental Services 2006)

Another example of an asset that could be vulnerable to a certain climate stressor and resilient to another is Structure 104, MD 173, which is a bridge crossing Rock Creek and is located 0.68 miles north of MD 607. The overall vulnerability score for precipitation change was 2.3 which is a moderate vulnerability; however the sea level rise vulnerability score was 3.0 for the year 2100, which is considered a high vulnerability.

The asset Score Query for Asset 104 (Figure 5-20) shows that the asset has a low exposure to sea level rise in the year 2050; however, the modeling results showed that it will be inundated by sea level rise by the year 2100. Because modeled inundation depth accounted to 90% of the exposure score, the asset obtained a high exposure score in the year 2100. The bridge inspection documents demonstrates that the bridge is in fair condition, however because the bridge was built in 1932 and is 82 years old, and scour was determined to be a fair concern at this bridge, the cumulative sensitivity score at this bridge was 2.4, which is considered moderate. The asset obtained a moderate adaptive capacity score based on scoring the 4 indicators that comprise the adaptive capacity; the asset is not located on an evacuation route, however, it has a functional class of 3 (a major collector), and the average daily traffic is over 9,000 vehicles. The overall vulnerability score for this structure in the year 2100 was 3.0 which are considered a highly vulnerable structure to the impacts of sea level rise.

Figure 5-19. Structure 104 Deck from Upstream, Structure 104 is Vulnerable to Sea Level Rise and Storm Surge (VAST 2.6)
Photo Source: (Maryland Environmental Services 2006)

Structure number 1, MD 423, is a bridge crossing a Branch of Herring Bay, and is located 2.44 miles east of MD 2. Figure 5-21 shows the Asset Score Query for this structure which shows that the vulnerability score of this asset is 2.6 despite being highly vulnerable to storm surge in the years 2050 and 2100. MD 423 is a coastal road with a modeled inundation depth of 2.9 feet in both 2050 and 2100. Because of limitations in the model used to project inundation, there was no considerable increase in inundation depth in 2100. More detailed modeling is needed to better identify inundation variations. Because of the projected inundation and its coastal location, the exposure score for structure 1 was 4.0; however the overall vulnerability score was 2.6 because the sensitivity and adaptive capacity scores were very low for this specific asset. The structure which was built in 1989 and the yearly inspection indicate that the structure is in good condition. Furthermore, the road associated with the structure is a minor collector that is not an evacuation route, and the average daily traffic on this road is close to 1,200 vehicles. The low sensitivity and adaptive capacity scores contributed to lowering the overall vulnerability score of the structure despite initially being considered a highly vulnerable structure.

Figure 5-20. Structure 1 Deck from Downstream, Structure 1 is Vulnerable to Changes, Sea Level Rise, and Storm Surge (VAST 2.6)
Photo Source: (Maryland Environmental Services 2006)

Asset Score Query

Back

Use this sheet to look up the full scores for a specific asset.

Select an asset type: Bridges

Select an asset ID: 134 MD 3 BU

Select a climate stressor: Precipitation Changes

Query Scores

Individual Asset Score Report

Asset ID: **134**

Asset Name: **MD 3 BU**

	Scenario 1	Scenario 2
Vulnerability Score:	**3.1**	**3.1**
Exposure Score	3.1	3.1
Sensitivity Score	3.3	
Adaptive Capacity Score	2.8	

Score Breakdown:

EXPOSURE	Scenario 1		Scenario 2		
	Value	*Score*	*Value*	*Score*	*Weight*
Location in FEMA 100-Year Flood Zone	Yes	2.5	Yes	2.5	40%
Change in Total Annual Precipitation	3.8	1	6	1	10%
Asset Clearance	2.0	4	2	4	50%
Exposure Score		**3.1**		**3.1**	

SENSITIVITY	*Value*	*Score*	*Weight*	*Actual Weight (adjusted for no data)*
Past Experience with Precipitation	4	4	50%	
Bridge Age	34	2	5%	
Scour Rating	8P	1	15%	
Proximity to the Coast	1095.65	2	10%	
Asset Clearance	2.28148	4	20%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
Sensitivity Score		**3.3**		

ADAPTIVE CAPACITY	*Value*	*Score*	*Weight*	*Actual Weight (adjusted for no data)*
ADT	17610	3	25%	
Function Classification	5	2	25%	
Evacuation Route	Y	4	25%	
Detour Length	ıdjacent flooding	2	25%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
Adaptive Capacity Score		**2.8**		

Figure 5-21. Structure 134 Asset Score Query for Precipitation

Asset Score Query

Back

Use this sheet to look up the full scores for a specific asset.

Select an asset type: Bridges

Select an asset ID: 104 MD 173

Select a climate stressor: Sea Level Rise

Query Scores

Individual Asset Score Report

Asset ID: **104**

Asset Name: **MD 173**

	Scenario 1	Scenario 2
Vulnerability Score:	**1.9**	**3.0**
Exposure Score	1.3	4.0
Sensitivity Score	2.4	
Adaptive Capacity Score	2.3	

Score Breakdown:

EXPOSURE	Scenario 1 Value	Scenario 1 Score	Scenario 2 Value	Scenario 2 Score	Weight
Modeled SLR Inundation Depth	3.2	1	-0.4	4	90%
Proximity to Coastline	18.5	4	18.5458	4	10%
	n/a	n/a	n/a	n/a	0%
Exposure Score		**1.3**		**4.0**	

SENSITIVITY	*Value*	*Score*	*Weight*	*Actual Weight (adjusted for no data)*
Past Experience with Tides/SLR	2	2	45%	
Asset Clearance	5.24933	2	20%	
Scour Rating	5A	4	15%	
Condition of Bridge Substructure	5 Fair Condition	2	5%	
Condition of Bridge Superstructure	5 Fair Condition	2	5%	
Condition of Bridge Deck	5 Fair Condition	2	5%	
Bridge Age	82	4	5%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
Sensitivity Score		**2.4**		

ADAPTIVE CAPACITY	*Value*	*Score*	*Weight*	*Actual Weight (adjusted for no data)*
ADT	9150	3	25%	
Function Classification	3	3	25%	
Evacuation Route	N	1	25%	
Detour Length	1.5	2	25%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
Adaptive Capacity Score		**2.3**		

Figure 5-22. Structure 104 Asset Score Query for Sea Level Rise

Asset Score Query Back

Use this sheet to look up the full scores for a specific asset.

Select an asset type: Bridges

Select an asset ID: 1 MD 423

Select a climate stressor: Storm Surge

Individual Asset Score Report

Asset ID: 1

Asset Name: MD 423

	Scenario 1	Scenario 2
Vulnerability Score:	**2.6**	**2.6**
Exposure Score	4.0	4.0
Sensitivity Score	1.7	
Adaptive Capacity Score	1.8	

Score Breakdown:

EXPOSURE	Scenario 1		Scenario 2		
	Value	*Score*	*Value*	*Score*	*Weight*
Modeled Surge Inundation Depth	-2.9	4	-2.9	4	80%
Proximity to Coastline	3.7	4	3.72865	4	20%
	n/a	n/a	n/a	n/a	0%
Exposure Score		**4.0**		**4.0**	

SENSITIVITY	*Value*	*Score*	*Weight*	*Actual Weight (adjusted for no data)*
Past Experience with Storm Surge	1	1	45%	
Asset Clearance	3.47768	4	20%	
Scour Rating	8L	1	15%	
Condition of Bridge Substructure	7 Good Condition	1	5%	
Condition of Bridge Superstructure	7 Good Condition	1	5%	
Condition of Bridge Deck	sfactory Condition	2	5%	
Bridge Age	25	2	5%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
Sensitivity Score		**1.7**		

ADAPTIVE CAPACITY	*Value*	*Score*	*Weight*	*Actual Weight (adjusted for no data)*
ADT	1262	2	25%	
Function Classification	6	1	25%	
Evacuation Route	N	1	25%	
Detour Length	5.5	3	25%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
	n/a	n/a	0%	
Adaptive Capacity Score		**1.8**		

Figure 5-23. Structure 1 Asset Score Query for Storm Surge

5.1.5 Final VAST Results

Anne Arundel County structures that were vulnerable to the identified three climate stressors for the years 2050 and 2100 were listed based on the vulnerability scores calculated in VAST. The location and asset ID of the most vulnerable structures were depicted on Anne Arundel County maps as shown in

Figure 5-24 though **Error! Reference source not found.** below. Table 5-8 through Table 5-12 show the sum of weighted averages of all the vulnerability components of the structures..

Despite being part of the initial assessment for Anne Arundel County, structures on all local roads that were identified as county roads or function class 7 were removed from the final VAST results, and all roads that were incorporated in the final results tables and maps were function class 1-6. Local knowledge from SHA operations and maintenance staff on bridge damage during historical flood events was collected and incorporated into the analysis.

In this VAST assessment, precipitation exposure indicators lacked any modeled data that define or separate assets that will be exposed to increased precipitation in the years 2050 and 2100, therefore the 2050 and 2100 exposure data were identical for both scenarios. Location in the 100-year floodplain and the asset clearance were the defining factor for the structure's exposure score. These values were very similar in many of the assessed structures, which explain the low variation in the overall vulnerability scores among assets. The vulnerability threshold was set at 2.0, which is an indicator of a medium vulnerability; therefore all structures that scored above the 2.0 vulnerability threshold were mapped and are presented on Figure 5-24. This figure shows that structures vulnerable to precipitation are scattered around the county, and there is no certain trend in relation to the structures location.

The assets with the highest scores in terms of vulnerability to sea level rise and storm surge in 2050 and 2100 are shown in Figure 5-29Figure 5-27 and Figure 5-28, below. The vulnerability threshold was also set at 2.0, and all structures that scored above the 2.0 vulnerability threshold were included in the most vulnerable structures table and map.

Vulnerability scores for sea level rise ranged from as low as 1.2 and as high as 3.0. Modeling results showed that very few structures in Anne Arundel will be exposed to sea level rise in the year 2050. Because exposure to sea level rise is an integral element to identify whether a structure is vulnerable, all non-exposed structures were considered resilient, regardless of their sensitivity or adaptive capacity scores, and only eight structures that obtained a moderate exposure score were considered vulnerable to sea level rise. Modeling results for 2100 showed that only 13 structures were exposed to inundation by sea level rise in 2100, which included the structures that were identified as vulnerable in 2050.

Vulnerability scores for storm surge in 2050 and 2100 ranged from scores as low as 1.3 and as high as 2.9. Storm surge modeling results for Anne Arundel County showed that a significant number of structures will be inundated by 2050 and 2100. Storm Surge inundation depths were modeled as high as 3.1 feet for 2050 and 3.9 feet for 2100.

Storm surge and sea level rise vulnerability results show that vulnerable structures seem to cluster in certain areas in Anne Arundel along US 50 as well as in Glen Burnie, with other scattered structures along the coast.

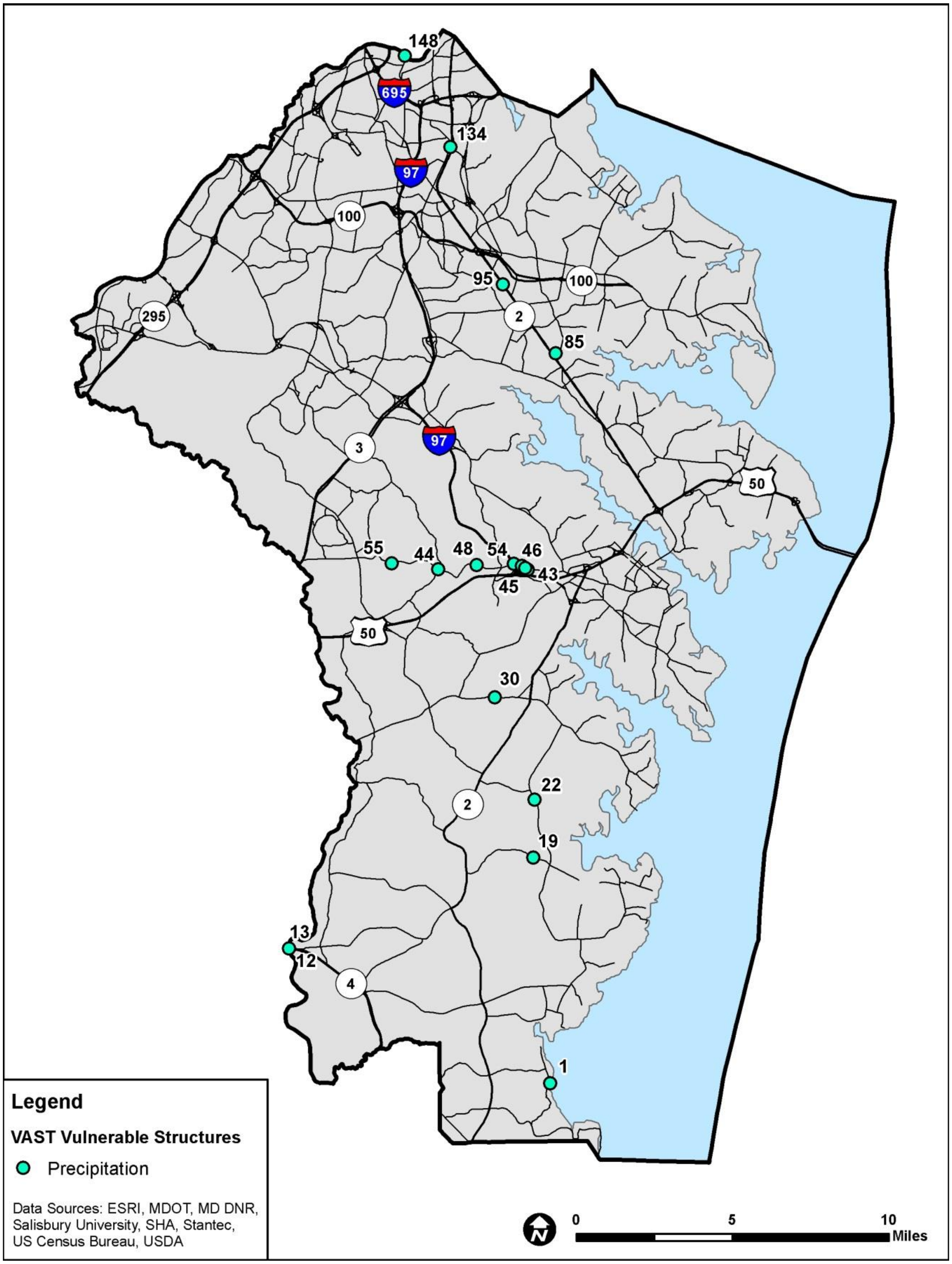


Figure 5-24. VAST 2050 and 2100 Anne Arundel Structures Most Vulnerable to Precipitation

Table 5-8. VAST 2050 and 2100 Anne Arundel Structures Most Vulnerable to Precipitation

Vulnerability to Precipitation		
Structure ID	**VAST Score**	**Evacuation Route**
134	3.1	Yes
44	2.8	No
30	2.8	No
43	2.8	No
45	2.8	No
46	2.8	No
1	2.6	No
22	2.6	No
95	2.5	Yes
148	2.5	No
48	2.5	No
55	2.5	No
12	2.4	Yes
13	2.4	Yes
54	2.2	No
85	2.1	No
19	2.1	No

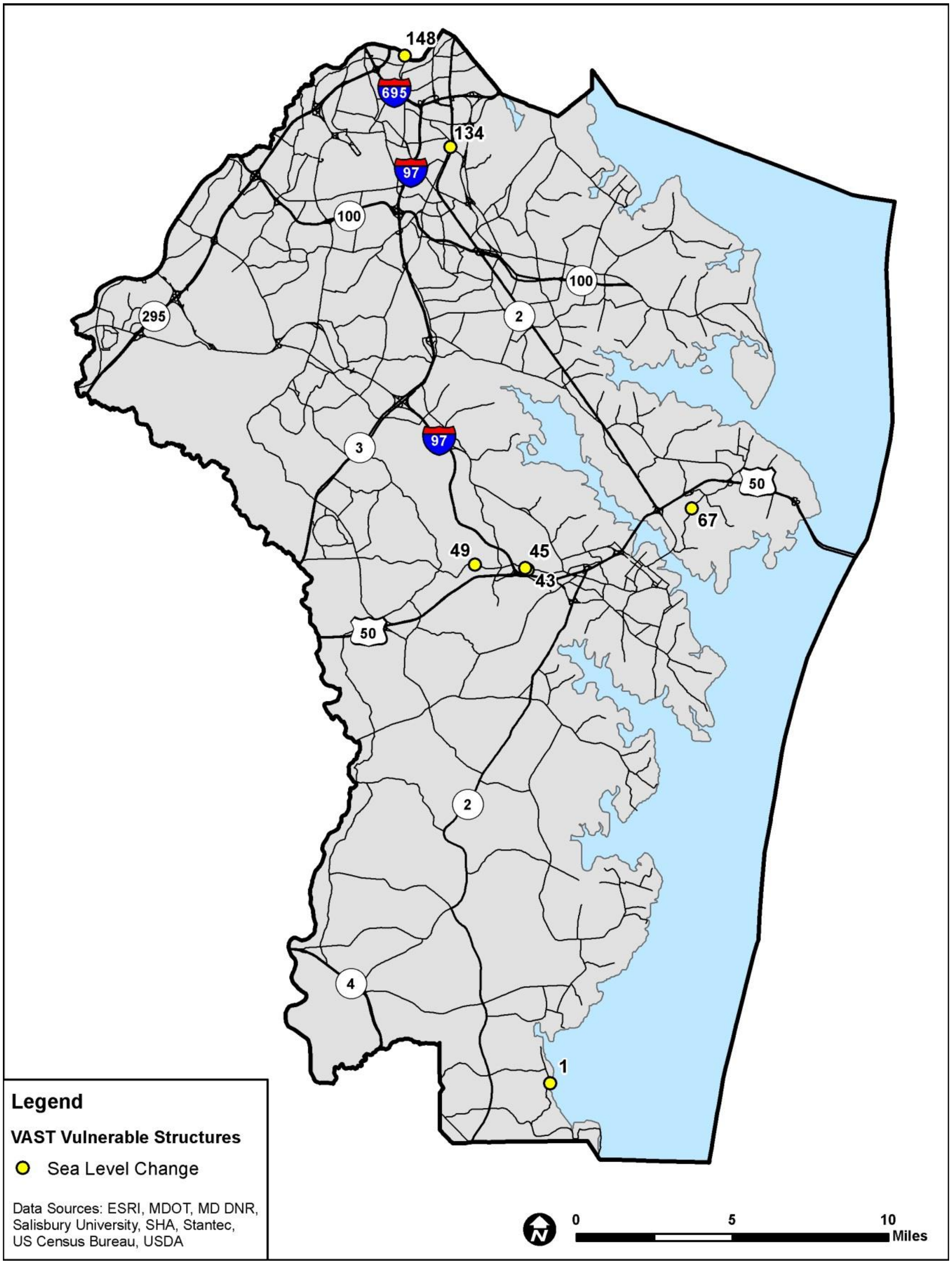


Figure 5-25. VAST 2050 Anne Arundel Structures Most Vulnerable to Sea Level Rise

Table 5-9. VAST 2050 Anne Arundel Structures Most Vulnerable to Sea Level Rise

Vulnerability to 2050 Sea Level Rise		
Structure ID	**VAST Score**	**Evacuation Route**
43	2.7	No
45	2.7	No
134	2.4	Yes
49	2.4	No
1	2.3	No
148	2.0	No
67	2.0	No

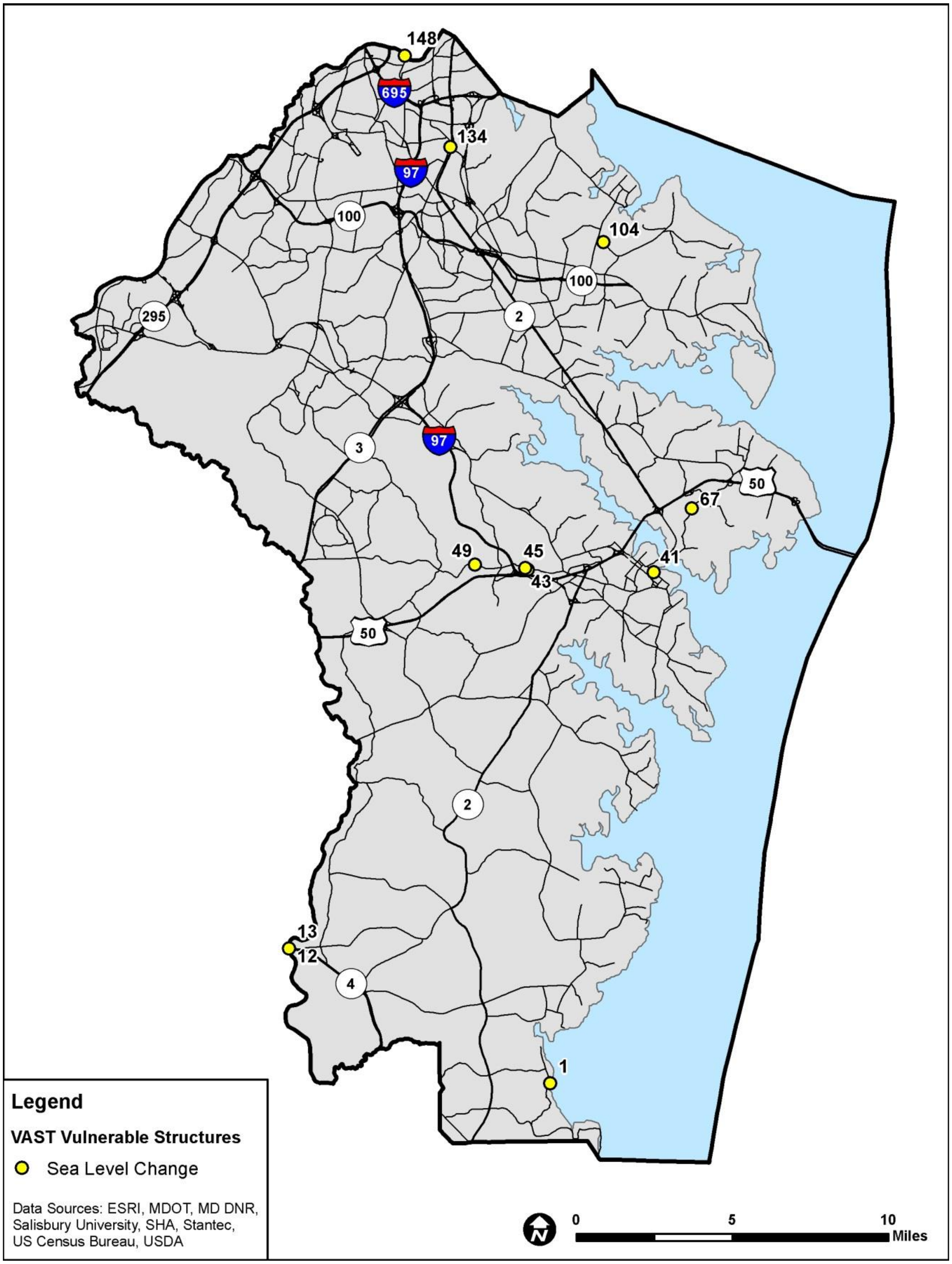


Figure 5-26. VAST 2100 Anne Arundel Structures Most Vulnerable to Sea Level Rise

Table 5-10. VAST 2100 Anne Arundel Structures Most Vulnerable to Sea Level Rise

Vulnerability to 2100 Sea Level Rise		
Structure ID	**VAST Score**	**Evacuation Route**
104	3.0	No
67	2.7	No
12	2.7	Yes
13	2.7	Yes
43	2.7	No
45	2.7	No
1	2.6	No
41	2.5	No
134	2.4	Yes
49	2.4	No
148	2.0	No

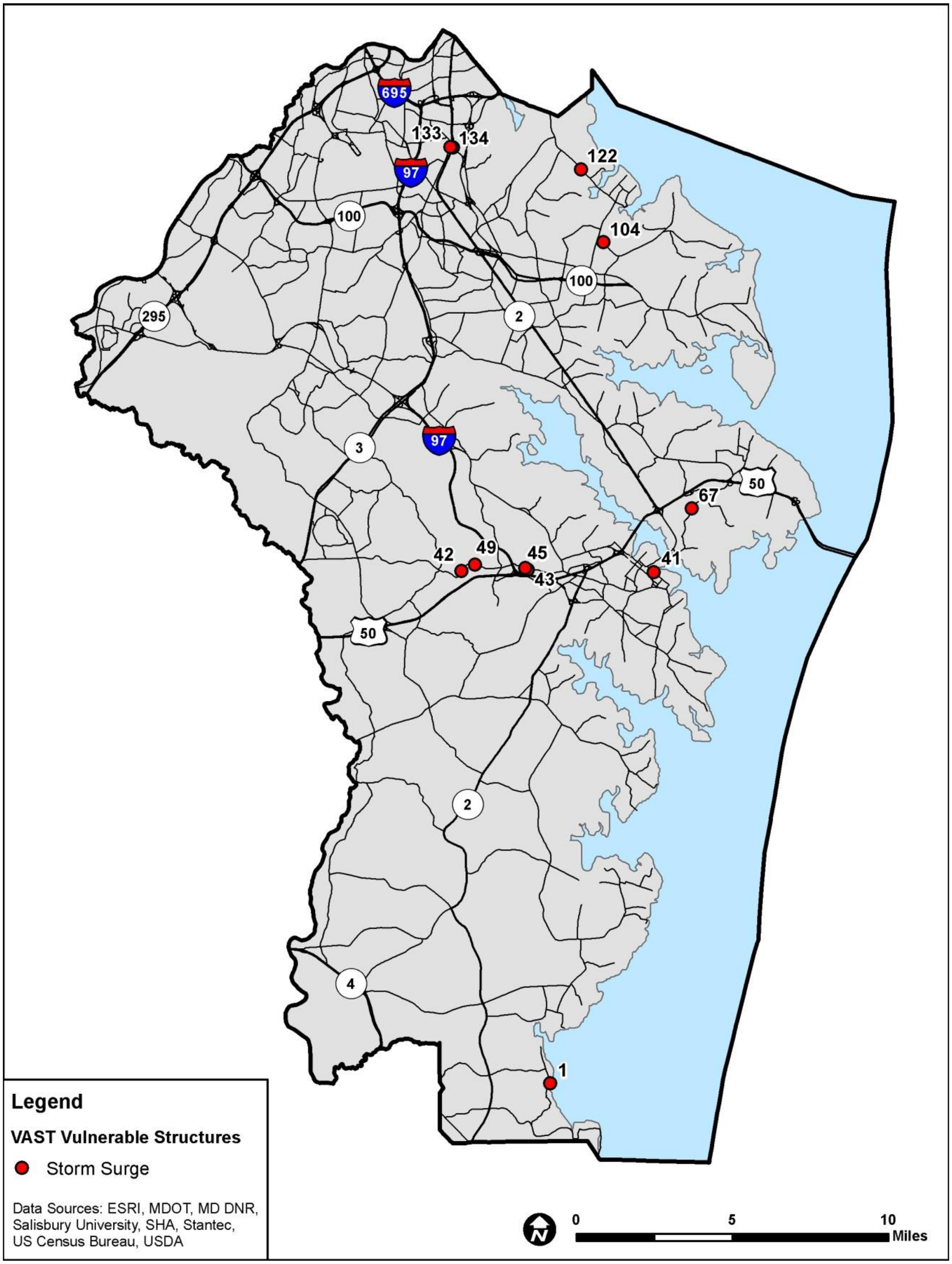


Figure 5-27. VAST 2050 Anne Arundel Structures Most Vulnerable to Storm Surge

Table 5-11. VAST 2050 Anne Arundel Structures Most Vulnerable to Storm Surge

Vulnerability to 2050 Storm Surge		
Structure ID	**VAST Score**	**Evacuation Route**
134	2.9	Yes
104	2.8	No
67	2.7	No
1	2.6	No
45	2.6	No
41	2.5	No
133	2.5	Yes
49	2.4	No
43	2.3	No
42	2.3	No
122	2.2	No

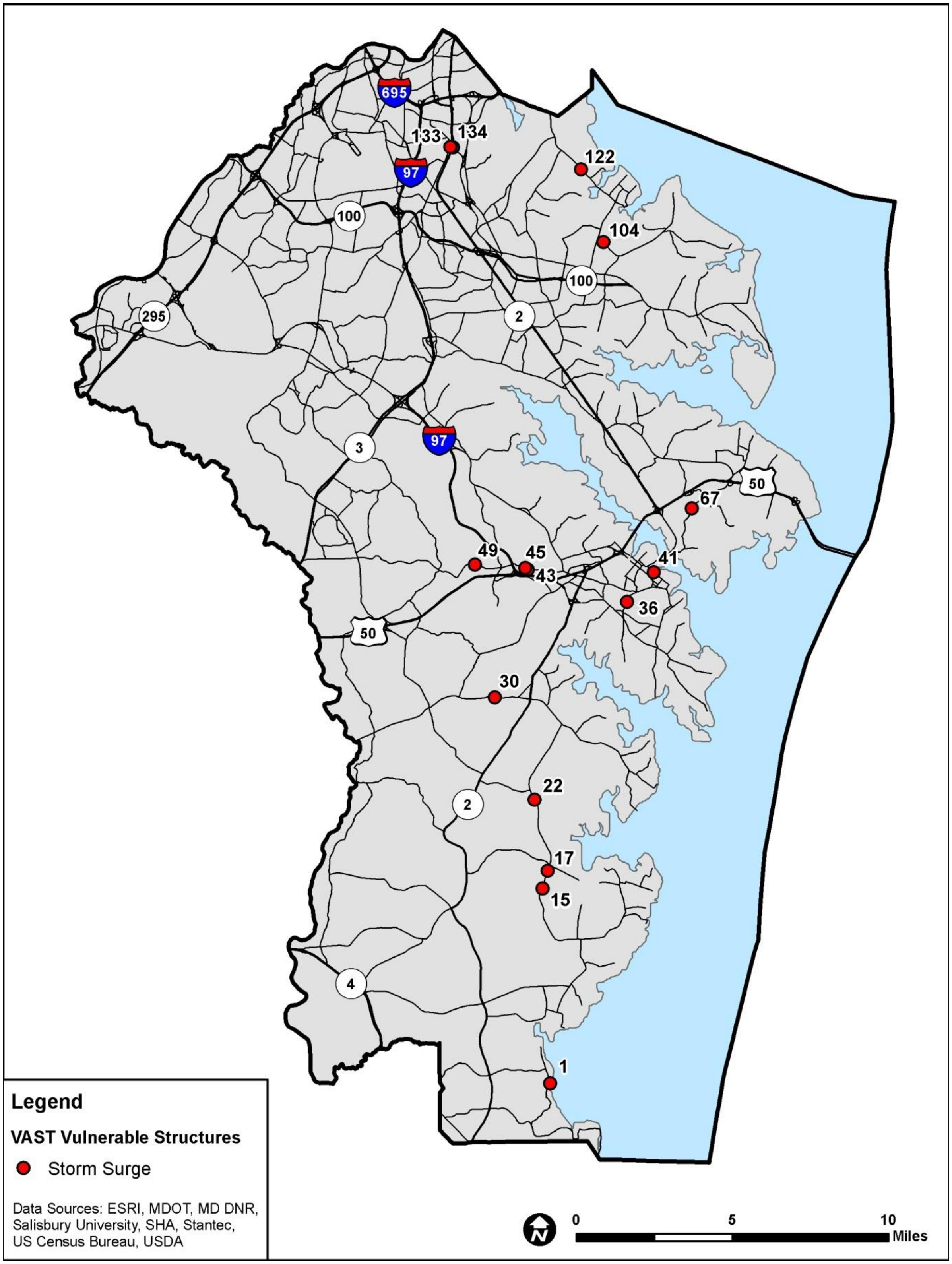


Figure 5-28. VAST 2100 Anne Arundel Structures Most Vulnerable to Storm Surge

Table 5-12. VAST 2100 Anne Arundel Structures Most Vulnerable to Storm Surge

Vulnerability to 2100 Storm Surge		
Structure ID	**VAST Score**	**Evacuation Route**
30	2.9	No
134	2.9	Yes
104	2.8	No
67	2.7	No
1	2.6	No
15	2.6	No
17	2.6	No
45	2.6	No
41	2.5	No
133	2.5	Yes
49	2.4	No
43	2.3	No
22	2.3	No
122	2.2	No
36	2.1	No

5.2 Somerset County

5.2.1 Somerset County Overview

Somerset County is located in southeast Maryland, along the Chesapeake Bay and according to the 2010 census, it has a population of 26,470 (US Census Bureau 2014). The county is located in SHA's District 1, which contains 19 roads and 87 bridges (SHA n.d.), 72 that are located in the Climate Change Impact Zone, in which 48 are SHA structures. The county is 610.78 square miles in size, but only 53 percent (327.21 square miles) of that area is land (US Census Bureau 2014). The elevation of the county is very low relative to the current mean sea level. The highest point in the county is a mere 53.89 feet above mean sea level (Salisbury University, 2014). The county has a long history of dynamic shoreline change. More than one Bay-front town has been abandoned due to rising sea levels (URS and RCQuinn Consulting, Inc. 2008). According to the 2008 *Somerset County Rising Sea Level Guidance*, three SHA roads are already experiencing flooding, sections of MD 361, MD 362, and MD 363 (URS and RCQuinn Consulting, Inc. 2008).

A multidisciplinary group of SHA employees attended two workshops to gather input and ideas for the Pilot Study. During the second engineering workshop participants input showed that the most important adaptive capacity indicators for SHA assets are replacement cost and access to critical areas. Somerset County is at greater risk of losing access to critical areas and evacuation routes. Somerset County has fewer evacuation routes four, than the mean 27; and therefore has fewer access roads than most Maryland counties. The county has a population density of 82.8 persons per square mile, which is much lower than the statewide average of 594.8 persons per square mile (US Census Bureau 2014). Somerset County is particularly at risk of losing access to critical areas because it is more sparsely populated and therefore has fewer access roads than most Maryland counties. Replacement cost is less of an issue, but still of concern.

The vulnerability assessment data for Somerset Country came from three sources, the SHA GIS department, Salisbury University and CMIP. These data sources are discussed in greater detail in Section 2.2.1. These data were used in the VAST and HVI vulnerability assessments for roadways, bridges and drainage structures in the county.

In the *Somerset County Rising Sea Level Guidance*, there are several suggested general policy changes to account for changes to sea level and floodplains. A number of these could affect SHA planning and design, including a re-delineation of the landward boundary of the Conservation Zone; delineation of a new ‘floodplain planning zone’; and creation of a stream buffer/conservation easement. The guidance document also has several suggested construction standards for roads and streets. In the case of low-lying areas it is suggested that elevation requirements be identified or lowered to avoid blocking drainage. On elevated roads, the guidance document suggests that roadway bedding may need to be improved to account for raising ground levels. This improvement may require a new requirement that unsuitable material be removed and replaced with thicker fill materials. However, the document states that the county currently requires that the subgrading is prepared based on test borings, so a minimum of 12 inches of subgrade is already expected (URS and RCQuinn Consulting, Inc. 2008).

To adapt to these climate stressors, policies will need to be created and/or updated. Similar to the Coast Smart freeboard requirement for buildings, consideration is needed for raising roadways, bridges, and approaches above predicted inundation zones. Further, the supports for these assets may need to be strengthened for greater erosive forces. Drainage system capacity standards (*e.g.*, culverts and ditches) may need to be increased to account for greater volumes of water, and backflow flaps may need to be required to stop tidal influx in newly affected areas. SHA policies may be affected outside immediate design standards. Any new roads may be better sited outside the Climate Change Impact Zone, where possible, because it reduces potential for future impacts due to flooding. Future consideration will also include wetland mitigation sites, if they are within the Climate Impact Area, and will be inundated by future sea level rise. Additionally, more projects will require hydraulic and hydrology studies in the future to determine the best design.

5.2.2 Somerset County: Result of Hazus Modeling

As described in the methodology section, Salisbury University provided sea level change and storm surge data for each pilot county. The following maps show the results of this modeling. Figure 5-29 and Figure 5-30 show mean sea level inundations for 2050 and 2100. Figure 5-31 shows the mean higher high water

(MHHW) inundation for 2050 and 2100. In 2050, the coastal shoreline shows inundation ranging from 2.5 to 5.0 feet. On average sea level is predicted to rise 2.11 feet (MSL) in 2050 and 5.78 feet (MSL) in 2100. These figures illustrate how major roadways utilized as evacuation routes from the coastal areas would be impacted including MD 413 and MD 363.

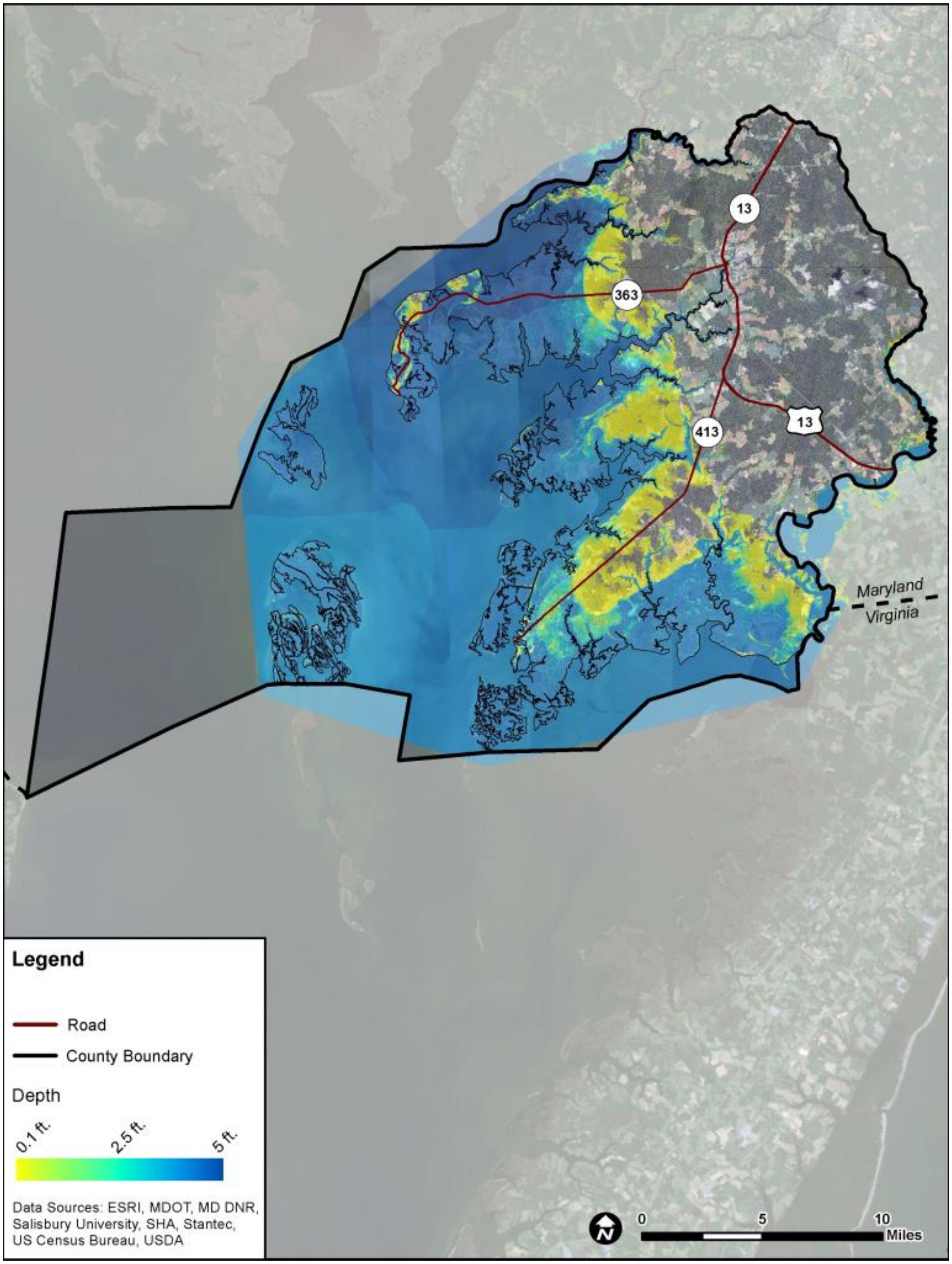


Figure 5-29. 2050 Sea Level Rise Inundation Levels in Somerset County

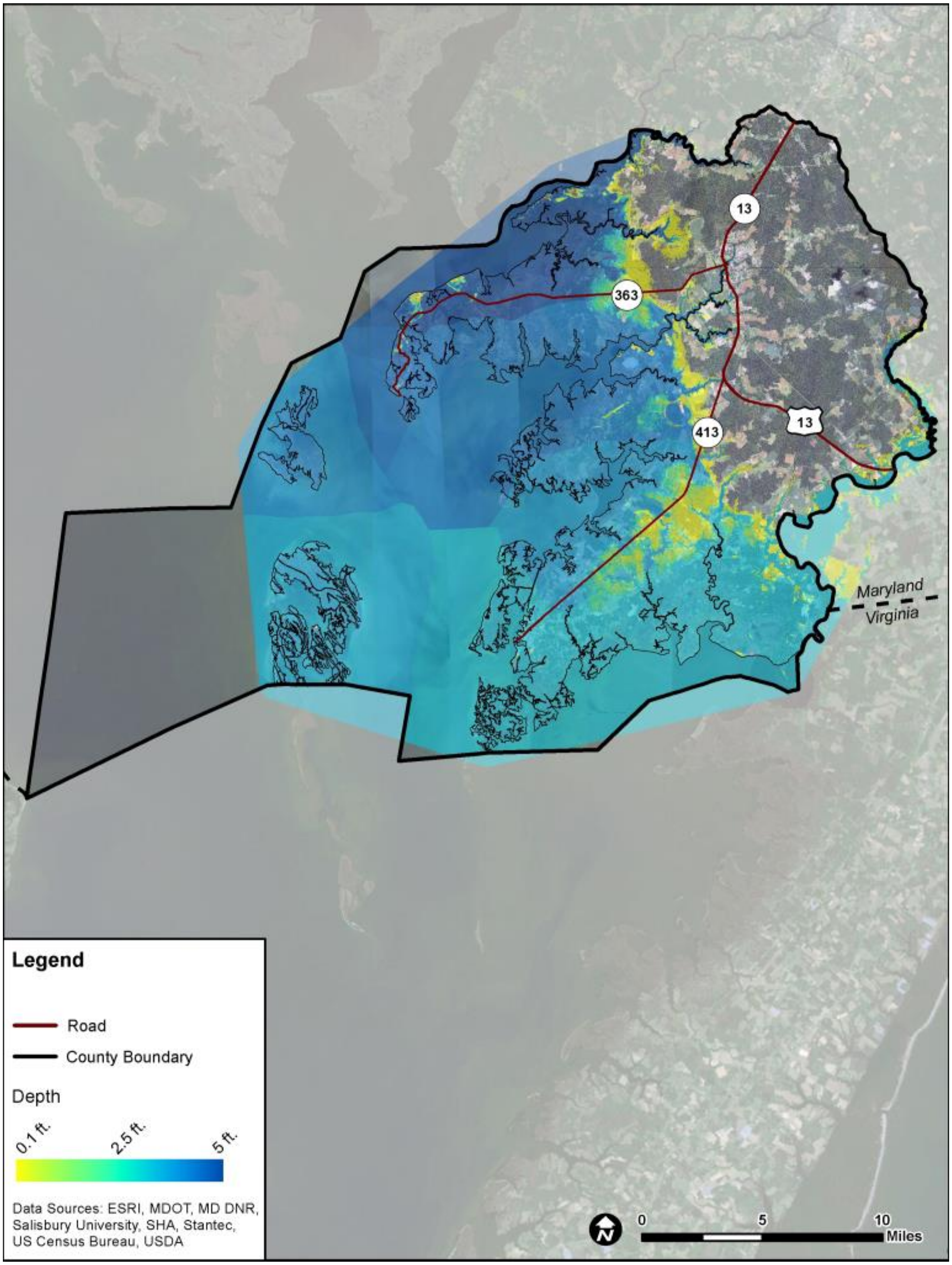


Figure 5-30. 2100 Sea Level Rise Inundation Levels in Somerset County

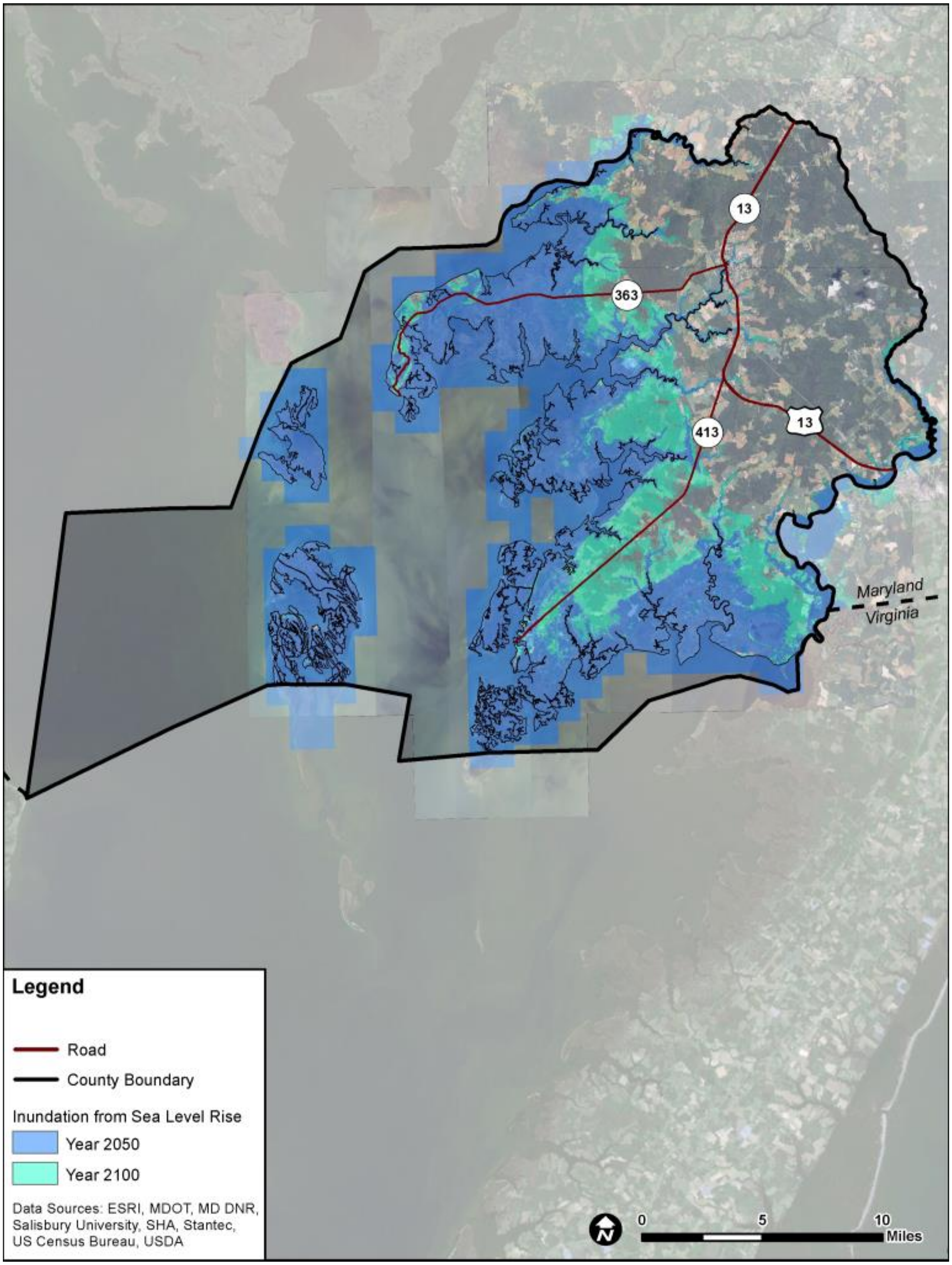


Figure 5-31. Mean Higher High Water for 2050 and 2100 Sea Level Change in Somerset County

5.2.3 Somerset County Result of HVI

SHA compiled an inventory of pertinent transportation assets within Somerset County. The total number of bridges, small culverts and conveyances as well as the miles of roadways present in Somerset County is listed on Table 5-13 below.

Table 5-13. Somerset County Assets evaluated in Flood Inundation Modeling, HVI or VAST

Asset Type	Somerset
Bridges	72
Small Culverts and Conveyances	1153
Miles of Roadways	156.33

Similar to Anne Arundel County, HVI provided a risk value for road segments to sea level change and storm surge. The risk value is derived from roadway evacuation route designation, functional classification and the flood depth code hazard indicator. The HVI assessment was applied to functional classification 1-6 roadways within the Climate Impact Zone. Appendix C includes a list of roadways within these parameters are identified with their location for further analysis purposes.

Figure 5-32 and Figure 5-33 depict the roads impacted by permanent inundation due to sea level rise, respectively in 2050 and 2100 within Somerset County. The Flood Inundation Modeling maps depict the roadways at risk for permanent inundation due to sea level rise regardless of the depth. Harmful effects to the roadway are projected to occur regardless of the depth, with the rendering of the roadway to be unusable by vehicles as a chief issue. The maps indicate that by 2050 the percentage of roads impacted is minor and limited to a couple areas closest to the coast. The 2100 maps depict a different situation in that the majority of the major roadways would be inundated further inland. This is important to note for the purpose of emergency evacuation planning. Figure 5-34 depicts the 2100 HVI inset maps which further call out the specific roadway segments at risk to permanent inundation from sea level rise. In these maps it is evident that the majority of the main arteries are at risk of permanent inundation.

The roadways most impacted by sea level rise, by 2050 and 2100 within Somerset County (Table 5-14 and

Table 5-15) and MD 460 is modeled to have 0.25 miles of permanent inundation by 2050. MD 430 is also known as Hall Highway and is located in southwestern Somerset County. This roadway is not identified as an evacuation route however, it is utilized by McCready Memorial Highway and therefore the potential threat would need to be further evaluated. Approximately 0.51 miles of MD 363 is modeled to be permanently inundated by 2100. MD 627 is also known largely as Oriole Road and runs from runs 2.48 miles (3.99 km) from the intersection of Oriole Back Road and Crab Island Road in **Oriole** east to **MD 363** near **Venton**. MD 363 is not classified as an evacuation route.

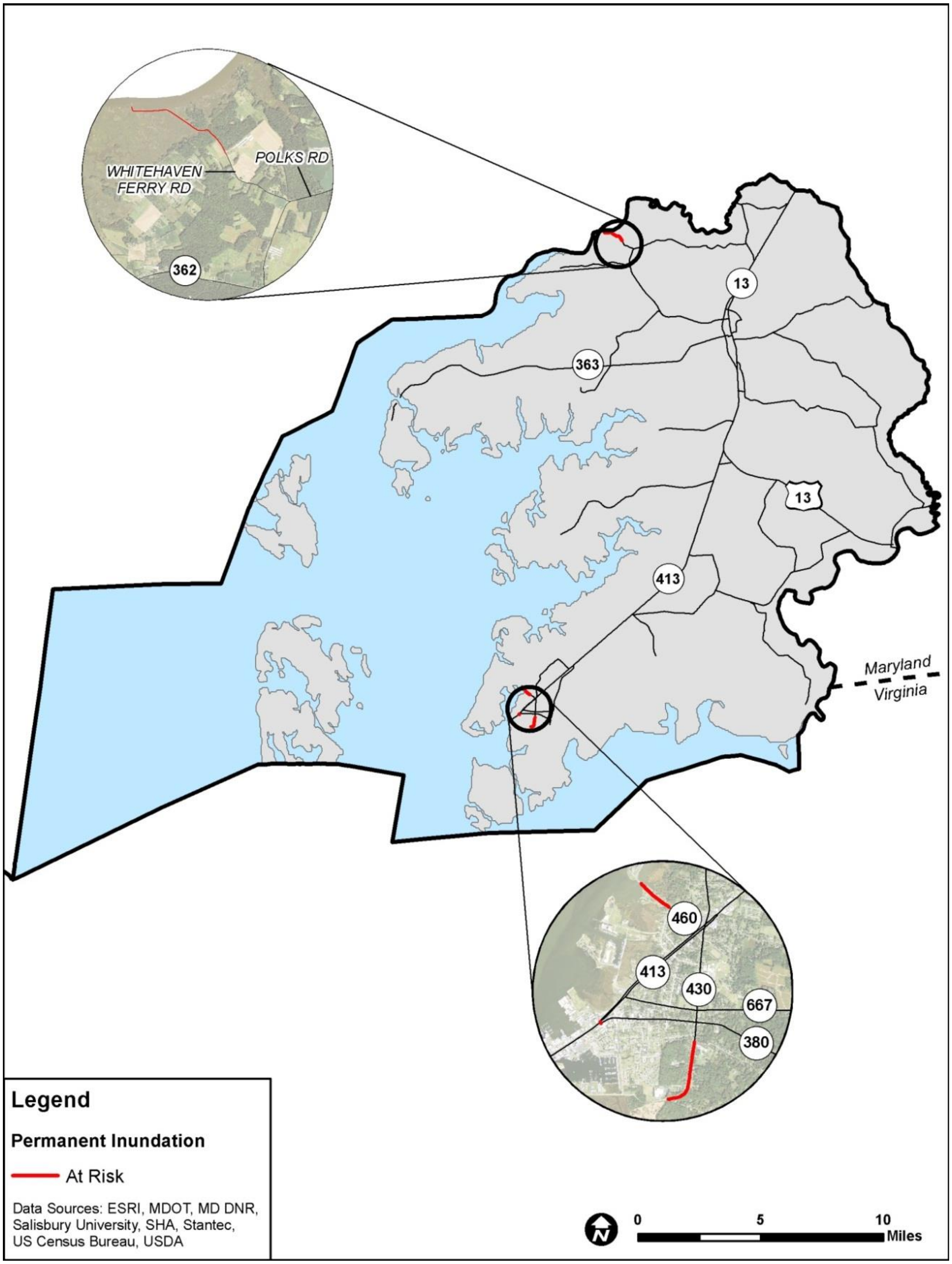


Figure 5-32. 2050 Sea Level Rise Results for Roadways within Somerset County

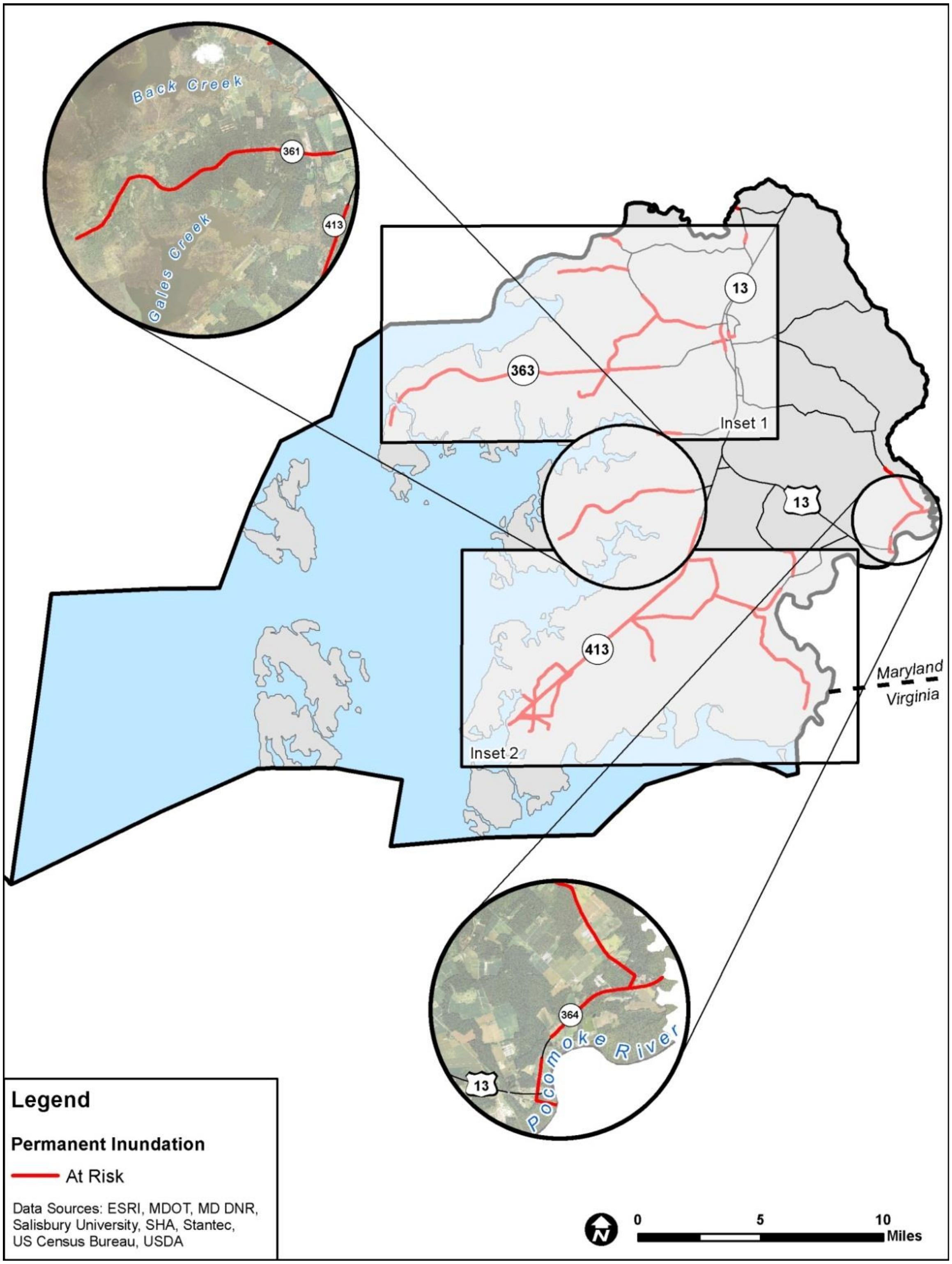


Figure 5-33. 2100 Sea Level Rise Results for Roadways within Somerset County

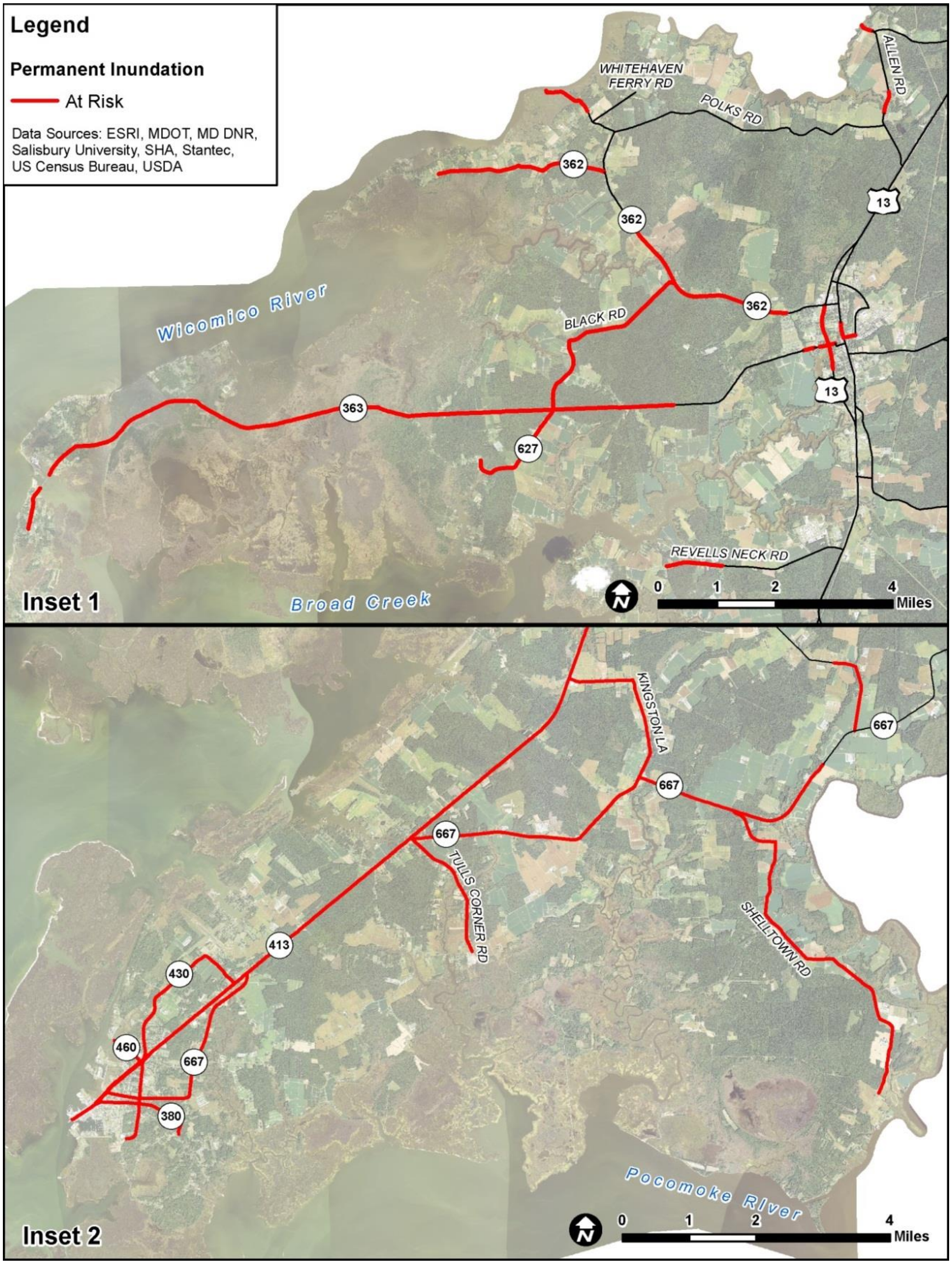


Figure 5-34. 2100 Sea Level Rise Results Inset #1 and Inset #2 Map

Table 5-14. 2050 Sea Level Rise Most Impacted Roadways

Route Number	Mileage of Roadway Permanent Inundation	Evacuation Route
MD460	0.25	No
MD627	0.05	No

Table 5-15. 2100 Sea Level Rise Most Impacted Roadways

Route Number	Mileage of Roadway Permanent Inundation	Evacuation Route
MD363	7.22	No
MD413	3.63	No
MD667	3.60	No
MD358	1.14	No
MD627	0.93	No
MD380	1.12	No
MD361	0.54	No
MD460	0.51	No
MD362	0.17	No
US13	0.16	Yes
MD675	0.12	No
MD918	0.03	No

As with Anne Arundel County, the road segments with a functional classification of 1-6 were categorized into Critical, High, Moderate or Low risk for the 2050 and 2100 timeframes. These categories are based on the risk value and are in reference to the modeled flooding risk associated with sea level rise and storm surge (100-year storm event), as well as the functional classification and evacuation route designation for each roadway. Logically the roadways most vulnerable to storm surge are the coastal areas. Inland sections of roads identified to be at risk are typically located within close proximity to a river or river crossing.

Figure 5-35 shows the HVI results for 2050 that indicates the most critical risk roadways are located in the coast areas. Similarly by 2100 (Figure 5-37) coastal roadways remain the most critically at risk; although to a more significant extent. The inset maps for both 2050 (**Error! Reference source not found.**) and 2100 (Figure 5-38). further exhibit which roadways are vulnerable. A significant portion of coastal roads within Somerset County are considered to be in the Critical, High or Moderate risk categories by 2050. Somerset County's flatter topography lends itself to further inland inundation to roadways than the other Pilot Study county of Anne Arundel.

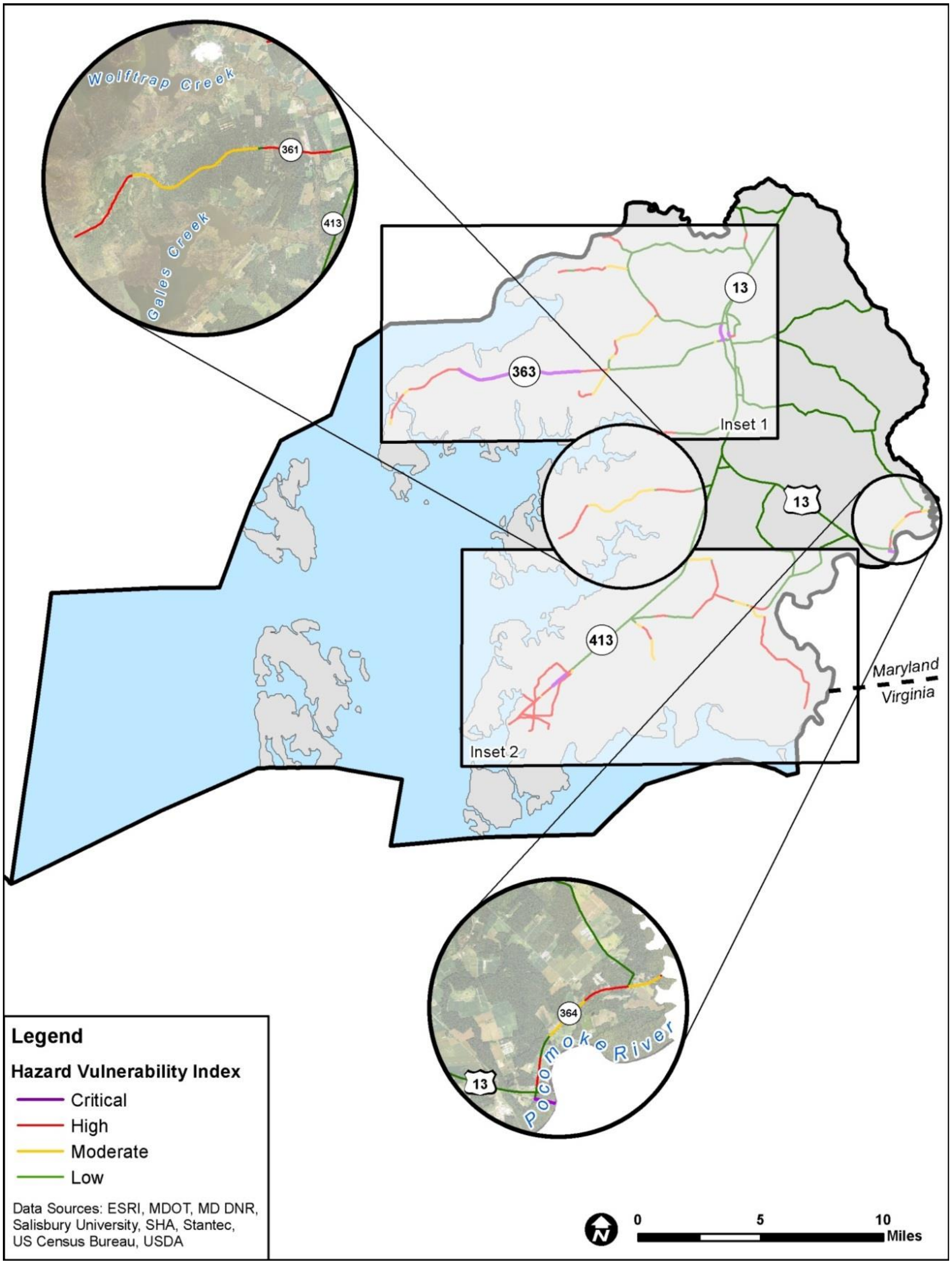


Figure 5-35. 2050 HVI Storm Surge Results for Roadways within Somerset County

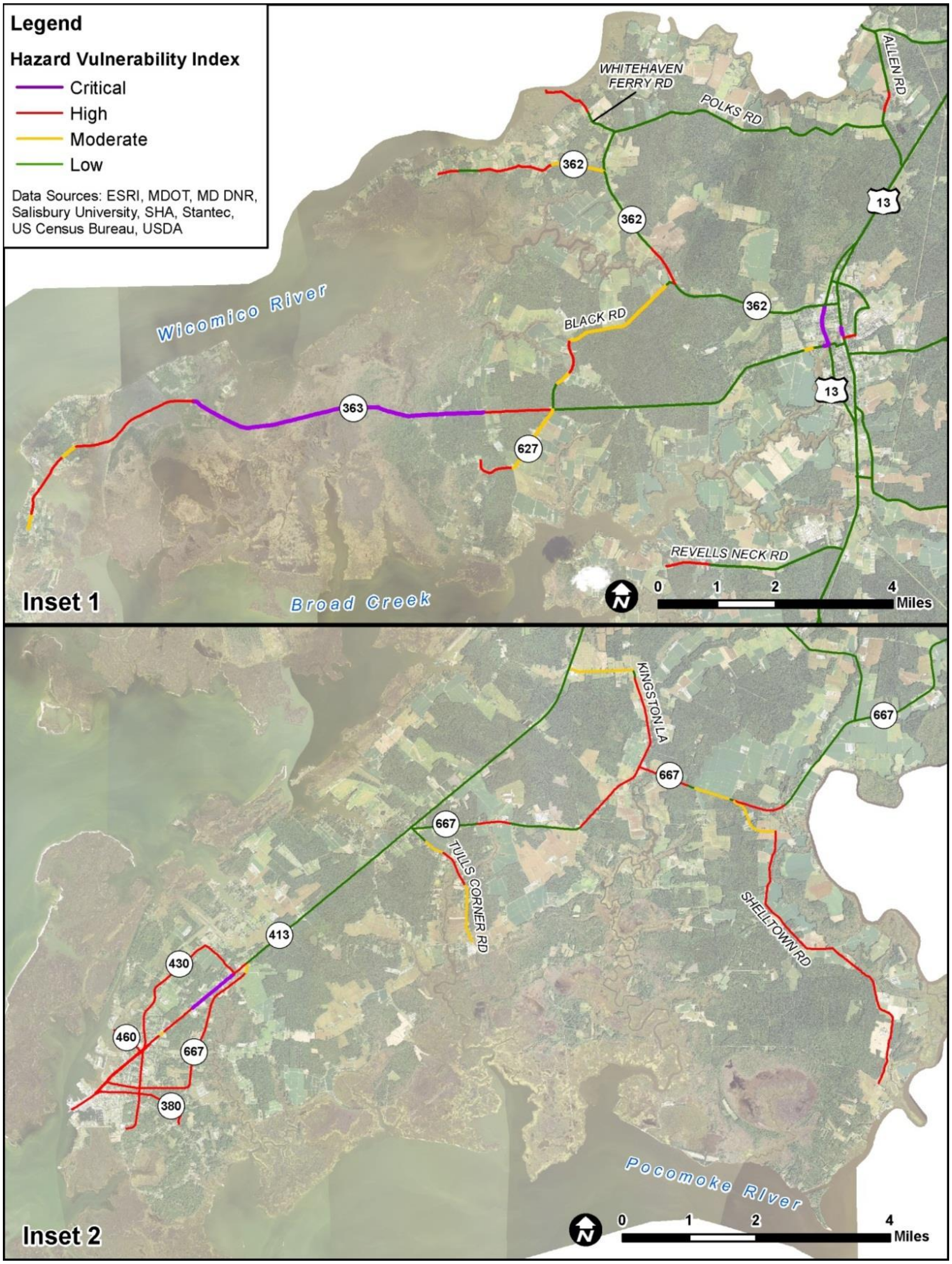


Figure 5-36. 2050 HVI Storm Surge Results Inset #1 and #2 Map

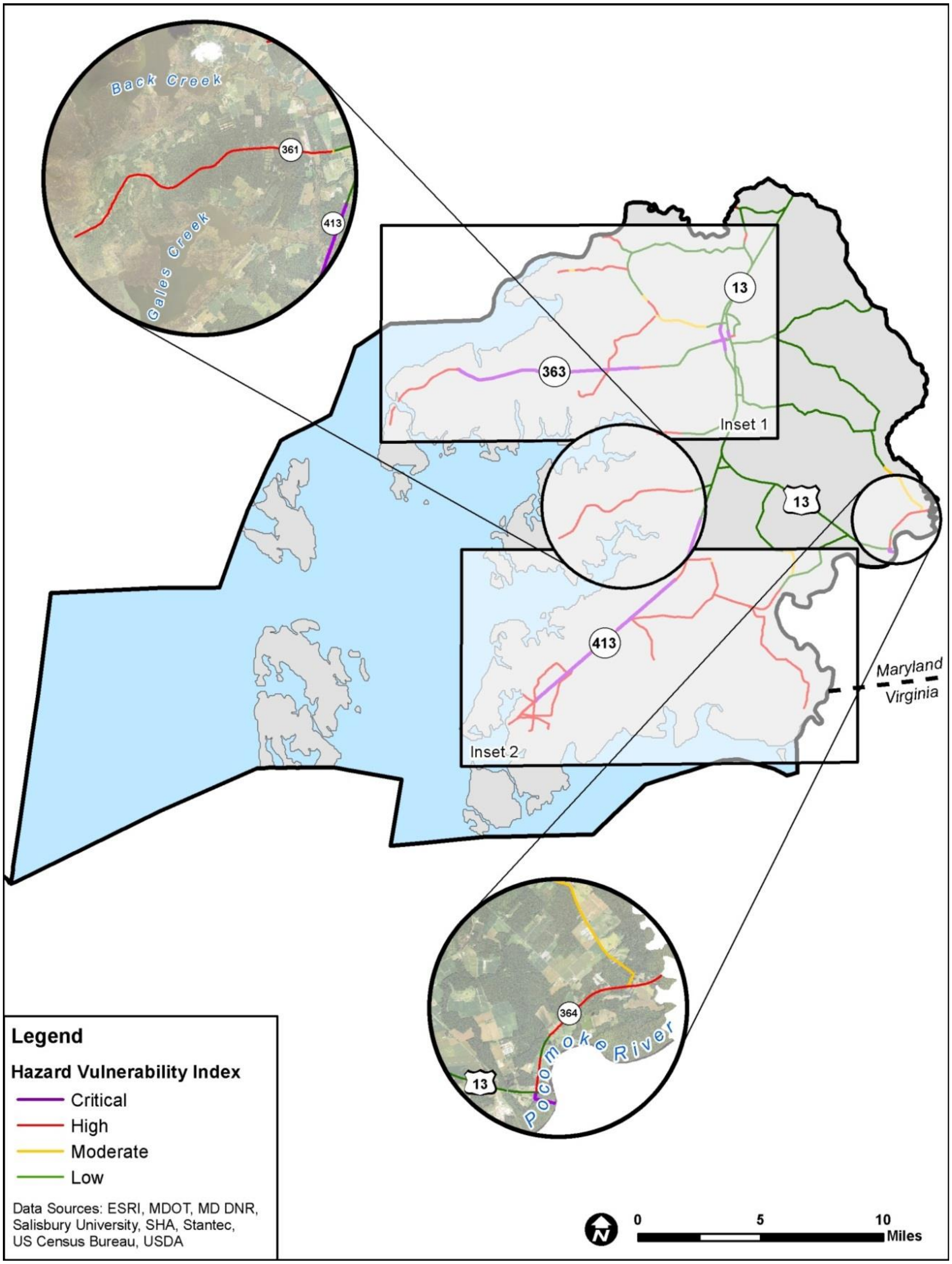


Figure 5-37. 2100 HVI Storm Surge Results for Roadways within Somerset County

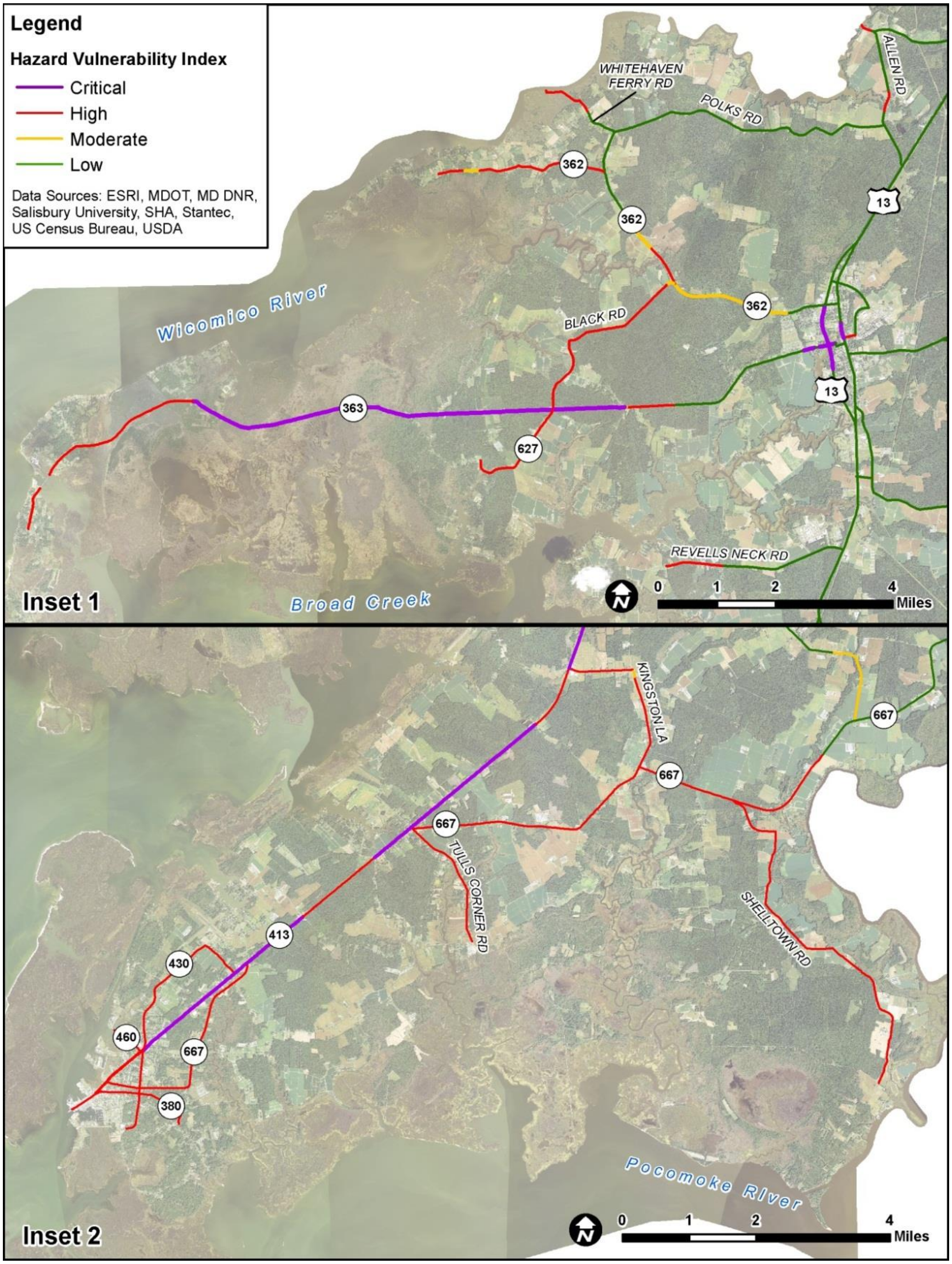


Figure 5-38. 2100 HVI Storm Surge Results Inset #1 and #2 Map

To highlight the Somerset County roadways most at risk and to allow for a similar comparison with the VAST bridge analysis output the top roadways at risk in 2050 and 2010 are presented in Table 5-16 and Table 5-17. At risk roadways are listed according to the most mileage within the Critical, then High risk categories. MD 363 includes the greatest amount of Critical risk roadway of 4.93 miles by 2050 with 2.81 and 1.13 miles at High and Moderate risk, respectively. US 13 has 0.40 miles of roadway at Critical risk of being impacted by storm surge by 2050, 0.04 miles of High risk and 0.03 miles of Moderate risk. The segment of US 13 at critical risk is at the point in which the road intersects with MD363. This roadway is a functional class 5 and is identified as an evacuation route, thus increasing the importance of this roadway. In 2100, MD 363 remains as the roadway with the most mileage in the Critical risk category. In addition to MD 363, 0.08 miles of MD 413 fall within the Critical category. This roadway runs from a dead end at Crisfield's city dock, which is located on the Tangier Sound, northeast to US 13 in Westover. It is the main highway leading into Crisfield, and is known as Crisfield Highway for much of its length. MD 413 is a functional class 5 and is not identified as an evacuation route.

Table 5-16. HVI 2050 Storm Surge Most Impacted Roadways

Route Number	Mileage of Roadway			Evacuation Route
	Critical	High	Moderate	
US13	0.40	0.04	0.03	Yes
MD675	0.10	0.03	0.02	No
MD413	0.08	3.48	0.79	No
MD667	--	3.55	0.33	No
MD358	--	0.85	0.28	No
MD380	-	0.73	-	No
MD627	-	0.63	0.61	No
MD361	-	0.48	1.73	No
MD460	-	0.51	0.01	No
MD362	-	0.26	0.14	No
MD364	-	-	0.20	No
MD918	-	-	0.01	No

Table 5-17. HVI 2100 Storm Surge Most Impacted Roadways

Route Number	Critical	Mileage of Roadway High	Moderate	Evacuation Route
MD363	7.75	4.20	0.34	No
MD413	2.67	4.70	1.93	No
US13	0.69	0.01	<0.01	Yes
MD675	0.18	0.02	0.01	No
MD667	-	8.44	0.41	No
MD361	-	4.68	0.12	No
MD362	-	0.63	0.23	No
MD627	-	1.93	-	No
MD358	-	1.13	-	No
MD364	-	1.04	0.53	No
MD380	-	0.73	-	No
MD460	-	0.53	-	No
MD918	-	0.08	-	No

5.2.4 Somerset Results of VAST

As explained in detail in Chapter 2 and in the VAST results for Anne Arundel County in section 5.1.4, VAST was used to identify the most vulnerable structures to the three identified climate stressors; sea level rise, precipitation changes and storm surge. Assets that were located within the Climate Change Impact Zone for Somerset County were inserted into VAST and given a unique ID that carried on with the structure throughout the assessment. A total of 72 structures were identified as being within the Climate Change Impact Zone, and a simple convention of “1” through “72” was used to identify those structures. These asset IDs were used to create the final vulnerability tables as well as the vulnerable structures map. A list of the bridges included in the VAST database and their location within Somerset County has been included in Appendix D to assist with any future analysis. The VAST vulnerability scoring was calculated by adding the final vulnerability scores of the three vulnerability components; exposure, sensitivity and adaptive capacity. These components were combined for each climate stressor and weighted to come up with the overall vulnerability of each structure. The list of VAST indicators used to describe each of the three vulnerability components for Somerset County were identical to those used in Anne Arundel County.

Somerset County structures vulnerable to the impacts of the three identified climate stressors for the years 2050 and 2100 can be found in Table 5-18 through Table below. Assests with the highest scores identified in the table were mapped in Figure 5-39 though Figure 5-43 show the exact location of those vulnerable assets. Roadways that have a function class of 7 are local roads that are not managed by SHA. Despite being part of the initial assessment for Somerset County, structures on roads that were a category 7 function class (i.e local) were removed from the final VAST results, and all roads that were incorporated in the final results table and maps were function class 1-6.

5.2.5 Final VAST Results

Vulnerable structures were listed based on the highest score of the three combined vulnerability indicators. Data on structures that have experienced damage during historical flood events were collected through a survey that was sent to operations and maintenance staff with local knowledge of structures in Somerset County. Input from maintenance staff were received and incorporated in the analysis which led to a more detailed vulnerability results that accounts to the structures history of flooding.

As explained in Chapter 2, no modeling was performed to identify assets that will be impacted by the increased precipitation in 2050 and 2100 for Somerset County, and therefore the 2050 and 2100 exposure data were identical. Location in the 100-year floodplain and the asset clearance were the defining factors for any structure's exposure to increased precipitation, and those values were very similar for many structures in Somerset County. As a result, the exposure scores were very similar in many of the assessed structures, which explain the low variation in the overall precipitation vulnerability scores among structures. However, data on historical flooding from precipitation in Somerset County helped refine the final VAST scores for vulnerability to precipitation. Because the vulnerability score was high for many structures, the most vulnerable structures were mapped and are presented on Figure 5-39, which shows that the vulnerable structures are located within the MD 363 corridor as well Princess Anne and Pocomoke City, along Pocomoke River.

The 20 structures with the highest scores in terms of the overall vulnerability to sea level rise and storm surge in 2050 and 2100 were identified and mapped in Figure 5-40 through Figure 5-43. Some of the most vulnerable lists included more than 20 structures and that was because of more than one structure shared the same score as the 20th place on the list.

Vulnerability scores for sea level rise ranged from a score as low as low as 1.3 and as high as 3.4. The vulnerability threshold was set at 2.0, which is an indicator of a medium vulnerability; therefore all structures that scored above the 2.0 vulnerability threshold were considered vulnerable structures. Figure 5-40 and Figure 5-41 show the locations within Somerset County of the most vulnerable structures to sea level rise in 2050 and 2100. The maps show that vulnerable structures appear in clusters in certain corridors especially along MD 363 all the way to Princess Anne. Another cluster of vulnerable structures appears near Pocomoke City, along Pocomoke River on the Somerset/ Worchester County lines. The clusters of vulnerable structures are more evident in Somerset County compared to Anne Arundel County because of its low lying topography which translated into a significantly higher number of structures that will be inundated by sea level rise in 2050 and 2100.

Storm surge was a serious concern in Somerset County, and modeling output demonstrated that many structures will be inundated by as much as 4 feet in both 2050 and 2100. Inundation depths of structures in Somerset were translated into a vulnerability score that corresponded with the projected inundation. Vulnerability scores for storm surge in Somerset County ranged from scores as low as 1.2 to as high as 3.2, with structures that scored 1.2 being the most resilient and structures that scored 3.2 being the most vulnerable. Figure 5-42 and Figure 5-43 depict the most vulnerable structures in Somerset County in relation to vulnerability to storm surge. The maps demonstrate that the most vulnerable structures appear in clusters along certain corridors especially along MD 363 and MD 362. Another cluster of vulnerable structures appears in Princess Anne and near Pocomoke City, along the Pocomoke River on the Somerset/ Worchester County lines. As is the case for sea level rise, the clusters of structures vulnerable to storm surge are more evident in Somerset County compared to Anne Arundel County because of its low lying topography.

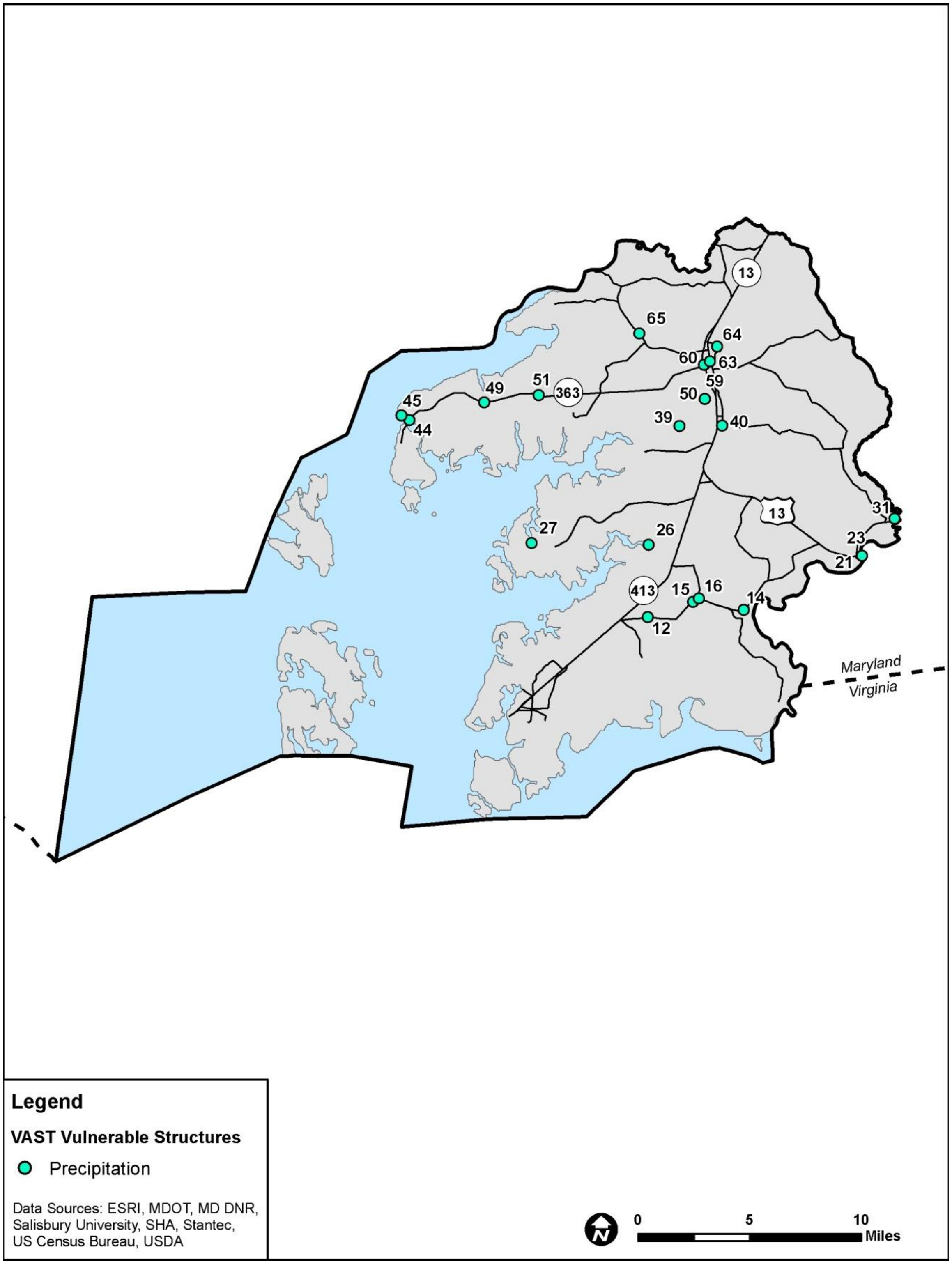


Figure 5-39. VAST 2050 and 2100 Somerset Structures Most Vulnerable to Precipitation

Table 5-18. VAST 2050 and 2100 Somerset Structures Most Vulnerable to Precipitation

Vulnerability to Precipitation		
Structures ID	**VAST Score**	**Evacuation Route**
31	3.1	No
23	2.9	Yes
44	2.9	No
21	2.9	Yes
63	2.8	No
59	2.7	Yes
60	2.7	Yes
65	2.6	No
12	2.6	No
14	2.6	No
15	2.6	No
16	2.6	No
40	2.5	No
49	2.5	No
51	2.5	No
27	2.4	No
45	2.4	No
64	2.4	No
39	2.4	No
26	2.3	No
50	2.3	No

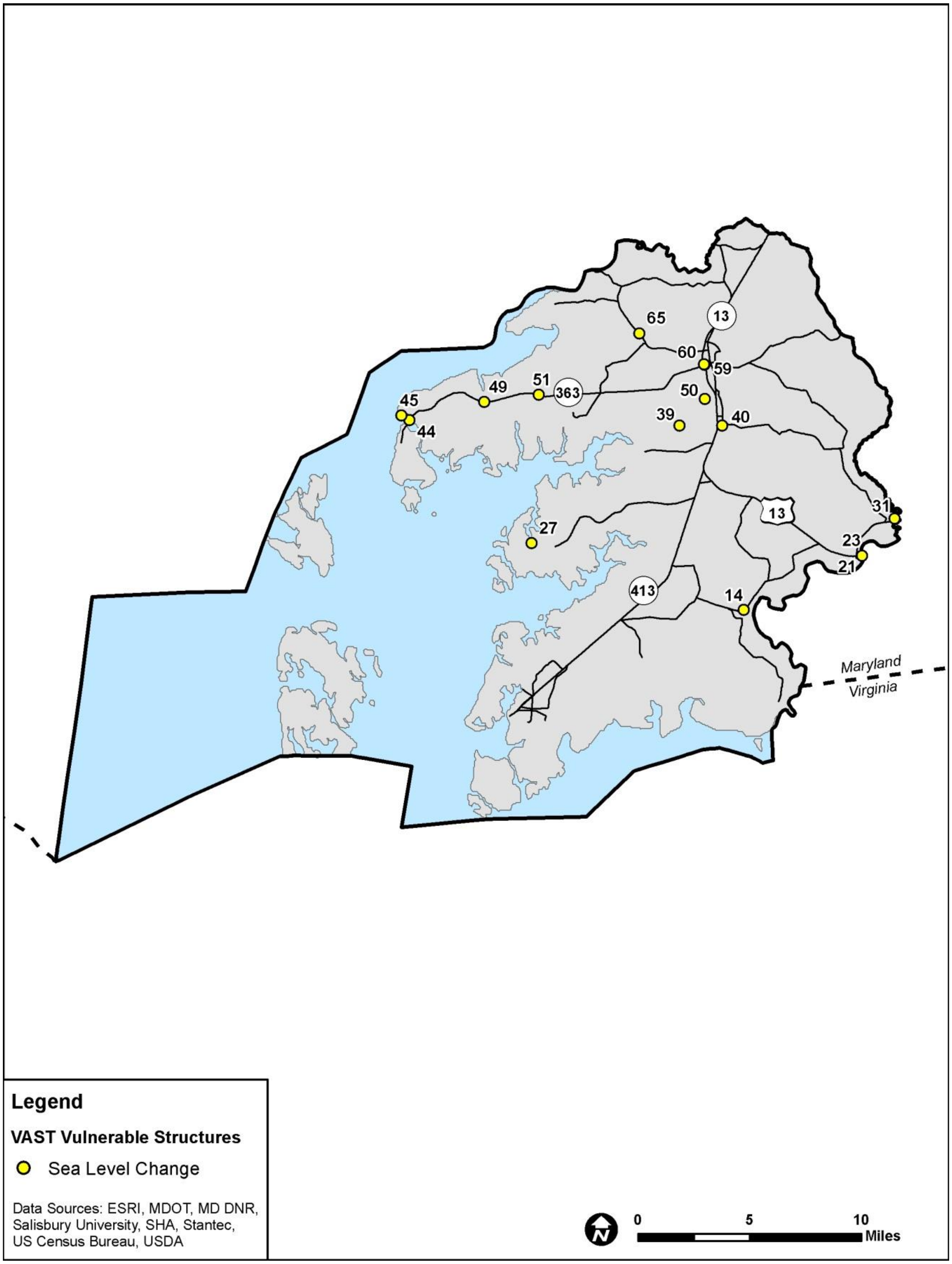


Figure 5-40. VAST 2050 Somerset Structures Most Vulnerable to Sea Level Rise

Table 5-19. VAST 2050 Somerset Structures Most Vulnerable to Sea Level Rise

Vulnerability to 2050 Sea Level Rise		
Structure ID	**VAST Score**	**Evacuation Route**
23	3.0	Yes
21	3.0	Yes
49	2.6	No
40	2.5	No
59	2.4	Yes
60	2.4	Yes
27	2.3	No
50	2.3	No
14	2.3	No
45	2.3	No
65	2.3	No
31	2.3	No
51	2.1	No
39	2.0	No
44	2.0	No

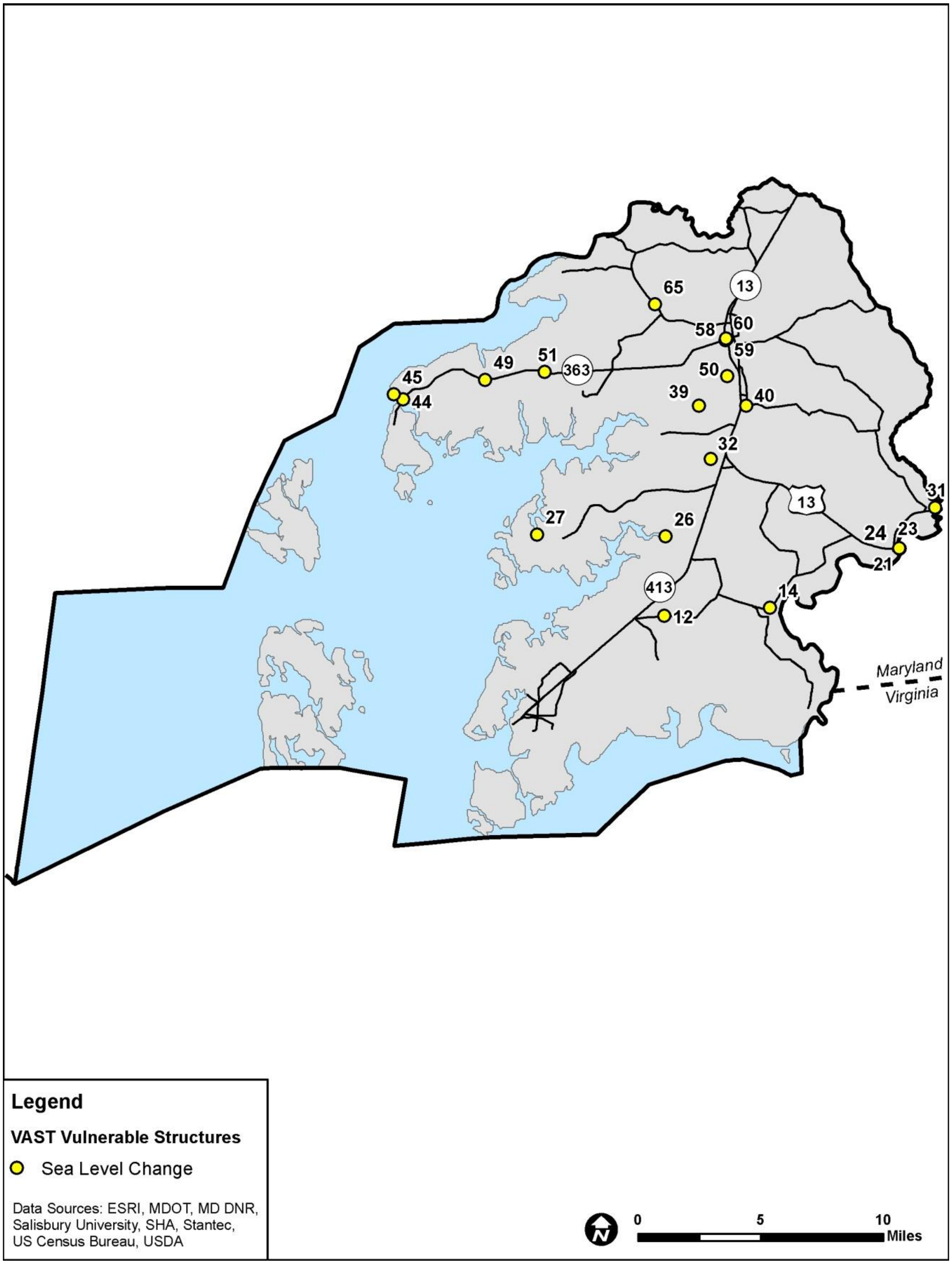


Figure 5-41. VAST 2100 Somerset Structures Most Vulnerable to Sea Level Rise

Table 5-20. VAST 2100 Somerset Structures Most Vulnerable to Sea Level Rise

Vulnerability to 2100 Sea Level Rise		
Structure ID	VAST Score	Evacuation Route
23	3.4	Yes
21	3.3	Yes
59	3.2	Yes
45	3.0	No
65	3.0	No
49	2.9	No
40	2.9	No
60	2.8	Yes
39	2.8	No
27	2.7	No
50	2.7	No
14	2.7	No
51	2.5	No
32	2.5	No
58	2.4	No
44	2.4	No
12	2.3	No
31	2.3	No
26	2.2	No

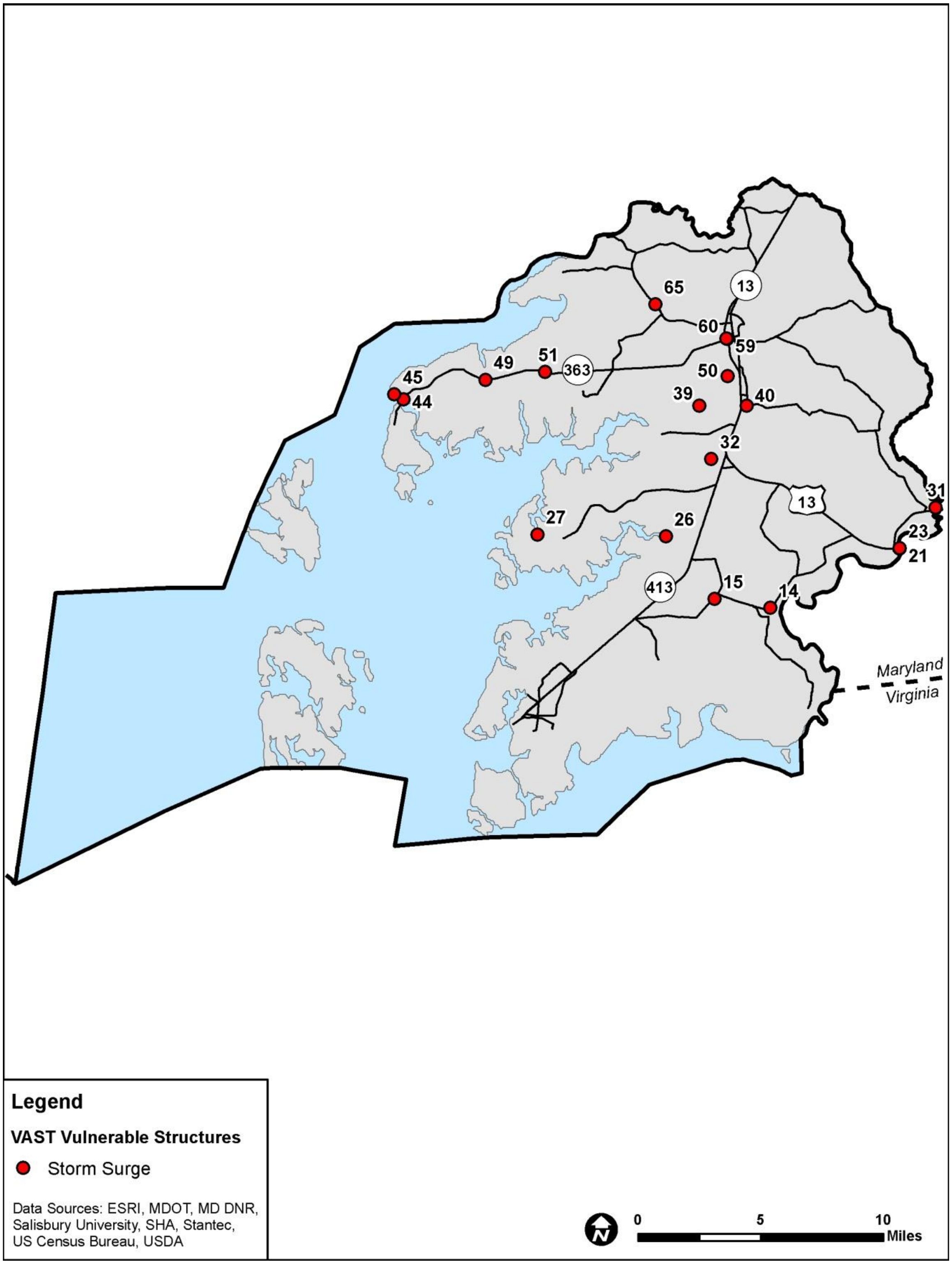


Figure 5-42. VAST 2050 Somerset Structures Most Vulnerable to Storm Surge

Table 5-21. VAST 2050 Somerset Structures Most Vulnerable to Storm Surge

Vulnerability to 2050 Storm Surge		
Structure ID	VAST Score	Evacuation Route
23	3.2	Yes
21	3.2	Yes
49	3.1	No
65	3.0	No
59	2.9	Yes
31	2.9	No
51	2.8	No
44	2.8	No
14	2.7	No
27	2.7	No
45	2.7	No
15	2.6	No
50	2.6	No
60	2.5	Yes
39	2.3	No
40	2.2	No
26	2.2	No
32	2.0	No

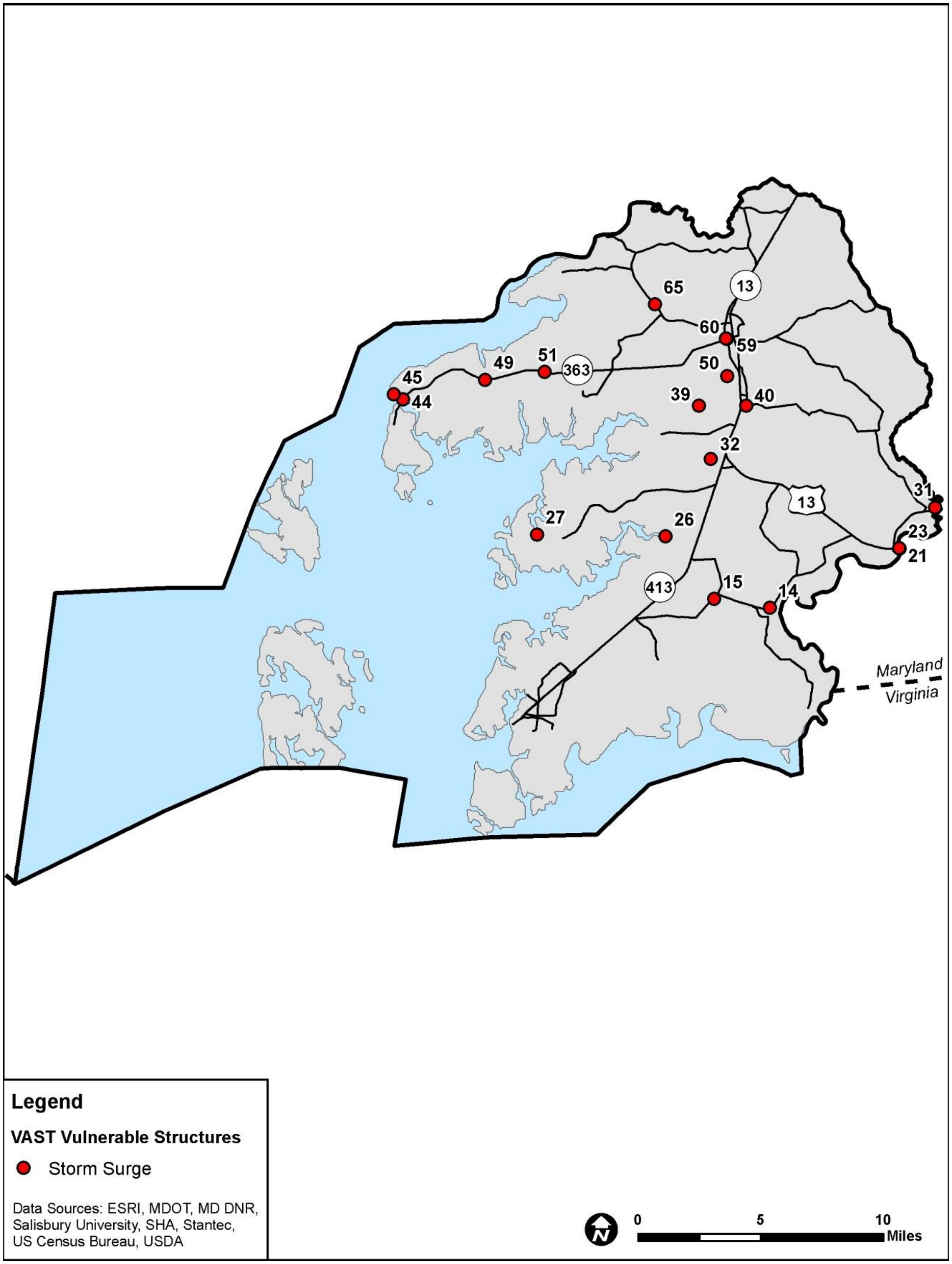


Figure 5-43. VAST 2100 Somerset Structures Most Vulnerable to Storm Surge

Table 5-22. VAST 2100 Somerset Structures Most Vulnerable to Storm Surge

Vulnerability to 2100 Storm Surge		
Structure ID	**VAST Score**	**Evacuation Route**
23	3.2	Yes
21	3.2	Yes
49	3.1	No
65	3.0	No
59	2.9	Yes
31	2.9	No
51	2.8	No
44	2.8	No
14	2.7	No
27	2.7	No
45	2.7	No
15	2.6	No
50	2.6	No
60	2.5	Yes
39	2.3	No
40	2.3	No
26	2.2	No
32	2.0	No

5.2.6 Small Drainage Feature Analysis Results

SHA has numerous small drainage features that could have vulnerabilities due to climate change. These include:

- Small Culverts (less than 36")
- Storm Drains
- Swales and Ditches
- Curbs and Gutters
- SWM ESD BMPs
- Structural SWM BMPs

The assets (small culverts, storm drains, swales and ditches, curbs and gutters, SWM ESD BMPs and Conventional SWM BMPs) that fall within the Climate Impact Zone might experience impacts due to sea level change, storm surge or increased precipitation. Assets that experience impacts directly related to sea level change and storm surge will generally be incorporated into the corresponding segment of impacted roadway. There may also be small drainage assets that are located just outside of the sea level change or storm surge areas that are impacted by a combination of increased tailwater (due to sea level change and storm surge) and increased precipitation, as well as numerous small drainage assets located further from the coast that may only be impacted by increased precipitation.

Identifying vulnerable individual small drainage features required collection and processing a large set of data, which requires time and resources beyond the scope of the Pilot Study. For example depending on hydrologic and hydraulic capabilities a 15-inch culvert with minimal cover may be oversized, and a 36-inch culvert with significant cover might be undersized, so culvert size and roadway height are not necessarily good indicators. Also note that an asset may be sized adequately, however there may be other circumstances that create drainage problems (i.e. clogging due to debris or sedimentation). A small drainage assets is generally designed to convey a given storm event with a required amount of freeboard. If a 30-inch culvert is determined to be too small, then a 36-inch culvert will be utilized. However at a ponding depth of 5 feet, the 36-inch culvert might have as much as 40% more capacity than the 30-inch culvert. This leads to many small drainage assets being slightly overdesigned. These assets are not as likely to be impacted by climate change since they already have extra carrying capacity available. Understanding an asset's vulnerability requires a detailed hydraulic and hydrology analysis and/or real-time data information about events or damages that were handled by maintenance. As discussed earlier, these assets are likely to experience impacts due to sea level rise, storm surge, or increased precipitation. Assets that experience impacts directly related to sea level rise and storm surge will generally be incorporated into the corresponding segment of impacted roadway. There may also be small drainage assets that are located just outside of the sea level rise or storm surge areas that are impacted by a combination of increased tailwater (due to sea level rise and storm surge) and increased precipitation. Other small drainage assets, which are further from the coast, will only be impacted by increased precipitation.

5.3 Vulnerable Areas at Risk

Due to the interrelationship of the bridges, roads and culverts the three assets were evaluated together to identify the geographic areas with the highest level of vulnerability. These geographic areas are identified as Vulnerable Areas at Risk. The maps below depict the Vulnerable Areas at Risk using the Flood Inundation Modeling, HVI and VAST data for 2050. The most vulnerable structures from VAST scores as identified in Table 5-8 through Table 5-12 (for Anne Arundel County) and Table 5-18 through Table (for Somerset County) were plotted on the maps below. Roadways with the greatest mileage values for permanent inundation according to Flood Inundation Modeling and roadways with Critical or High risk road segments as derived from the HVI assessment were included on the maps. The Vulnerable Areas at Risk were then grouped based on a watershed approach and the location of the identified, at risk assets. The 2050 vulnerability results were utilized due to their more critical, timely considerations. Using best scientific judgment assets only identified to be at risk in 2100 were included on the 2050 vulnerable areas map when they supported the overall watershed approach. Pictures of vulnerable structures within Vulnerable Areas of Risk and included in the Maryland Department of the Environment survey data are provided for visual context.

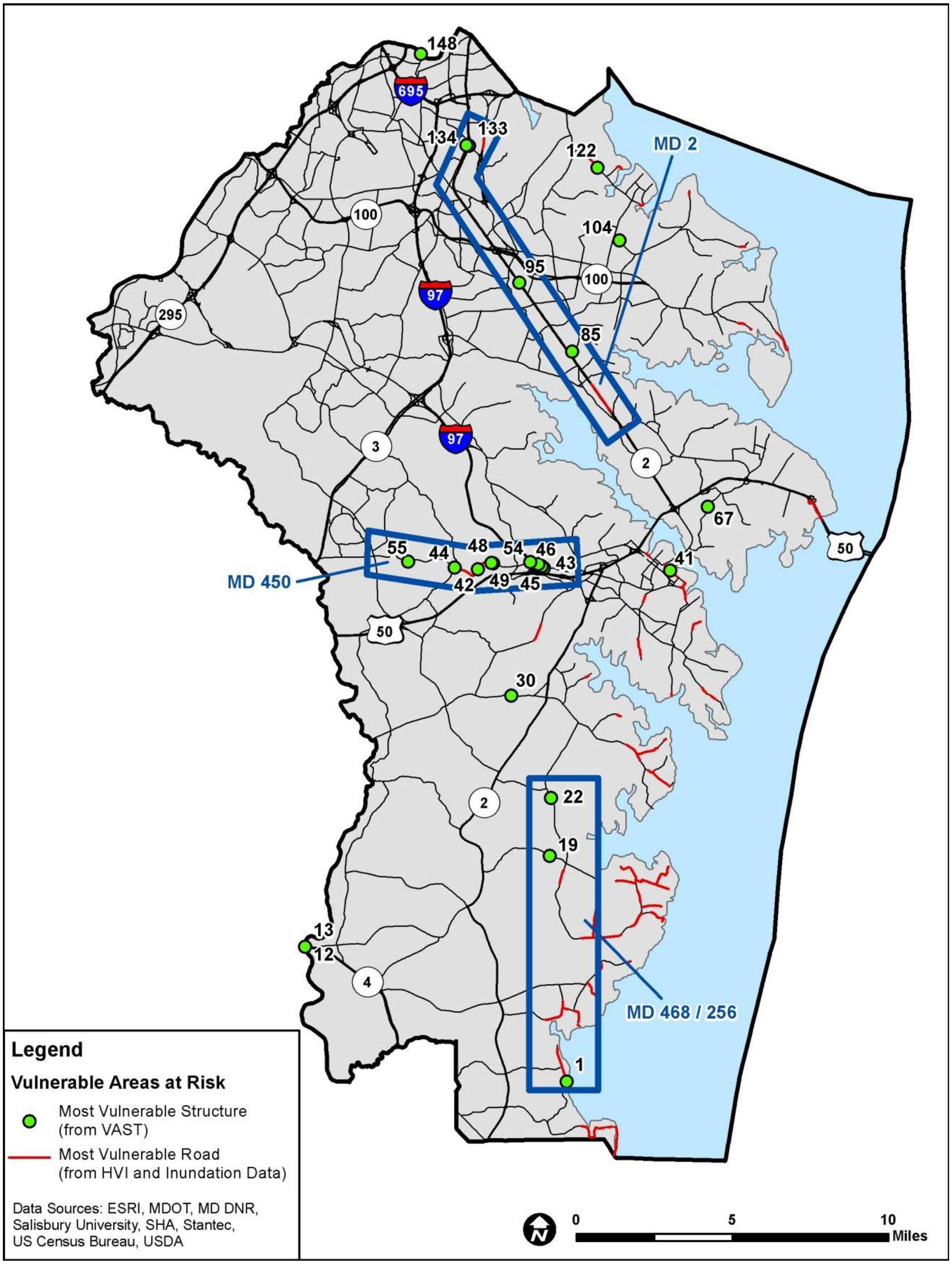


Figure 5-44.Vulnerable Areas at Risk in Anne Arundel County

Anne Arundel County

Maryland Route 2

The area encompassing MD 2, also known as Governor Richie Highway, was identified as a vulnerable area at risk due to the number of vulnerable structures identified along the route and a section of the roadway identified as Critical (0.02 miles in 2050 and 0.37 in 2100). The identified section MD 2 runs north south from Arnold through Severna Park. The bridges affected along this roadway include Structure 82, 95, 105 and 134. Structure 84 is vulnerable to precipitation changes and has a VAST score of 2.4. Structure 95 is vulnerable to precipitation changes (VAST score 2.6). Structure 105 is vulnerable to storm surge and has a VAST score of 2.0 in 2050 and in 2100. Structure 134 is vulnerable to sea level change and storm surge. The structure's year 2050 and 2100 VAST score for sea level rise is 2.4 and is 2.9 for storm surge.

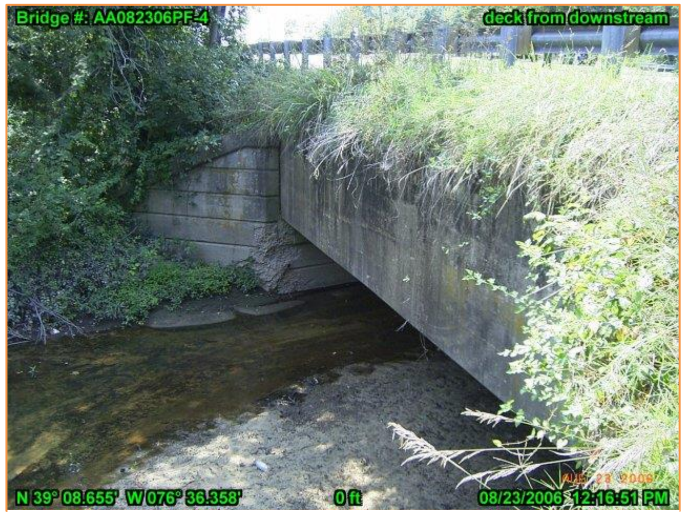


Figure 5-45. Structure 95 is Vulnerable to Precipitation Changes (VAST 2.6)
Photo Source: (Maryland Environmental Services 2006)

MD 450

MD 450 is an east west directional road in Anne Arundel County. The identified stretch of MD 450 and surrounding area has been selected due to the amount of structures identified along the route and the section of vulnerable roadway. MD 450 is not expected to be permanently inundated in 2050 but 0.11 miles of roadway is modeled to be permanently inundated due to sea level rise by 2100. The HVI results for MD 450 show 0.14 miles as Critical for storm surge impacts and 0.37 miles as High in 2050. By 2100 the numbers increase to 0.19 miles of Critical and 0.61 miles of High. Structures 43, 45, 46, 49, 44, 48, 57 and 55 all occur along MD 450. All of the structures except for Structure 49 are

Figure 5-46. Structure 45 Deck from Downstream, Source: (Maryland Environmental Services 2006)

considered vulnerable to precipitation changes. Their vulnerability scores range from 2.4 to 2.5. Structure 49 and 45 are vulnerable to sea level change with a VAST score of 2.0 and 2.3 respectively in 2050. Lastly Structures 45 and 49 are also determined to be vulnerable to storm surge by 2050.

MD 468/256

Figure 5-47. Structure 17
Photo Source: (Maryland Environmental Services 2006)

MD 468/256 has been identified as a vulnerable area at risk due to the amount of vulnerable roadway and structures. MD 468 is the main road accessing Shady Side and MD 256 is connected to MD 468 and runs north south near Churchton. Neither MD 468 nor MD 256 is expected to be permanently inundated by 2050; however, by 2100, 0.16 miles of MD 468 are expected to be permanently inundated due to sea level rise. By 2050, 0.29 miles of MD 468 are critically at risk to the 100-year storm event according to HVI and 0.49 miles are in the High risk category. MD 256 has 0.14 miles in the Critical risk category and 0.37 miles at High risk by 2050. In 2100, these numbers increase for MD 456 to 2.72 miles of Critical risk roadway and 1.35 miles of High risk roadway. Also for MD 256, 2.22 miles of roadway are modeled as Critical risk and 0.70 miles at High risk. Structures within this vulnerable area include 25, 22, 17, 15, and 4. Structures 25, 22, and 17 are vulnerable to precipitation. Structure 17 is also vulnerable to sea level change by 2100 and Structure 4 is considered vulnerable to storm surge by 2050.

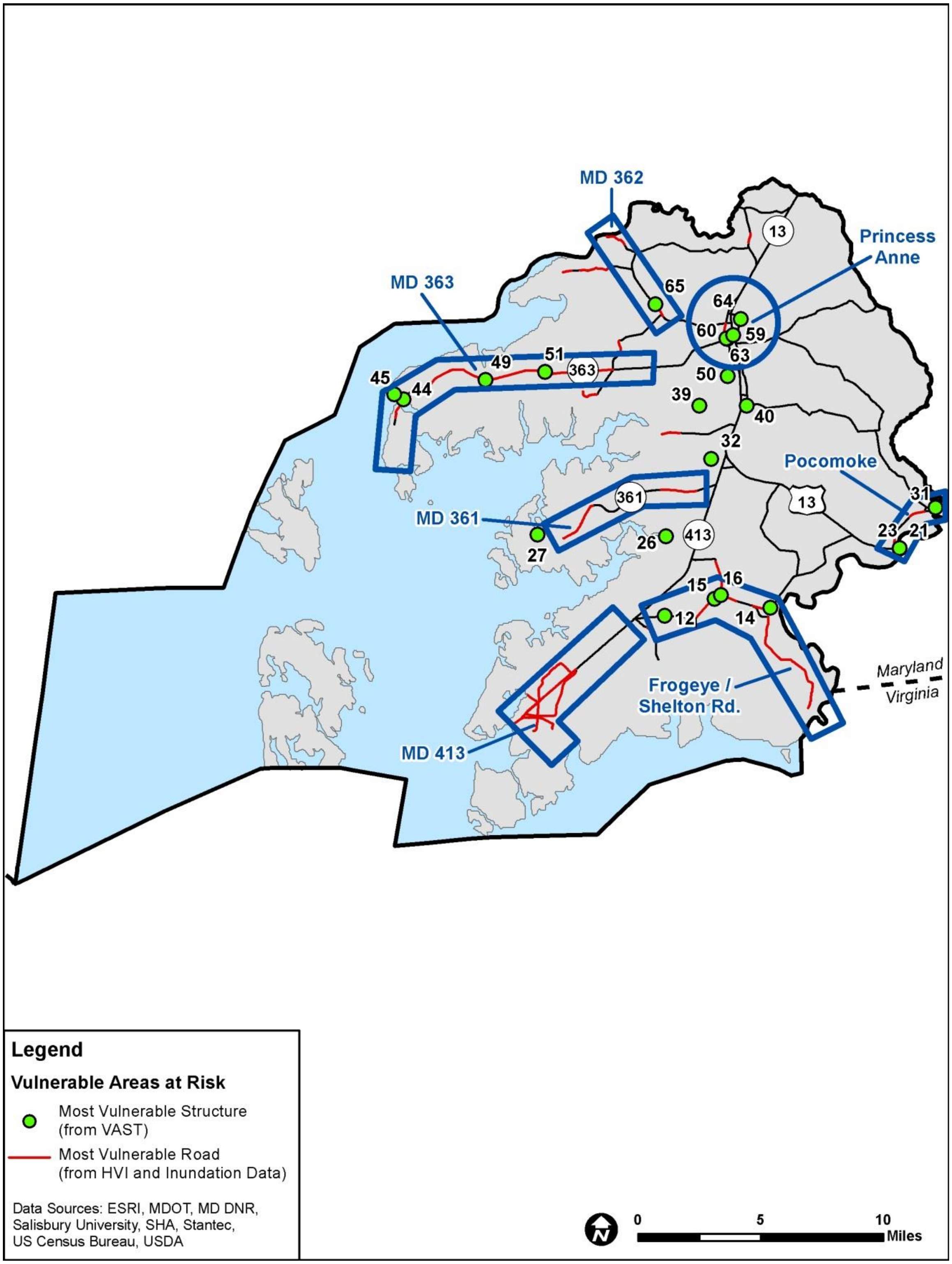


Figure 5-48. Vulnerable Areas at Risk in Somerset County

Somerset County

MD 362

MD 362 was identified as a vulnerable area by 2050 due to the abundance of bridges identified as vulnerable in VAST along the route (65, 66, 67 and 70). Structures 65 and 70 have been identified as vulnerable for precipitation changes with a VAST score of 2.6 and 2.4, respectively. Structures 65, 66, 67 and 70 are all vulnerable to sea level rise by 2050. Lastly Structure 65 is considered vulnerable to precipitation changes, sea level rise and storm surge by 2050. In 2050, a limited section of MD 362 (Whitehaven Ferry Road) located near the northern border of Anne Arundel County is modeled as permanently inundated in 2050; however, by 2100 this increases to 0.19 miles. In 2050, sections of MD 362 are at Moderate to Low risk of being affected by storm surge according to HVI results.

MD 363

MD 363 is also known largely as Deal Island Road and runs from a dead end on Deal Island east to Mansion Avenue in Princess Anne. This roadway was identified as a Vulnerable Area at Risk due to a significant amount of roadway modeled as permanently inundated by 2100 (7.24 miles). In addition, this roadway is critically vulnerable to storm surge in 2050 (4.90 miles) and 2100 (7.72 miles). There are a total of 7 structures (i.e. 37, 43, 44, 48, 49, 51, and 53) identified as vulnerable for at least one of the climate variables. Structure 37 is considered vulnerable to precipitation changes (VAST Score 2.8), 2050 sea level rise (2.3), and 2050 storm surge (3.0). Structure 43 is vulnerable to precipitation changes (VAST score 2.3) and 2050 storm surge (2.3). Structures 44, 48, 49 and 51 are considered vulnerable to precipitation changes, 2050 sea level rise and 2050 storm surge. Lastly, structure 53 is vulnerable to 2050 sea level rise. Structures vulnerable by 2050 are similarly vulnerable by 2100, often to a significantly greater extent.

MD 361

The vulnerable assignment to MD 361 is due to prevalent roadway impacts modeled for 2050 and 2100. MD 361 is also known as Fairmount Road and runs approximately 5.62 miles between Upper Fairmount and MD 413. In 2100, 0.57 miles are modeled to be permanently inundated due to sea level rise. In 2050, 0.51 miles are predicted to be at a High risk of effects from storm surge and 1.80 miles at Moderate risk, both according to the HVI assessment. This vulnerability increases to 3.89 miles of High risk and 0.05 miles at Moderate risk by 2100.

MD 413

MD 413 is a selected Vulnerable Area at Risk due to the extent of vulnerable roadways and Structure 10. This vulnerable area also comprises smaller feeder roadways including MD 430, MD 380, MD 460 and MD 667. By 2050, some of the smaller roadways are modeled to be permanently inundated and by 2100 all the aforementioned roadways in the vulnerable area are expected to be permanently inundated due to sea level rise. By 2050, sections of MD 413, MD 430, MD 380, MD 460 and MD 667 are considered to be at High or Moderate risk to storm surge according to HVI. In 2100, the amount of mileage for all the roadways impacted by storm surge increases.

Frogeye/Shelton Road

Within this Vulnerable Area of Risk, Shelton Road (MD 667) runs parallel to the Pocomoke River and extends through a predominantly agricultural area. By 2100, 3.59 miles of MD 667 are modeled to be permanently inundated due to sea level rise. In 2050, segments of this roadway will be at High (3.52 miles) and Moderate risk of storm surge impacts according to HVI calculations. By 2100, the vulnerability of the roadway increases to 5.66 miles at High risk and 0.25 at Moderate risk. Structures 12, 14, 15, and 16 along this road are also vulnerable with the majority of these structures (*i.e*., Structures 12, 14 and 16) vulnerable to precipitation changes, sea level rise and storm surge.

Pocomoke

Figure 5-49. Structure 31 Facing Downstream
Photo Source: (Maryland Environmental Services 2006)

The area of Pocomoke was identified as a Vulnerable Area at Risk due to the significant amount of vulnerable structures and some roadway impacts. A total of five structures are within the vulnerable area including 21, 23, 24, 30 and 31 and all are vulnerable to precipitation. Structure 24 is vulnerable to 2050 sea level rise (VAST score 2.0) and storm surge (VAST score 2.4). Structure 31 is vulnerable to 2050 sea level rise (2.3) storm surge (2.9) and precipitation. In Pocomoke, MD 364 is vulnerable to 2100 storm surge impacts according to the HVI calculations; however, it is important to note that it is a local road (*i.e*., functional classification 7), which is why the roadway is not called out in Table .

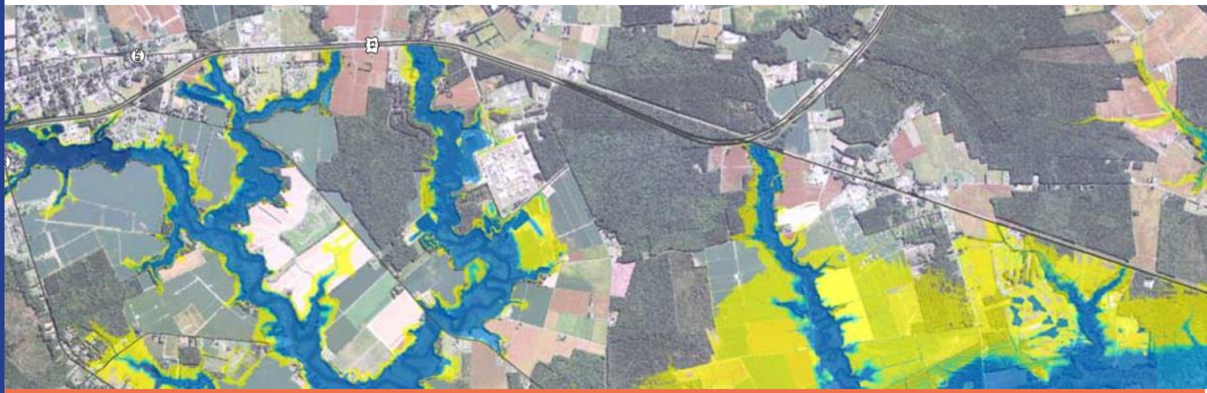
Princess Anne

Figure 5-50. Structure 60
Photo Source: (Maryland Environmental Services 2006)

Princess Anne has been identified as a Vulnerable Area at Risk due to amount of vulnerable structures and roadways. Structures 61, 63, 60, 64, and 59, all with modeled vulnerabilities, are within this area. Structure 61 is vulnerable to precipitation changes (VAST score 2.3). Structures 63, 60, and 59 are vulnerable to precipitation changes, 2050 sea level rise and 2050 storm surge. Structure 64 is vulnerable to precipitation and 2050 sea level rise. US 13 is the main road in Princess Anne and it is modeled as permanently inundated due to sea level rise by 2100 (0.16 miles). In 2050, US 13 is modeled to have segments at risk in the Critical (0.15 miles) and High (0.04 miles) categories based on impacts from storm surge as indicated in the HVI results.

Chapter 6

Key Findings, Lessons Learned, Next Steps, and Conclusion



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6 Key Findings, Lessons Learned, Next Steps, and Conclusion

Figure 6-1 Road Failure Caused by Severe Weather Event in Reisterstown, MD
Photo source: (FEMA/Skoogfors 2006)

According to the best available science, changes to Maryland's climate will result in sea level change, increased precipitation intensity and frequency of significant storm events, and increased storm surge. Maryland's extensive coast line and low lying topography make the state one of the most vulnerable in the United States to sea level change (Johnson, Z P 2013). As a result, SHA's transportation infrastructure is projected to be substantially impacted by climate change, leading to challenges in maintaining the current transportation network. This Pilot Study focuses on those climate stressors and asset vulnerabilities that are considered to cause the greatest magnitude of risk to Maryland's transportation system. Other climate stressors such as increased temperatures could also have an impact on certain aspects of the highway network (*i.e.*, pavement), but were not considered due to an emphasis within the Pilot Study on water-related climate change impacts. As a steward of the Maryland transportation system, SHA faces the task of adequately managing the risks associated with impacts caused by climate change and making the transportation system more resilient to such challenges, including sea level change and extreme weather events. Building on the *SHA/MDTA Adaptation Strategy* (2013), the Pilot Study will establish a detailed framework to assess asset vulnerability and apply adaptation strategies moving into the future. The Pilot Study evaluated two pilot counties, developing a framework and corresponding methodologies used to assess these counties that will be refined for future assessments of Maryland's transportation assets. The key findings, lessons learned, and next steps/recommendations are presented in this chapter.

6.1 Summary of Key Findings

6.1.1 Maryland Key Climate Variables

Different climate stressors were assessed based on current scientific publications and literature from transportation management agencies in the U.S. and internationally. Climate variables deemed to pose the highest potential risk to transportation assets in Maryland (sea level change, storm surge and precipitation) were considered for evaluation in this report. Methods, described in chapter 2, were utilized to obtain localized data for each of the pilot counties. The corresponding sea level change values, changes in precipitation patterns and change in storm intensity and frequency information related to the pilot Counties are presented in detail in Chapter 3.

6.1.2 Vulnerabilities to Climate Change

Each of the three climate stressors were evaluated for the impacts to Maryland's highway transportation assets. One of the first steps was to create a general table of impacts from a literature review and field operational experience with past weather events in Maryland. Three primary asset categories were evaluated: bridges (including small structures), roadways, and small culverts/drainage conveyances. General vulnerabilities to each asset were identified based on existing literature and assembled professional experience of transportation engineers and planners. Table gives an overview of the types of vulnerabilities that could be caused by exposure to climate stressors identified for Maryland and corresponding potential impacts to transportation infrastructure.

Table 6-1. Types of Impacts to SHA's Transportation Infrastructure from Maryland Specific Climate Stressors

Climate Stressor	Potential Impacts to Transportation Infrastructure
Sea level change	▪ Inundation of roadway and bridge causing loss of roadway operations ▪ Exacerbated flooding from storm surges ▪ Reduced emergency response capabilities ▪ Increased salinity impacts including corrosion
Increase in precipitation amount and intensity	▪ Increased flooding resulted from extreme precipitation events ▪ Erosion causing stream bank and roadway embankment failures ▪ Ground destabilization affected by fluctuating groundwater levels ▪ Increased scour at bridges and culverts ▪ Increased drainage pipe and outfall failures
Increased hurricane intensity/storm surge	▪ Wave action causing damage to infrastructure ▪ Loss of shoreline habitats serving as a natural protection of infrastructure ▪ Flooding and increased inundation ▪ Accelerated shoreline erosion

6.1.3 Characterization of Vulnerabilities and General Adaptation Measures

A key step in the Pilot Study was to conduct a general assessment of the vulnerabilities and failures for each type of asset and to identify possible adaptation measures to address these vulnerabilities. Examples of general vulnerabilities and corresponding adaptation options are provided in Table with a more comprehensive list provided in Appendix A.

Table 6-2. Examples of General Transportation Asset Vulnerabilities and Adaptation Response Options

Asset Type	Examples of Vulnerability to Climate Change	Examples of General Adaptive Measures
Bridge	▪ Scour of abutments and foundations ▪ Corrosion caused by saltwater intrusion ▪ Superstructures buoyancy causing structure to float away	▪ Scour protection ▪ Raise components of bridge susceptible to corrosion or apply coatings ▪ Anchor or raise bridge
Roadway	▪ Pavement impacts due to inundation ▪ Impacts to subbase caused by rise in water table ▪ Erosion of roadway embankments and support structures ▪ Loss of vegetation that stabilize embankments	▪ Evaluate pavement designs to be more resilient to water ▪ Change subbase composition in new designs ▪ Additional erosion control and slope stabilization features in design ▪ Assess type of vegetation species used for resiliency
Drainage Conveyances/Small Culverts	▪ Undermining of culverts ▪ Flooding and roadway overtopping ▪ Erosion of headwalls and banks ▪ Loss of functionality or failure caused by debris	▪ Evaluate stability of inflow and outflow channels. Identify potential of SWM for water quantity control ▪ Evaluate and potentially increase capacity of the culverts ▪ Design banks stabilization to be more resilient to erosion ▪ Implement systematic inspections program and increase frequency of maintenance to clean culverts

6.1.4 Evaluation of Asset Vulnerability and Risk

VAST and HVI were utilized to assess asset vulnerability and to determine which assets were at the most risk in the two pilot counties. Prior to using VAST and HVI, a Climate ChangeImpact Zone was defined to eliminate those assets that are at no to little risk from the identified climate stressors. Using GIS, key vulnerability indicators for the bridge assets within the Climate

Change Impact Zone were obtained and then entered into VAST. From vulnerability verification information obtained in Workshop #2, the importance of each vulnerability indicator was assessed to develop a scoring/ranking of assets for each pilot county. An HVI was developed and used to prioritize roadway segments at risk. Assets were then plotted onto a map along with their relative vulnerability scores. Using the scoring and subject matter expert input, areas where transportation assets were considered vulnerable and at high risk were identified, allowing definition of critical zones where high risk assets were geographically concentrated. Chapter 5 presents the results of the detailed analysis for each pilot county. Areas of high risk for each county based on the numerical input of the tools used for this study are presented in Table 6-1Types of Impacts to SHA's Transportation Infrastructure from M

Table.

Table 6-3. Vulnerability Areas at Risk Based on Results of VAST and HVI

County	Vulnerable Areas at Risk Based on Results of VAST
Anne Arundel County	▪ MD 450 ▪ MD 468/256 ▪ US 50/Bay Bridge Approach ▪ MD 2
Somerset County	▪ MD 363 ▪ MD 361 ▪ MD 413 ▪ Frogeye/Shelton Rd. ▪ Pocomoke ▪ Princess Anne ▪ MD 362

6.2 Lessons Learned

During the development and implementation of the framework for this Pilot Study, many challenges were encountered related to data collection, development of the data for future climate stressors, and the use of tools developed for other purposes. Each DOT and MPO will face their own challenges, but hopefully, the lessons learned as documented in this report can be useful to others beginning vulnerability assessments. The key lessons learned in the Pilot Study are as follows:

- **Importance of Asset Data Collection -** Data on bridges is more readily available than the other assets and was obtained using existing SHA GIS and NBI records data. Information on smaller culverts and drainage conveyances was available only for those counties that had a reporting requirement required by their NPDES permits. Invert information would have been helpful in this evaluation; however this data was not easily available for small culverts and drainage conveyances. Information on various structures supporting roads and bridge infrastructure such as retaining walls and seawalls was also not readily available. This level of research was not conducted as part of this study, but can be obtained if needed in future evaluations. These are assets that could be considered vulnerable, and could lead to impacts to roadways reliant upon those assets. This mechanism was witnessed during the course of this study on April 30, 2014 when old retaining walls adjacent to a CSX rail line collapsed after a heavy precipitation event causing damage to the roadway and parked automobiles on a street in Baltimore, MD.

Historical and real time information on asset vulnerabilities, emergency response, and post storm event maintenance in response to extreme weather events such as Hurricane Sandy or a smaller event such as the April 30, 2014 extreme rainfall event would be valuable. Using this information, planners and designers could better identify assets susceptible to extreme weather, design site-specific solutions to make these assets more resilient. Operational personnel could better assess adequacy of current maintenance operations and identify resources needed to adequately maintain infrastructure to prevent asset failure, which can result in loss of service and costly post damage rehabilitation.

- **Need for Effective Workshops -** Engineering workshops are an effective and efficient way of involving various stakeholders in the assessment and prioritization process, and are an effective way to get comprehensive feedback and perspectives from representatives of all departments within the agency. These different perspectives validate the assessment results and address issues of interest to the different stakeholders (*i.e*., design, operations, maintenance, etc.). Scenarios developed for engineering workshops should be designed to address a regional system rather than a specific asset. Engineers, planners and maintenance personnel agreed that a big picture approach that identifies "vulnerable areas at risk" would be more valuable for prioritization and implementation of adaptation strategies due to the interdependency of various transportation assets. While assessment of single assets will help define the nature of climate vulnerabilities for a given transport asset category (*i.e*., bridge), it is important to also consider vulnerabilities within the interconnecting infrastructure that connects each individual asset to its broader transport network.
- **Need for Collaboration and Sharing of Information** – Bi-annual collaboration with agencies in other states through webinars and peer exchanges is imperative to building a national framework of climate related data that transportation planners could utilize and build upon. Experiences from other states were useful in identifying how those states are addressing transportation infrastructure vulnerability to climate change, as well as their lessons learned. Increased collaboration between policy makers and engineering planners at all stages of policy development is crucial to bridging the gap in transferring the science of climate change into policies that will increase the Administration's resilience and mitigate future impacts.
- **Secondary Impacts such as Snow Melt -** Although this was not a focus of this study, increased intensity and frequency of snow storms will lead to increased de-icing of roadways using road

salt or other methods, which can kill roadside vegetation. This dead vegetation can cause blockage of storm drains and small culverts and lead to additional erosion of destabilized soil. Additionally, salt can penetrate and deteriorate concrete and reinforcing rods on bridges and compromise the structure's reliability. Best Management Practices need to be considered to provide solutions to address these important issues.

- **How to Consider Nearby Flood Control Structures -** Flood control structures that are located in the vicinity of SHA transportation infrastructure need to be taken into consideration when assessing vulnerability of those transportation assets. Any failure or overtopping of privately or publicly owned flood control structures due to increased precipitation or storm surge could adversely impact downstream transportation infrastructure and increase their risk of failure. Data pertaining to ownership and condition of flood control structures is typical of the types of information that could be acquired through adequate data sharing between state and county agencies.
- **Small Rainfall Events are Also Important -** Engineers design for extreme events and the location of an asset within FEMA's 100-year floodplain is an important indicator during the design process; however, when assessing the vulnerability of structures to precipitation events, small more frequent events such as the 1-year or 2-year storm are a better indicator of the structure or drainage asset vulnerability. The cumulative effect of these smaller frequent events also causes increased structural vulnerability.
- **Use of Climate Projection Models** - Climate projection models and tools such as Hazus, SLOSH, and others, are more informative for long term spans and larger areas; however, they could be problematic and inaccurate for riverine systems projections.
- **Use and Functionality of VAST -** A key lesson learned is that VAST might not be appropriate for every DOT's application and a localized version will likely be more practical for most vulnerability studies. VAST was useful to downscale the number of indicators and assets through different screening approaches, which offers the benefit of greatly reducing the level of effort by means of refining the assessment scope. Obtaining the asset data and populating VAST was the most labor intensive/time consuming work element within the Pilot Study. To effectively use VAST, the key indicators for vulnerability need to be identified and the applicable data obtained. A benefit of VAST's application in the Pilot Study is that the parameters have now been established, for the Maryland context. Future assessment efforts can make use of the baseline assessment's VAST parameter selection, assigned weighting factors and documented assumptions.
- **Increased Maintenance is Inevitable –** In many instances on Maryland's eastern shore, feasible engineering solutions maybe limited or cost prohibitive in the short-term. To enhance resiliency of existing assets, intensified maintenance programs may provide added coping capacity prior to implementing engineered solutions. For example, increased maintenance programs for clearance of culverts and drainage systems are an important part of a strategy to prevent disruption and asset failures due to inadequate drainage capacities. Regular cleaning of culverts and removal of

flow-restricting debris and accumulated sediment will be needed to reduce the risk of infrastructure failures and road closures.

- **Forward Thinking Approach** - Engineering design codes and practices are generally based on historical climate data. However, establishing infrastructure resiliency in the face of a changing climate requires asset planning to be forward focused, as consideration of historical climate exclusively will not yield results applicable to the expanded range of future climate. Climate projections define an operational setting of conditions that may exceed the range of historical climate variances. Transportation planners need to incorporate projections for the asset lifecycle to the conditions posed by this changing climate variability. It is necessary to provide a framework and support system in which engineers can better incorporate projections, averages and estimates related to changes in climate into infrastructure design.
- **Analytical Comparison of TP-40 vs. Atlas 14**

  For more than a generation, the standard method for performing hydrological computations has been either the *United States Soil Conservation Service (SCS) Hydrograph Method* (TR-55 or Tr-20) for culverts, stormwater management facilities and open channels or the *Rational Method* for closed storm drain systems. The rainfall data which was utilized in each of the three methods was taken from the *National Weather Service (NWS) Technical Paper 40* (TP-40). Utilizing TP-40 data, SCS developed 4 synthetic 24-hour rainfall distributions (I, Ia, II and III). The State of Maryland falls within the region that utilizes Type II rainfall distribution. Comparisons of TP-40 and Atlas 14 24-hour rainfall depths in Maryland indicate that for most of the counties, the rainfall depths for the 1- and 2-year storms remain unchanged (within 0.1 inch) or decrease slightly. The majority of the counties have decreased rainfall depths for the 10-year storm and significant increases in the rainfall depths for the 100-year storm. Additionally, Atlas 14 rainfall distribution indicates less rainfall intensity during the most intense period than TP-40. The results of this comparison mean that culverts that were designed previously using the TP-40 standards were conservatively designed and therefore can most likely withstand slight increases in flow due to sea level rise and/or precipitation. The details of this study and results have been included in Appendix C.

6.3 Next Steps and Recommendations

6.3.1 General Next Steps and Recommendations for SHA Climate Change Program

1. **Delineate and Adopt a Climate Change Impact Zone or Zone of Influence**

   A Climate Change Impact Zone would assist SHA planners and engineers determining if infrastructure is within a geographic area exposed to the climate stressors (sea level change, increased precipitation, and storm surge). This Climate Change Impact Zone should be added to SHA e-GIS and used as the initial screening for project planning and design projects. At a minimum, this Climate Change Impact Zone would include projections for sea level change and precipitation which is consistent with the approach in *Plan Maryland*. This zone should be revisited at an interval of at least every five years, based on the latest sea level model information and climate data. This interval could be shorter if superior data becomes available in the climate change science from reputable research findings.

2. **Refine Framework and Methodology and Assess Vulnerability to Assets State-Wide**

   This Pilot Study helped to accomplish a number of goals/objectives set forth in the *SHA/MDTA Adaptation Strategy* (January 2013) including assessing vulnerability for at least one pilot county and gaining a better understanding of the risk of climate change to SHA's assets. The pilot Counties, Anne Arundel and Somerset, were chosen because they represent very different topography and land use within the State of MD. Going forward, the framework and methodologies from this study will need to be refined based on lessons learned from implementation on the two pilot counties Following peer review and feedback on this Pilot Study, the framework will be revised as needed, for project implementation statewide.

3. **Incorporate Data Collection into Current SHA Practices for Key Vulnerability Indicators**

   This Pilot Study identified useful data and its sources to help in determining an assets sensitivity to a given climate stressor and other information to assess criticality based on the assets adaptive capacity. Using the data sets from this Pilot Study, it is important to communicate which information is needed in the future for adaptation planning and vulnerability assessment. Based on the lessons learned and desirable information identified during the Pilot Study, coordination should continue with asset management and adoption of future technologies utilized in maintenance. The issue of data availability and accessibility is a major challenge within vulnerability assessment efforts. Continued collection of electronic asset data is important as demonstrated in the VAST indicators table, as well as adding data related to asset's adaptive capacity and real time information about surrounding areas. During this study a data collection effort began to complete the MD inventory of small drainage assets and it was important to include invert elevation during data collection because previous data sets did not include this and can only be found on as-built plans. The data should be updated regularly and readily accessible for use in climate change vulnerability assessment and adaptation planning.

   Collection of data is important related to functionality and structural integrity of critical drainage systems, especially aging metal cross culverts under major highways. Investment in video cameras for pipe inspections should be made and a business process should be defined for how these inspections will be conducted and how remedial activities will be implemented.

   Data needs to be organized and managed to move away from traditional silo systems and improve data flow and access to information within the organization. Providing data on asset condition and location to maintenance in a format that is easily accessible is important for routine activities as well as during emergency operations.

4. **Field Data Collection App and Data Collection During/Following Extreme Weather Events**

   Data documentation process, protocols and guidelines should be developed that would likely leverage the capabilities of current mobile devices. Data collection by the first responders for maintenance and emergency situations stemming from severe weather events would be very helpful for asset management and vulnerability assessments. Documentation of each situation and long-term records would provide engineers and planners with a better understanding of the variables causing the problems and assist in developing adaptive measures to make the system more resilient. Ideas for data collection include a real time GIS applications/program, used on a mobile device such as smart phone, tablet, or laptop computers that would allow maintenance personnel to insert and document data collected on site during routine inspection or following a storm event. Reports and tables with historic data on regularly flooded areas are helpful, however inserting data in real time and the ability to interact with this data immediately and through the GIS database would be of great value and would allow identification and increased monitoring of key triggers useful in management of transportation asset impacts.

This data collection could be combined with current protocols for reporting road closures and traffic disruptions during various climate events. This data should be accessible to all transportation planners through shared access database.

Crowd sourcing and social media are two other effective methods for obtaining data during flooding events. The widespread integration of social media within all layers of society, and the ease of obtaining data collected by the general public, should be considered a valuable tool to increase the organizations range of useful information.

5. **Develop and Maintain a Comprehensive List of Adaptive Measures by Asset**

   To support project planning and design, a comprehensive list of adaptive design measures should be developed and maintained. Each measure should be evaluated for potential concerns/obstacles related to the regulatory approval process and SHA policies. This list should also include a section for "lessons learned" as adaptive measures are being applied.

6. **Develop Procedures to Evaluate the Existing SHA MD 378 dams**

   Procedures should be developed to determine the validity of the current dam safety classifications to evaluate the existing SHA MD 378 dams. The projected increases in precipitation, due to climate change, could adversely impact existing dams by causing overtopping or by reducing the available freeboard to unsafe levels. Both situations could cause the dam hazard to either be reclassified, or require the dam to be retrofitted in order to pass the increased discharge. In addition, MD 378 dams should be evaluated to ensure that building construction has not occurred within the downstream danger reach, which could create a need to modify or reclassify the dam.

7. **Develop Procedures for Changing Precipitation Frequency Information**

   Past hydrology and hydraulics studies have utilized the TP-40 precipitation-frequency data. The most up to date precipitation-frequency data is the NOAA Atlas 14 Volume 2 Version 3. Procedures and design guidelines should outline which source of data should be utilized for specific design parameters. SHA procedures and, guidelines should also outline how those decisions will be modified as future precipitation-frequency data is developed.

8. **Ongoing Evaluation on Climate Change Vulnerability/Adaptation Needed**

   The scope of this Pilot Study obtained for the FHWA Type II Grant was proposed to be specific to assets impacted by flooding, which could be impacted by sea level rise and severe storm events. Assets studied in the Pilot Study included the transportation network with limited consideration given to SHA facilities. There are other climate variables and assets that in the future should be evaluated such as:

- the impacts of an increase of temperature on pavement or other materials,
- the effects of increased snowfall, and
- the indirect effects of snow removal/melt and deicing operations

These impacts would not be limited to the Climate Change Impact Zone as it has been defined for flood related impacts.

9. Incorporate Climate Change Consideration into Existing Programming, Planning and Design Process

It is important to incorporate climate change considerations and screening early in the project programing to account for any additional time and cost consideration. All proposed projects should be screened for vulnerability to future climate impacts, which will allow for further dialogue concerning cost effective design alternatives. The screening process could include flagging all projects that fall within the Climate Change Impact Zone, as well as completing an internal checklist that could reveal an asset's susceptibility to future climate related risks.

10. Review and Amend Policies, Procedures and Processes to Incorporate Climate Change Vulnerability Assessment and Adaptation Planning

A comprehensive review of existing policies, procedures and design criteria should occur to identify changes needed to incorporate climate change considerations and adaptive measures into planning, design, and implementation. In some cases, design or operational changes to make SHA's infrastructure more resilient to climate change may be in conflict with existing industry practices or regulations. Policy review and changes likely necessary would include:

- Land Protection
- Disinvestment, Relocation, and Retreat
- Life Span of Infrastructures – Time Limit
- Use of Future Precipitation Projections in Design
- Assets and Localities Prone to Irreversible or Repetitive Flooding
- Regulatory conflicts

When proposing adaptation measures to reduce the risk of future flooding, the maximum allowable limit for raising a structure should be restricted. This limit should be defined based on the compatibility of the proposed elevation with the surrounding environment. Proposed adaptation measures should focus on Maryland's Interstates routes, evacuation routes and main arteries before addressing secondary routes.

11. Promote Awareness and Educate SHA Staff on Climate Change

Knowledge transfer between various Offices and Divisions proved helpful and of great value during all stages of the pilot assessment. One benefit of the two workshops conducted for this Pilot Study was the opportunity to present key issues and challenges to a multi-disciplinary group and hear their respective perspectives. The workshops helped to get each staff thinking long-term about their role and responsibilities within the context of climate change impacts on transportation assets. It would be helpful to develop a formal climate change impacts and resiliency training module tailored to the different roles and audiences. It is recommended that planners, design engineers, and maintenance staff become more educated on the impacts of climate change on transportation infrastructure to help inform decision makers on cost and time effective techniques to design better solutions to increase the resilience of the State-maintained highway network.

12. Partnership with Local Governments

In most cases, the local roadway networks will be impacted prior to the State transportation assets. Also, local governments will be faced with many other decisions related to land use planning and how to maintain services to local communities. Coordination will be needed to consider communities long-range plans and local adaptation planning efforts relative to sea level change.

13. Public Outreach

Consider development of public outreach materials. A website should be considered to include information on the climate change program, progress, initiatives such as this Pilot Study, and future activities. Other forms of media can also be utilized to reach the public including print media (newspapers) and social media (Facebook and Twitter).

14. Consistency with MAP-21 Goals for Integrated Asset Management

Moving Ahead for Progress (MAP-21) is a bill signed into law by President Obama on July 6, 2012, extending through Federal Fiscal Years 2013 and 2014 and expiring on September 30, 2014. This bill creates a streamlined and performance based surface transport program. MAP-21 emphasizes the importance of performance measures and also requires that the state develop a risk-based asset management plan for the National Highway System to preserve assets and improve system performance. This includes sustainable asset management practices and Maryland's plan for adaptation to climate change. The methodologies and lessons learned from this Pilot Study can be leveraged to further integrate climate change impacts into this overall asset management plan.

The integration of climate change into the overall asset management plan is in alignment with three of MAP-21's national goals:

a. safety, achieving significant reduction in traffic fatalities and serious injuries on all public roads,
b. infrastructure condition, maintaining the highway infrastructure asset system in a state of good repair, and
c. system reliability, improving the efficiency of the surface transportation system.

15. Develop a Short list of Planning Studies Affected by Climate Change

Upon completion of this Pilot Study, one of the next steps is to conduct more detailed studies for those projects or areas identified to be critical and at risk. After the statewide assessment is completed, a list of vulnerable assets or transportation segments should be identified and prioritized. Using a list of five to ten study areas, more detailed assessment should be conducted that includes: (1) detailed hydraulic modeling to further assess vulnerability, (2) engineering evaluation of different adaptation alternatives to assess the resiliency, costs, and environmental impacts, (3) conflict analysis with policy and regulations, (4) cost-to-benefits analysis, and (5) detailed costs and risks stemming from inaction (the “do nothing” approach). The results of each study should be summarized, shared, and considered in future decisions on adaptation planning.

16. Assess Funding Levels Needed to Implement Adaptation and Cost of Inaction

Using the shortlist of projects above, assess the funding levels necessary to implement successful adaptation and compare it to the cost incurred by impacts resulting from inaction. Furthermore, the need for changes in funding levels to support the required enhanced maintenance programs in those areas subject to storm surge and flooding should be evaluated.

17. Maintenance Data Collection

The wealth of knowledge that individual maintenance personnel possess is a significant organizational asset that should be incorporated into routine data collection. Increased collaboration between maintenance and planning should be promoted through well designed strategies that ensure the sustainability of such collaboration.

18. Track and Measure Effectiveness and Cost of Adaptation

As adaptation projects are implemented, it is important to track and measure the effectiveness of selected adaptation options through asset management. This information will be valuable to planners to further refine the cost-to-benefit analysis of future projects. Adaptation success stories should be widely publicized.

6.3.2 General Recommendations for Additional Information/Guidance Needed for Practitioners

19. Usefulness of the FHWA Vulnerability Framework

The FHWA Framework was useful in getting started with this Pilot Study. The Framework outlines the three key steps; defining study objectives and scope, assessing vulnerability and incorporating results into decision making. The processes, lessons learned, and resources outlined in the framework are geared toward State departments of transportation (DOTs), metropolitan planning organizations (MPOs), and other agencies involved in planning, building, or maintaining the transportation system. It also includes suggestions and examples applicable to a wide range of applications, from small qualitative studies to large, detailed, data-intensive analyses. The framework is informed by and draws examples from five climate change vulnerability and risk assessment pilot projects that the FHWA sponsored in 2010-2011. The understanding of what other DOTs have completed with respect to each step in the framework was helpful.

20. **Regional Climate Information**

Climate conditions in Maryland are unique due to the state's location between southeast and northeast regions and numerous geographic provinces. Most regional studies do not fully describe the unique climate characteristics of Maryland. Ideally, a regional climate study would furnish specific climate projections and extreme events trend data for each subregion defined within the State of Maryland. It is recommended that a comprehensive climate study that addresses historical and projected precipitation and storm surge data be performed for various regions of Maryland. Furthermore, changes in total annual precipitation and changes in seasonal precipitation are not an accurate indication of the projected changes in riverine flow. Unlike sea level rise and storm surge projections that could be projected using one model, flow resulting from projected changes in precipitation is more difficult to define and model, and require detailed data to define characteristics that may drive different runoff responses within each area assessed. It is recommended that a study be developed for Maryland to project changes in current regression equations and changes in total flow and flow velocities for major riverine systems due to changes in precipitation.

21. **CMIP Climate Data Processing Tool Recommendations:**

The precipitation output that is generated through CMIP Climate Data Processing Tool (CDPT) does not allow the users to view or review variables they have selected to generate the downscaled climate data, which is the input for the CMIP CPDT. The MS Excel spreadsheet should be able to extract and save that data from the downscaled climate data directly, otherwise, the CMIP CDPT instructions sheet should alert the users, during the downscaled climate data identification stage, that selected variables in terms of location, coordinates and emission scenarios, cannot be retrieved and should be manually recorded.

The precipitation output of CMIP CDPT is an input that is used for VAST processing, but is not relevant for hydrologists or engineers who design flood control structures. CMIP provides projections for the annual rainfall, 95th percentile rainfall, 99th percentile rainfall, and largest 3-day rainfall event per season, none of which particularly relate to any design criteria. It would be helpful if data is presented in ways that correspond with NOAA's Atlas 14 or other relevant and widely used precipitation outputs.

Additionally, the 95th percentile and 99th percentile rainfall output from CMIP CDPT do not accurately correspond with other sources. The CMIP CDPT projections for the 95th and 99th percentile precipitation for Anne Arundel County were 0.7 and 1.2 inches respectively. EPA's EISA Section 438 uses a 95th percentile of 1.6 and 1.7 inches for Baltimore and Washington respectively. UFC 3-210-10 (rainfall analysis 1978-1997) uses a 95th and 99th percentile of 1.53 and 2.36 inches for Baltimore.

CMIP CDPT should include a section that explains and justifies the process that was used to obtain the input data. Additionally, more explanation on what each output represents needs to be better detailed within the Excel sheet.

22. VAST Recommendations:

It would be very important to add an exposure indicator to consider assets for indicating the proximity to water holding structures such as dams, levees and floodwalls. Each of these nearby flood controls could pose more vulnerability to the assessed asset. This indicator will then be weighted based on the degree of the disruption this asset might cause if it's performance compromised or damaged due to the failure of an upstream water holding structure.

VAST does not have a unique set of indicators designed specifically for structures that are not listed within the considered set of assessed infrastructure covered in the Gulf Coast Study such as small culverts, conveyances, and tunnels, etc. To make VAST more practical and usable by a larger audience, it is recommended that more specific indicator sets, intended for broader application in the U.S. beyond the Gulf Coast Study considerations, are included to help guide the users on which variables need to be addressed for certain types of structures.

VAST indicates that precipitation indicators such as the change in the amount of rain associated with 100-year 24-hour storm, change in peak discharge, change in flow velocity and change in discharge volume could all be obtained from DOT's CMIP CDPT. These indicators cannot be obtained from CMIP CDPT in its current format, therefore this information should be reflected on VAST instructions to better guide the users.

23. Feedback on the Functionality of VAST

Use of the "draft" VAST was extremely helpful for this Pilot Study. A quantitative based decision support tool is important to help document and justify climate change risk management decisions. A key lesson learned is the need for a localized version of VAST. A localized VAST product would allow drop-down selection of only relevant indicators for a given assessment region within Maryland. The current version of VAST contains lists with several indicators that are inapplicable to the Maryland setting. To effectively use VAST, the key indicators for vulnerability need to be identified and data should be obtained in a format compatible with VAST inputs. Extensive data collection and data entry is necessary to populate the tool's input requirements. It was helpful to conduct additional screening prior to using VAST to eliminate assets deemed to present little or no risk, allowing a dismissal of those assets from further consideration in VAST, thereby reducing the overall data input necessary. Although it was the intention at the onset of this study to use VAST for all assets, data and time constraints made it unpractical to use VAST for the roadway and furthermore, found overlap with the Hazard Vulnerability Index (HVI) analysis. It was decided that HVI would be used to map roadway segments vulnerability .

24. Maintain and Update Micro-Scale Data for Sea-Level Rise, Storm Surge and Precipitation

Access to quality data is essential to assure consistency and effective risk and vulnerability reduction strategies. Comprehensive asset data is maintained in GIS and is growing over time. For this Pilot Study, Salisbury University prepared sea level and storm surge inundation maps using the latest LiDAR information for each county studied. As better LiDAR and updated climate science are available, the mapping will be updated and is recommended to be updated at least on a five-year cycle.

6.4 Conclusion

The SHA Pilot Study establishes a framework for assessing vulnerability, prioritizing assets, and provides guidance on adaptive measures to make SHA's transportation system more resilient to impacts arising from climate change. Climate stressors were identified that present the highest risk to SHA infrastructure: sea level change, storm surge, and increased intensity and frequency of precipitation. Other stressors, such as increases in temperature or changes to snowfall levels in western regions were beyond the scope of this study. This final report presents a series of recommendations that are intended to guide SHA's Climate Change Program and assist planners and engineers in preparing for impacts arising from climate change. This Pilot Study also increased awareness by SHA staff of the potential impacts of climate change and the strong need for adaptation.

The report's recommendations are not limited to changes in planning and design. Operational and maintenance-oriented adaptive measures are also very important and can offer additional coping capacities that can be highly effective in the preparation for onset of some severe weather events. Data collection has been and will continue to be an important step in adaptation planning. Although this Pilot Study was intended to support SHA and is specific to Maryland's climate, the final report was written in a manner to share information and lessons learned for the purposes of informing other practitioners of the applied methods and assessment results. SHA would like to extend a special thanks to FHWA for their support and hope that this Pilot Study will be useful to FHWA and other transportation planners in developing their vulnerability assessments and adaptation plans in response to climate change.

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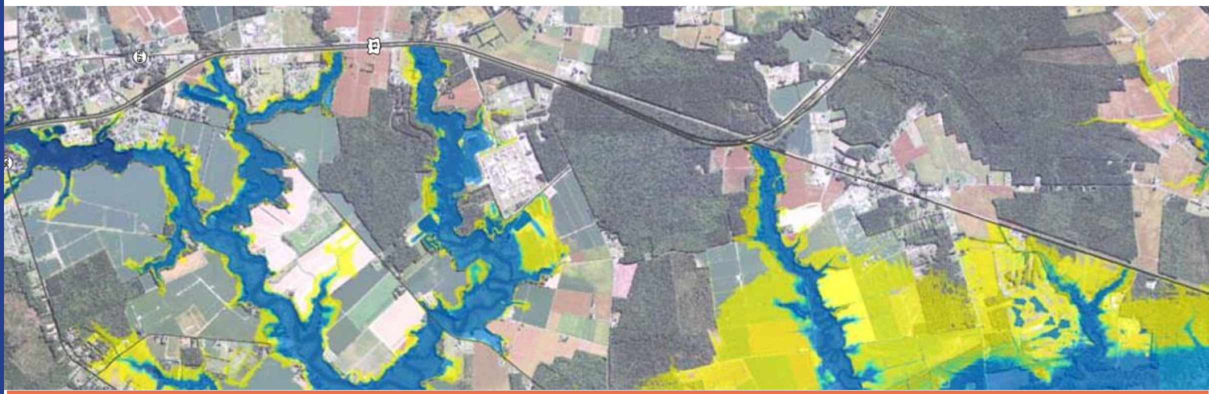
Chapter 7

Acronyms, Glossary, and References



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List of Acronyms

ARWG	Adaptation and Response Working Group
AR5	Intergovernmental Panel on Climate Change - Fifth Assessment Report
BCA	Benefit Cost Analysis
BMP	Best Management Practice
CCSP	US Climate Change Science Project
CCZ	Climate Change Zone
CHART	Coordinated Highway Action Response Team
COMAR	Code of Maryland Regulations
CMIP	Coupled Model Intercomparison Project
CWA	Clean Water Act
CDPT	Climate Data Processing Tool
DEM	Digital Elevation Model
dFIRM`	Flood Insurance Rate Maps
DNR	Maryland Department of Natural Resources
DOT	Department of Transportation
EPA	US Environmental Protection Agency
ESD	Environmental Site Design
ESRGC	Eastern Shore Regional GIS Cooperative
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FIS	Flood Insurance Study
GCM	General Circulation Model(s)
GHG	Greenhouse Gasses
GIS	Geographic Information Systems
GPS	Global Positioning Systems
HB	House Bill
HGL	Hydraulic Grade Line

HHD	Highway Hydraulics Division
HVI	Hazard Vulnerability Index
IPCC	Intergovernmental Panel on Climate Change
LID	Low Impact Development
LiDAR	Light Detection and Ranging
MCCC	Maryland Commission on Climate Change
MDOT	Maryland Department of Transportation
MDA	Maryland Department of Agriculture
MDE	Maryland Department of Environment
MDNR	Maryland Department of Natural Resoures
MDP	Maryland Department of Planning
MDTA	Maryland Transportation Authority
MEMA	Maryland Emergency Management Agency
MHHW	Mean Higher High Water
MIP	Model Intercomparison Project
MPO	Metropolitan Planning Organization
MS4	Municipal Separate Storm Sewer Systems
MSL	Mean Sea Level
MWG	Mitigation Working Group
NBI	National Bridge Inventory
NED	National Elevation Dataset
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
NPDES	National Pollution Discharge Elimination System
RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
ROW	Right of Way
SHA	Maryland State Highway Administration
SLOSH	Sea, Lake and Overland Surge from Huricanes
SLR	Sea Level Rise

SFHA	Special Flood Hazard Areas
STWG	Scientific Technical Working Group
SWM	Stormwater Management
TMDL	Total Maximum Daily Load
USGS	US Geological Survey
USFWS	US Fish and Wildlife Service
VAST	Vulnerability Assessment Scoring Tool
WCRP	World Climate Research Program
WG I	Working Group I
WSEL	Water Surface Elevation

Glossary

Adaptive Capacity – The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (FHWA 2012).

Asset – A physical component of the highway system, such as section of asphalt, a drain pipe, or overhead lighting, that contributes to the overall function of the highway.

Culvert – A culvert is a closed conduit, such as a pipe or concrete cell, that is used to convey water from one area to another, usually from one side of a road to the other side.

Climate Change – Climate change refers to any significant change in the measures of climate lasting for an extended period of time. In other words, climate change includes major changes in temperature, precipitation, or wind patterns, among others, that occur over several decades or longer (EPA, 2014a).

Coordinated Highway Action Response Team (CHART) – Coordinated Highways Action Response Team (CHART) is a joint effort of the Maryland Department of Transportation, Maryland Transportation Authority and the Maryland State Police, in cooperation with other federal, state and local agencies. CHART's mission is to improve "real-time" operations of Maryland's highway system through teamwork and technology.

Digital Elevation Model (DEM) – A format for elevation data, tiled by map sheet, produced by the National Mapping Division of the United States Geological Survey.

FEMA 100 year Flood – The 100-year flooding event is the flood having a 1 percent chance of being equaled or exceeded in magnitude in any given year**.**

FHWA Functional Classification of Roads – A grouping of highways, roads and streets by the character of service they provide and was developed for transportation planning purposes.

Flood – 1) period when tide level is rising; often taken to mean the flood current which occurs during this period. 2) a flow beyond the carrying capacity of a channel (FHWA, 2008).

Floodplain – land area adjacent to a river, stream, lake, estuary, or other water body that is likely to be inundated during a flood.

Freeboard – 1) the vertical distance between the design water level and the top of a coastal levee or dike; 2) the distance from the design waterline to the low-chord of the bottom of a suspended deck such as a bridge deck or offshore platform; or 3) the distance from the crest of the design wave to the low-chord of the bottom of a suspended deck such as a bridge deck or offshore platform (FHWA, 2008).

Geographic Information Systems (GIS) – A geographic information system, or GIS, is a computerized data management system used to capture, store, manage, retrieve, analyze, and display spatial information. Data captured and used in a GIS commonly are represented on paper or other hard-copy maps.

Hazard – An event which affects the ability of the highway system, or an element thereof, to functioned as designed.

Hazard Vulnerability Index (HVI) – A vulnerability index is a measure of the exposure of a group of assets to some hazard. Typically, the index is a composite of multiple ratings that via some formula, delivers a single numerical result.

Hazus Modeling – Hazus is a nationally applicable standardized methodology, developed by the Federal Emergency Management Agency (FEMA) that contains models for estimating potential losses from earthquakes, floods and hurricanes. Hazus uses Geographic Information Systems (GIS) technology to estimate physical, economic and social impacts of disasters.

Mean Higher High Water Sea Level – The average maximum elevataion of the daily high tide as observed within the National Tidal Datum Epoch.

Mean Sea Level – The average height of the surface of the sea for all stages of the tide over a 19-year period, usually determined from hourly height readings.

National Elevation Dataset (NED) –The National Elevation Dataset is the primary elevation data product of the United States Geological Survey and serves as the elevation layer of The National Map. The NED provides basic elevation information for earth science studies and mapping applications in the United States.

National Pollution Discharge Elmination System (NPDES) – As authorized by the Clean Water Act, the National Pollutant Discharge Elimination System (NPDES) permit program controls water pollution by regulating point sources that discharge pollutants into waters of the United States. Point sources are discrete conveyances such as pipes or man-made ditches.

Light Detection and Ranging (LiDAR) – LIDAR, stands for Light Detection and Ranging and is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses—combined with other data recorded by the airborne system— generate precise, three-dimensional information about the shape of the Earth and its surface characteristics.

National Tidal Datum Epoch – The specific 19-year period adopted by the National Ocean Service as the official time segment over which tide observations are taken and reduced to obtain mean values (e.g., mean lower low water, etc.) for tidal datums. It is necessary for standardization because of periodic and apparent secular trends in sea level. The present NTDE is 1983 through 2001 and is actively considered for revision every 20-25 years. Tidal datums in certain regions with anomolous sea level changes (Alaska, Gulf of Mexico) are calculated on a Modified 5-Year Epoch.

Resiliency – 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 (FHWA 2012).

Sea Level Rise or Sea Level Change – The long-term trend in mean sea level (FHWA, 2008).

Sea Level Change Depth Grids – Digital maps which predict the depth of water at certain location under a specific flooding scenario.

Scour – Removal of underwater material by waves and currents, especially at the base or toe of a structure (FHWA, 2008).

SLOSH Data – The Sea, Lake and Overland Surges from Hurricanes (SLOSH) model is a computerized numerical model developed by the National Weather Service (NWS) to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes by taking into account the atmospheric pressure, size, forward speed, and track data. These parameters are used to create a model of the wind field which drives the storm surge.

Special Flood Hazard Area – The land area covered by the floodwaters of the base flood is the Special Flood Hazard Area (SFHA). The SFHA includes Zones A, AO, AH, A1-30, AE, A99, AR, AR/A1-30, AR/AE, AR/AO, AR/AH, AR/A, VO, V1-30, VE, and V on FEMA Flood Insurance Rate Maps (FIRMs). http://www.fema.gov/floodplain-management/special-flood-hazard-area

Storm Surge – An abnormal rise in sea level accompanying a hurricane or other intense storm, whose height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the cyclone (EPA, 2014a).

Transportation Asset – Infrastructure associated with roadway networks such as bridges, culverts, and roadways including pavement.

Vulnerability Assessment Scoring Tool (VAST) – Acrosoft Excel-based analytical tool that uses key asset information (e.g. bridge age), climate data (e.g. flood elevation), and other vulnerability indicators (e.g. current frequency of flooding) to develop a composite vulnerability score.

Vulnerability – The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (FHWA, 2012).

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Chapter 8

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Appendices

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Appendix A – General Adaptation Measures by Asset Type Specific to Maryland's Climate

General Adaptation Measures by Asset Type Specific to Maryland's Climate
Bridges

Climate Stressor	Vulnerability/Failure	Adaptation Measure	Standards
1 Sea Level Rise	• Tidal effect in areas where previously no tidal influence; raising tailwater; undermining foundations (scour)	• Scour protection; increase bridge opening; increased monitoring of infrastructure and conditions	• Notes 3 & 4. site dependent, based on a hydraulic analysis.
	• Girders (Concrete/Steel) in or near saltwater may corrode over time	• Change coating type or apply coating; utilize more rebar cover and exclude material types like weathering steel etc. for saltwater applications; increased monitoring of infrastructure and conditions	• No known SHA standards for saltwater. AASHTO provides design guidance.
	• Water flowing over roadway approaches causing uplifting of road approaches	• Raise roadway if possible; install more hydraulic structures (depending on the hydraulic analysis); improve roadway/pavement design; increased monitoring of infrastructure and conditions; consider asphalt/concrete mixtures that withstand flood conditions	• Notes 1 & 2. Issues would be accounted for in design.
	• Superstructure floats away (timber bridge high risk) due to buoyancy	• Anchor structure to abutments/piers	No known standard. Issues would be accounted for in design.
	• For moveable structures -Mechanical systems flooding (in MD - Low likelihood due to the elevation of systems)	• Install pumps; flood proofing	No known standard. Issues would be accounted for in design.
	• Water damage to/failure of utilities attached to structures	• Raise the utility above the anticipated SLR elevation, where applicable	No known standard. Issues would be accounted for in design.

General Adaptation Measures by Asset Type Specific to Maryland's Climate
Bridges

	Climate Stressor	Vulnerability/Failure	Adaptation Measure	Standards
2	Storm Surge	• Superstructure floats away due to buoyancy	• Anchoring of Superstructure; temporary placement of mass on superstructure	No known standard. Issues would be accounted for in design.
		• Increase in flow and velocity causes undermining foundations (scour)	• Reevaluate the scour analysis - increase monitoring/inspection of critical structures on emergency routes, provide more/better scour protection; retrofit/replace bridges as required for new scour conditions	• Notes 3 & 4. Site dependent, based on a hydraulic analysis.
		• Water flowing over roadway approaches causing uplifting of road approaches	• Raise roadway if possible; install more hydraulic structures (depending on the hydraulic analysis); improve roadway/pavement design	• Notes 1 & 2. Issues would be accounted for in design.
		• Severe/flash rain events cause undermining foundations (scour)	• Reevaluate the scour analysis - increase monitoring/inspection of critical structures on emergency routes, provide more/better scour protection	• Notes 3 & 4. Site dependent, based on a hydraulic analysis.
3	Riverine Flooding	• Floating debris buildup and damage to bridges due to increased velocity	• Depends on the hydraulic analysis. Raising the bridge is not always the best option; station equipment for rapid debris removal where possible	• None. Site dependent, based on a hydraulic analysis.
		• Water flowing over parapets onto superstructure deck and down roadway approaches - debris can get left on the deck between the parapets	• Provide open parapets so flow will go from on side to the other	• Bride design manual, adaptation to other usages
		• Water flowing over roadway approaches/causing uplifting of road approaches	• Raise roadway (if possible); install more hydraulic structures (depends on the hydraulic analysis); improve roadway/pavement design; deploy super sand bags (or equivalent to Syn-Tex Geo product) along critical evacuation routes where feasible	• Notes 1 & 2. Issues would be accounted for in design.

General Adaptation Measures by Asset Type Specific to Maryland's Climate
Bridges

	Climate Stressor	Vulnerability/Failure	Adaptation Measure	Standards
4	Precipitation	• Water flowing off of the structure and approach roadway pavement causing embankment / side slope erosion and possible failure	• Add robust slope protection such as matting riprap vegetation or possible a closed drainage system around the structure	• Notes 1 & 2. Issues would be accounted for in design.
		• Undersized scuppers cause ponding on bridge surface	• Add/Enlarge/Maintain; upgrade bridge deck and drainage systems; during extreme precipitation events; continuously monitor drainage system	• None. Site dependent, based on a hydraulic analysis.

General Adaptation Measures by Asset Type Specific to Maryland's Climate
Roadways

	Climate Stressor	Vulnerability/Failure	Adaptation Measure	Standards
1	Sea Level Rise	• Approaches to structures washing out	• Elevate the approaches; provide extension of wing walls; add strength (i.e. riprap , armoring, etc.) to side slopes	
		• Inundation of pavement structure	• Elevate the pavement structure; design the pavement structure to function during inundation	
		• Inundation of subgrades	• Replace the subgrades with materials so that the pavement structure will function during inundation and for multiply inundations	
		• Sinkhole/roadway undermining or collapse		
2	Storm Surge	• Failure of embankments and/or retaining structures	• Provide protections to the embankments (i.e. armoring, retaining walls, additional culverts, etc.)	
3	Riverine Flooding	• Failure of embankments and/or retaining structures; debris accumulation on roadway fixtures	• Provide protections to the embankments (i.e. armoring, retaining walls, additional culverts, etc.); deploy super sand bags (or equivalent to Syn-Tex Geo product) along critical evacuation routes; protect evacuation routes; assess drainage system materials for options that allow easier inspection and maintenance to account for increased need for repair due to excessive moisture impacts	

General Adaptation Measures by Asset Type Specific to Maryland's Climate
Roadways

	Climate Stressor	Vulnerability/Failure	Adaptation Measure	Standards
4	Precipitation	• Failure of embankments and/or retaining structures	• Provide protections to the embankments (i.e. armoring, retaining walls, additional culverts, etc.); reducted slopes/usage of more erosion-resistant materials in slope retention systems	
		• Roadside / slope vegetation death (not enough precipitation, too much salt from increased snow fall)	• Provide hardy vegetation, use a product that does not kill vegetation, riprap the slopes	

General Adaptation Measures by Asset Type Specific to Maryland's Climate
Culverts: Pipe or Box, Drains, Drainage Ditches

	Climate Stressor	Vulnerability/Failure	Adaptation Measure	Standards
1	Sea Level Rise	• Tidal effect in areas where previously no tidal influence; raising tailwater; undermining foundations (scour)	• Reevaluate the scour analysis; increase monitoring/inspection of critical structures on emergency routes; provide more/better scour protection	• Notes 3 & 4. site dependent, based on a hydraulic analysis.
		• Metal culvert buoyancy/wash out	• Limited use of metal culverts; provide anchoring system/anti-seepage devices	
		• Clogging, piping and washout of culverts	• Increase capacity of crossing (i.e. replacement), adding culverts at higher elevation, etc.	• Notes 3 & 4. site dependent, based on a hydraulic analysis.
		• Clogging of ditches	• Increase maintenance of ditches and inspection of areas along the ditches around the upstream and downstream ends of the culverts on either side of the roadway crossings; enhanced vegetation control program	
		• Corrosion due to salt water	• Change coating type or apply coating; utilize more rebar cover and exclude material types like weathering steel etc. for saltwater applications	
		• More frequent overtopping of roadway	• Raise roadway; improve culverts to increase capacity; add smaller culverts at higher elevation; install more hydraulic structures (depends on the hydraulic analysis); improve the ditches to handle more flow, maintaining the areas around the upstream and downstream ends of the culverts	• Notes 1 & 2. Issues would be accounted for in design.
2	Storm Surge	• More frequent overtopping	• Improve culverts to increase capacity; add smaller culverts at higher elevation as overtopping protection; maintain the areas around the upstream and downstream ends of the culverts	• Notes 1 & 2. Issues would be accounted for in design.

General Adaptation Measures by Asset Type Specific to Maryland's Climate
Culverts: Pipe or Box, Drains, Drainage Ditches

	Climate Stressor	Vulnerability/Failure	Adaptation Measure	Standards
3	Riverine Flooding	• More frequent overtopping	• Improve culverts to increase capacity; add smaller culverts at higher elevation as overtopping protection; maintain the areas around the upstream and downstream ends of the culverts	• Notes 1 & 2. Issues would be accounted for in design.
		• Culvert hydraulics change such that embankment changes from road embankment to dam embankment	• Improve culverts to increase capacity; add smaller culverts at higher elevation as overtopping protection	• Notes 1, 2, & 5. Issues would be accounted for in design.
4	Precipitation	• Metal culvert buoyancy/wash out	• Limited use of metal culverts; provide anchoring system/anti-seepage devices	
		• Clogging, piping and washout of culverts	• Increase capacity of crossing (i.e. replacement, adding culverts at higher elevation, etc.); during extreme precipitation events, continuously monitor drainage systems	• Notes 3 & 4. site dependent, based on a hydraulic analysis.
		• Clogging of ditches	• Increase maintenance of ditches and inspection of areas along the ditches around the upstream and downstream ends of the culverts on either side of the roadway crossings; enhanced vegetation control program; during extreme precipitation events, continuously monitor drainage systems	
		• More frequent overtopping	• Raise roadway; improve culverts to increase capacity; add smaller culverts at higher elevation; install more hydraulic structures (depends on the hydraulic analysis); improve the ditches to handle more flow, maintaining the areas around the upstream and downstream ends of the culverts; increase or implement new water retention storage systems	• Notes 1 & 2. Issues would be accounted for in design.

General Adaptation Measures by Asset Type Specific to Maryland's Climate
Retaining Walls/Seawalls

	Climate Stressor	Vulnerability/Failure	Adaptation Measure	Standards
1	Sea Level Rise	• Failure of retaining structures due overtopping	• Increase the height of the wall either by adding to the wall or installing a new wall	
2	Storm Surge	• Failure of retaining structures due to overtopping	• Increase the height of the wall either by adding to the wall or installing a new wall. Provide something in front of the wall to reduce the energy of the storm surge.	
3	Riverine Flooding	• Failure of retaining structures due to river flooding and/or overtopping	• Increase the height of the wall either by adding to the wall or installing a new wall. Provide something in front of the wall to reduce the energy of the river; increase or implement new water retention storage systems; during flood stage water levels, continuously monitor structural conditions	
4	Precipitation	• Failure of retaining structures due to increased runoff resulting in increased scour	• Provide scour protection to direct the water away from the structure; improve monitoring system for runoff flows in critical locations	
		• Failure of retaining structures due to increased runoff flow over and down the wall	• Review and/or revise drainage from slope that would go over wall, add curbing or road, add ditch behind wall	

General Adaptation Measures by Asset Type Specific to Maryland's Climate
SWM, BMPs, Ponds, Convential BMPs, ESD, BMPs

	Climate Stressor	Vulnerability/Failure	Adaptation Measure	Standards
1	Sea Level Rise	• Hydraulic function of SWM Ponds could be impacted by higher tailwaters (SHA or private ponds that SHA stormwater drains into)	• Modify SWM pond hydraulic control/size; raise top of dam	• Notes 5 & 6; would require redesign.
		• Higher sea level could result in higher ground water levels which could impact infiltration or ESD BMPs	• Reevaluate the type of BMP installed to see if it still works or needs to be modified	• Notes 5 & 6; would require redesign.
2	Storm Surge	• Higher storm surge alone may have no adverse impact, but if you couple it with sea level rise you could cause SWM pond dam failures	• Modify SWM pond hydraulic control/size; raise top of dam	• Notes 5 & 6; would require redesign.
3	Riverine Flooding	• Groundwater rise/limits effectiveness of SWM and BMPs	• Modify SWM pond hydraulic control/size; raise top of dam; reevaluate the type of BMP installed to see if modifications are required	• Notes 5 & 6; would require redesign.
		• Hydraulic function of SWM Ponds could be impacted by higher tailwaters (SHA or private ponds that SHA stormwater drains into)	• Modify SWM pond hydraulic control/size; raise top of dam	• Notes 5 & 6; would require redesign.
4	Precipitation	• Increased precipitation could raise dam (upstream SHA & private dams) classification from class 'a; (low hazard) to class 'b' (significant hazard) or class 'c' (high hazard)	• Modify SWM pond hydraulic control/size; raise top of dam; increase or implement new water retention storage systems; continuously monitor during extreme precipitation conditions	• Notes 5 & 6; would require redesign.
		• Increase precipitation/dam failure/safety issue	• Modify SWM pond hydraulic control/size; raise top of dam; increase or implement new water retention storage systems; continuously monitor during extreme precipitation condition	
		• Increased precipitation could cause failure of infiltration and ESD/BMPs	• Reevaluate the type of BMP installed to see if it still works or needs to be modified	• Notes 5 & 6; would require redesign.

General Adaptation Measures by Asset Type Specific to Maryland's Climate
Maintenance Facilities: Buildings and Related Infrastructure

Climate Stressor	Vulnerability/Failure	Adaptation Measure	Standards
1 Sea Level Rise	• Buildings may be impacted by storm surge	• Provide flood protection or flood proof measures; raise building; relocate building; evaluate the building use (i.e. building would store items not affected by water); move items to higher floors; install shelving to have items out of the water; re-location critical systems and data holdings to hight elevation if currently susceptible to flooding; back up power systems	
	• Access to facility	• Evaluate access route and determine if the route can be maintained by raising the elevation of the access or can a new access be provided that would not be affected by the SLR	
2 Storm Surge	• Higher flood elevations due storm surge could impact buildings, parking, storage, & mechanical/electrical equipment.	• Provide flood protection or flood proof measures; raise building; relocate building; evaluate the building use (i.e. building would store items not affected by water); move items to higher floors; install shelving to have items out of the water; re-locate critical systems and data holdings to higher elevation if currently susceptible to flooding from storm surge; back-up power systems • Prepare and implement flood warning/education/training system to address site specific flooding	
	• Access to facility	• Evaluate access route and determine if the route can be maintained by raising the elevation of the access or can a new access be provided that would not be affected by the storm surge	

General Adaptation Measures by Asset Type Specific to Maryland's Climate
Maintenance Facilities: Buildings and Related Infrastructure

	Climate Stressor	Vulnerability/Failure	Adaptation Measure	Standards
3	Riverine Flooding	• Higher flood elevations due river flooding could impact buildings, parking, storage, & mechanical/electrical equipment.	• Provide flood protection or flood proof measures; raise building; relocate building; evaluate the building use (i.e. building would store items not affected by water); move items to higher floors; install shelving to have items out of the water	• Notes 7 & 8; would require redesign.
			• Prepare and implement flood warning/education/training system to address site specific flooding; during extreme precipitation events, continuously monitor critical building system functions and relocate valued assets susceptible to immersion damage.	
3	Riverine Flooding	• Access to facility	• Evaluate access route and see if the route can be maintained by raising the elevation of the access or can a new access be provided that would not be affected by riverine flooding	
4	Precipitation	• Access to facility	• Provide improved onsite drainage; during extreme precip events, continuously monitor critical systems and infrastructure	
		• Higher, flash rain events can impact building, parking, storage, and mechanical/electrical equipment	• Provide flood protection or flood proof measures; raise building; relocate building; evaluate the building use (i.e. building would store items not affected by water); move items to higher floors; install shelving to have items out of the water	
			• Prepare and implement flood warning/education/training system to address site specific flooding	

Appendix B – Results of Vulnerability Assessment for Pilot Counties Using VAST Tool

Asset ID	Asset Name	Precipitation Changes_ Exposure _Scenario1	Precipitation Changes_ Sensitivity	Precipitation Changes_ Adaptive Capacity	Precipitation Changes_ "Damage"_ Scenario1	Precipitation Changes_ Vulnerability_ Scenario1
1	MD 423	3.10	2.45	1.75	2.78	2.57
4	MD 256	2.10	1.55	1.75	1.83	1.81
5	MD 258	2.10	1.70	#N/A	1.90	#N/A
6	MD 256	1.60	1.35	1.75	1.48	1.53
7	MD 258	1.60	1.20	#N/A	1.40	#N/A
8	MD 258	3.10	1.80	2.00	2.45	2.36
10	MD 258	1.60	1.30	2.00	1.45	1.56
12	MD 4 EBR	2.10	2.20	3.50	2.15	2.42
13	MD 4 WB	2.10	2.20	3.50	2.15	2.42
15	MD 468	3.10	1.74	#N/A	2.42	#N/A
17	MD 468	3.10	1.74	#N/A	2.42	#N/A
19	MD 255	2.10	2.30	#N/A	2.20	#N/A
21	MD 468	2.10	1.80	#N/A	1.95	#N/A
22	MD 468	3.10	2.30	#N/A	2.70	#N/A
25	MD 468	3.10	1.70	#N/A	2.40	#N/A
26	MD 468	1.60	1.20	#N/A	1.40	#N/A
27	MD 468	2.10	1.40	#N/A	1.75	#N/A
29	MD 214	0.64	1.20	#N/A	0.92	#N/A
30	MD 214	3.10	2.80	#N/A	2.95	#N/A
31	MD 2	1.60	1.25	#N/A	1.43	#N/A
34	MD 665 EB	1.60	1.20	#N/A	1.40	#N/A
35	MD 665 WB	1.60	1.20	2.75	1.40	1.67
37	MD 181(SIXTH ST)	2.10	1.60	2.00	1.85	1.88
38	IS 595	1.60	2.30	4.00	1.95	2.36
39	MD 70	1.60	1.30	2.00	1.45	1.56
40	IS 595 & RAMPS	1.60	1.15	#N/A	1.38	#N/A
41	MD 450	2.10	1.55	2.00	1.83	1.86
42	MD 450	2.10	2.50	2.25	2.30	2.29
43	MD 450	3.10	2.79	#N/A	2.94	#N/A
44	MD 450	3.10	2.75	2.25	2.93	2.79
45	MD 450	3.10	2.79	#N/A	2.94	#N/A
46	MD 450	3.10	2.79	#N/A	2.94	#N/A
47	MD 3 SB	1.60	1.05	3.00	1.33	1.66
48	MD 450	3.10	2.20	#N/A	2.65	#N/A
49	MD 450	2.14	2.79	#N/A	2.46	#N/A
51	MD 450	1.14	1.84	#N/A	1.49	#N/A
52	MD 450	2.10	1.84	#N/A	1.97	#N/A

Asset ID	Asset Name	Precipitation Changes_ Exposure _Scenario1	Precipitation Changes_ Sensitivity	Precipitation Changes_ Adaptive Capacity	Precipitation Changes_ "Damage"_ Scenario1	Precipitation Changes_ Vulnerability_ Scenario1
54	MD 450	2.10	2.26	#N/A	2.18	#N/A
55	MD 450	3.10	2.16	#N/A	2.63	#N/A
56	IS 595	1.60	1.30	3.50	1.45	1.86
57	MD 450	3.10	1.70	#N/A	2.40	#N/A
58	MD 70	1.60	1.30	2.00	1.45	1.56
59	MD 436	1.60	1.30	2.00	1.45	1.56
60	MD 450	1.60	1.65	2.00	1.63	1.70
61	MD 3	3.10	1.70	#N/A	2.40	#N/A
62	MD 3	2.14	1.63	#N/A	1.89	#N/A
65	IS 97	1.60	1.35	3.50	1.48	1.88
66	US 50	1.60	1.70	3.50	1.65	2.02
67	MD 179	2.10	2.05	1.75	2.08	2.01
68	MD 908D	2.14	1.19	2.50	1.66	1.83
69	US 50	3.10	1.70	#N/A	2.40	#N/A
72	MD 908C & RAMP A	2.14	1.70	#N/A	1.92	#N/A
73	MD 3 NBR	1.60	1.30	#N/A	1.45	#N/A
74	MD 3 SBR	1.60	1.10	#N/A	1.35	#N/A
81	IS 97 SBR	1.60	1.60	3.50	1.60	1.98
84	MD 648AA	2.10	1.95	#N/A	2.02	#N/A
85	MD 648H	2.10	2.25	2.00	2.18	2.14
86	MD 32	2.10	1.20	2.75	1.65	1.87
87	MD 32	1.60	1.00	2.75	1.30	1.59
88	MD 198 WB	3.10	1.65	2.25	2.38	2.35
92	MD 648H	2.10	1.32	#N/A	1.71	#N/A
93	MD 10	1.60	1.10	2.25	1.35	1.53
94	MD 174	2.10	1.80	#N/A	1.95	#N/A
95	MD 2	3.10	1.75	#N/A	2.43	#N/A
96	MD 32	1.60	1.05	2.75	1.33	1.61
102	MD 100	1.60	1.20	3.50	1.40	1.82
104	MD 173	2.10	2.60	2.25	2.35	2.33
106	MD 2	2.10	1.35	3.00	1.73	1.98
108	MD 100 WBR	1.10	1.00	3.00	1.05	1.44
109	MD 100 EBR	1.60	1.00	3.25	1.30	1.69
110	MD 10 NBR	1.60	1.35	2.50	1.48	1.68
111	MD 10 SBR	1.60	1.35	2.50	1.48	1.68

Asset ID	Asset Name	Precipitation Changes_ _Scenario1 Exposure	Precipitation Changes_ Sensitivity	Precipitation Changes_ Adaptive Capacity	Precipitation Changes_ "Damage"_ Scenario1	Precipitation Changes_ Vulnerability_ Scenario1
112	MD 648E	1.60	1.85	2.00	1.73	1.78
113	MD 100 & RPS A & D	1.60	1.00	3.25	1.30	1.69
114	MD 100	1.60	1.00	#N/A	1.30	#N/A
116	IS 97 & RAMP F(2)	1.60	1.00	#N/A	1.30	#N/A
118	MD 173	1.60	1.35	2.25	1.48	1.63
119	MD 100	1.60	1.00	3.50	1.30	1.74
120	MD 176	2.10	1.75	1.75	1.93	1.89
121	MD 648E	1.60	1.70	#N/A	1.65	#N/A
122	MD 173	2.10	1.45	2.25	1.78	1.87
124	MD 270 & RAMP 2	2.10	1.35	2.00	1.73	1.78
128	MD 100 WBR	1.60	1.00	3.50	1.30	1.74
131	MD 10 SBR	1.60	1.35	2.50	1.48	1.68
134	MD 3 BU	3.10	3.25	2.75	3.18	3.09
136	MD 170	1.60	1.10	2.25	1.35	1.53
140	IS 195 RAMP 'A'	1.60	1.00	2.50	1.30	1.54
143	MD 2	1.60	1.15	3.00	1.38	1.70
144	MD 695	2.10	1.35	3.50	1.73	2.08
146	MD 295	1.60	1.10	#N/A	1.35	#N/A
148	MD 648E	2.10	3.25	2.00	2.68	2.54
149	MD 295 NBR	1.60	1.15	3.50	1.38	1.80

Asset ID	Asset Name	Precipitation Changes_ "Damage"_ Scenario2	Precipitation Changes_ Vulnerability_ Scenario2	Sea Level Rise_ Exposure _Scenario1	Sea Level Rise_ Exposure _Scenario1	Sea Level Rise_ Sensitivity
1	MD 423	2.78	2.57	3.10	4.00	1.70
4	MD 256	1.83	1.81	1.30	1.30	1.35
5	MD 258	1.90	#N/A	1.00	1.00	1.85
6	MD 256	1.48	1.53	1.30	1.30	1.10
7	MD 258	1.40	#N/A	1.10	1.10	1.10
8	MD 258	2.45	2.36	2.00	2.00	1.70
10	MD 258	1.45	1.56	1.30	1.30	1.10
12	MD 4 EBR	2.15	2.42	1.00	2.80	2.10
13	MD 4 WB	2.15	2.42	1.00	2.80	2.10
15	MD 468	2.42	#N/A	1.10	1.10	1.95
17	MD 468	2.42	#N/A	2.00	2.00	1.95
19	MD 255	2.20	#N/A	1.10	1.10	2.10
21	MD 468	1.95	#N/A	1.10	1.10	1.20
22	MD 468	2.70	#N/A	1.10	1.10	1.85
25	MD 468	2.40	#N/A	2.00	2.00	1.60
26	MD 468	1.40	#N/A	1.10	1.10	1.25
27	MD 468	1.75	#N/A	1.10	1.10	1.45
29	MD 214	0.92	#N/A	1.10	1.10	1.25
30	MD 214	2.95	#N/A	1.10	1.10	2.70
31	MD 2	1.43	#N/A	1.20	1.20	1.20
34	MD 665 EB	1.40	#N/A	1.20	1.20	1.15
35	MD 665 WB	1.40	1.67	1.20	1.20	1.15
37	MD 181(SIXTH ST)	1.85	1.88	1.30	2.20	1.45
38	IS 595	1.95	2.36	1.30	1.30	1.95
39	MD 70	1.45	1.56	1.30	1.30	1.05
40	IS 595 & RAMPS	1.38	#N/A	1.10	1.10	1.20
41	MD 450	1.83	1.86	1.30	4.00	1.25
42	MD 450	2.30	2.29	1.30	2.20	2.10
43	MD 450	2.94	#N/A	2.90	2.90	2.74
44	MD 450	2.93	2.79	1.10	1.10	2.70
45	MD 450	2.94	#N/A	2.90	2.90	2.74
46	MD 450	2.94	#N/A	1.10	1.10	2.74
47	MD 3 SB	1.33	1.66	1.00	1.00	1.05
48	MD 450	2.65	#N/A	1.10	1.10	1.60
49	MD 450	2.46	#N/A	2.00	2.00	3.05
51	MD 450	1.49	#N/A	1.10	1.10	1.53
52	MD 450	1.97	#N/A	1.10	1.10	1.53

Asset ID	Asset Name	Precipitation Changes_ "Damage"_ Scenario2	Precipitation Changes_ Vulnerability_ Scenario2	Sea Level Rise_ Exposure _Scenario1	Sea Level Rise_ Exposure _Scenario1	Sea Level Rise_ Sensitivity
54	MD 450	2.18	#N/A	1.10	1.10	1.79
55	MD 450	2.63	#N/A	1.90	1.90	1.79
56	IS 595	1.45	1.86	1.30	1.30	1.10
57	MD 450	2.40	#N/A	2.00	2.00	1.60
58	MD 70	1.45	1.56	1.30	1.30	1.00
59	MD 436	1.45	1.56	1.30	1.30	1.00
60	MD 450	1.63	1.70	1.20	1.20	1.50
61	MD 3	2.40	#N/A	1.90	1.90	1.70
62	MD 3	1.89	#N/A	1.90	1.90	1.79
65	IS 97	1.48	1.88	1.10	1.10	1.25
66	US 50	1.65	2.02	1.20	1.20	1.60
67	MD 179	2.08	2.01	2.20	4.00	1.90
68	MD 908D	1.66	1.83	0.20	0.20	1.06
69	US 50	2.40	#N/A	1.10	1.10	1.60
72	MD 908C & RAMP A	1.92	#N/A	1.10	1.10	1.60
73	MD 3 NBR	1.45	#N/A	1.00	1.00	1.45
74	MD 3 SBR	1.35	#N/A	1.00	1.00	1.25
81	IS 97 SBR	1.60	1.98	1.10	1.10	1.05
84	MD 648AA	2.02	#N/A	1.20	1.20	1.53
85	MD 648H	2.18	2.14	1.10	1.10	1.80
86	MD 32	1.65	1.87	1.00	1.00	1.35
87	MD 32	1.30	1.59	1.00	1.00	1.00
88	MD 198 WB	2.38	2.35	1.00	1.00	1.65
92	MD 648H	1.71	#N/A	1.10	1.10	1.37
93	MD 10	1.35	1.53	1.10	1.10	1.15
94	MD 174	1.95	#N/A	1.00	1.00	1.45
95	MD 2	2.43	#N/A	1.90	1.90	1.90
96	MD 32	1.33	1.61	1.00	1.00	1.05
102	MD 100	1.40	1.82	1.10	1.10	1.10
104	MD 173	2.35	2.33	1.30	4.00	2.40
106	MD 2	1.73	1.98	1.10	1.10	1.40
108	MD 100 WBR	1.05	1.44	0.10	0.10	1.00
109	MD 100 EBR	1.30	1.69	1.00	1.00	1.00
110	MD 10 NBR	1.48	1.68	1.30	1.30	1.15
111	MD 10 SBR	1.48	1.68	1.30	1.30	1.05

Asset ID	Asset Name	Precipitation Changes_ "Damage"_ Scenario2	Precipitation Changes_ Vulnerability_ Scenario2	Sea Level Rise_ Exposure _Scenario1	Sea Level Rise_ Exposure _Scenario1	Sea Level Rise_ Sensitivity
112	MD 648E	1.73	1.78	1.30	1.30	1.65
113	MD 100 & RPS A & D	1.30	1.69	1.00	1.00	1.15
114	MD 100	1.30	#N/A	1.00	1.00	1.15
116	IS 97 & RAMP F(2)	1.30	#N/A	1.00	1.00	1.15
118	MD 173	1.48	1.63	1.30	1.30	1.20
119	MD 100	1.30	1.74	1.00	1.00	1.00
120	MD 176	1.93	1.89	1.00	1.00	1.40
121	MD 648E	1.65	#N/A	1.10	1.10	1.70
122	MD 173	1.78	1.87	1.20	1.20	1.25
124	MD 270 & RAMP 2	1.73	1.78	1.10	1.10	1.25
128	MD 100 WBR	1.30	1.74	1.00	1.00	1.05
131	MD 10 SBR	1.48	1.68	1.30	1.30	1.20
134	MD 3 BU	3.18	3.09	2.00	2.00	2.70
136	MD 170	1.35	1.53	1.00	1.00	1.25
140	IS 195 RAMP 'A'	1.30	1.54	1.00	1.00	1.00
143	MD 2	1.38	1.70	1.10	1.10	1.20
144	MD 695	1.73	2.08	1.10	1.10	1.40
146	MD 295	1.35	#N/A	1.00	1.00	1.25
148	MD 648E	2.68	2.54	1.10	1.10	3.00
149	MD 295 NBR	1.38	1.80	1.10	1.10	1.20

Asset ID	Asset Name	Sea Level Rise_ Adaptive Capacity	Sea Level Rise_ "Damage" _Scenario1	Sea Level Rise_ Vulnerability_ Scenario1	Sea Level Rise_ "Damage"_S cenario2	Sea Level Rise_ Vulnerability _ Scenario2	Storm Surge_ Exposure _Scenario1
1	MD 423	1.75	2.40	2.27	2.85	2.63	4.00
4	MD 256	1.75	1.33	1.41	1.33	1.41	2.40
5	MD 258	#N/A	1.43	#N/A	1.43	#N/A	1.00
6	MD 256	1.75	1.20	1.31	1.20	1.31	1.60
7	MD 258	#N/A	1.10	#N/A	1.10	#N/A	1.20
8	MD 258	2.00	1.85	1.88	1.85	1.88	2.00
10	MD 258	2.00	1.20	1.36	1.20	1.36	1.60
12	MD 4 EBR	3.50	1.55	1.94	2.45	2.66	1.00
13	MD 4 WB	3.50	1.55	1.94	2.45	2.66	1.00
15	MD 468	#N/A	1.52	#N/A	1.52	#N/A	1.20
17	MD 468	#N/A	1.97	#N/A	1.97	#N/A	2.00
19	MD 255	#N/A	1.60	#N/A	1.60	#N/A	1.20
21	MD 468	#N/A	1.15	#N/A	1.15	#N/A	1.20
22	MD 468	#N/A	1.48	#N/A	1.48	#N/A	1.20
25	MD 468	#N/A	1.80	#N/A	1.80	#N/A	2.00
26	MD 468	#N/A	1.18	#N/A	1.18	#N/A	1.20
27	MD 468	#N/A	1.28	#N/A	1.28	#N/A	1.20
29	MD 214	#N/A	1.18	#N/A	1.18	#N/A	1.20
30	MD 214	#N/A	1.90	#N/A	1.90	#N/A	1.20
31	MD 2	#N/A	1.20	#N/A	1.20	#N/A	1.40
34	MD 665 EB	#N/A	1.18	#N/A	1.18	#N/A	1.40
35	MD 665 WB	2.75	1.18	1.49	1.18	1.49	1.40
37	181(SIXTH	2.00	1.38	1.50	1.83	1.86	2.40
38	IS 595	4.00	1.63	2.10	1.63	2.10	1.60
39	MD 70	2.00	1.18	1.34	1.18	1.34	1.60
40	IS 595 &	#N/A	1.15	#N/A	1.15	#N/A	1.20
41	MD 450	2.00	1.28	1.42	2.63	2.50	4.00
42	MD 450	2.25	1.70	1.81	2.15	2.17	2.40
43	MD 450	#N/A	2.82	#N/A	2.82	#N/A	2.00
44	MD 450	2.25	1.90	1.97	1.90	1.97	1.20
45	MD 450	#N/A	2.82	#N/A	2.82	#N/A	2.80
46	MD 450	#N/A	1.92	#N/A	1.92	#N/A	1.20
47	MD 3 SB	3.00	1.03	1.42	1.03	1.42	1.00
48	MD 450	#N/A	1.35	#N/A	1.35	#N/A	1.20
49	MD 450	#N/A	2.53	#N/A	2.53	#N/A	2.00
51	MD 450	#N/A	1.31	#N/A	1.31	#N/A	1.20
52	MD 450	#N/A	1.31	#N/A	1.31	#N/A	1.20

Asset ID	Asset Name	Sea Level Rise_ Adaptive Capacity	Sea Level Rise_ "Damage" _Scenario1	Sea Level Rise_ Vulnerability_ Scenario1	Sea Level Rise_ "Damage"_S cenario2	Sea Level Rise_ Vulnerability _ Scenario2	Storm Surge_ Exposure _Scenario1
54	MD 450	#N/A	1.44	#N/A	1.44	#N/A	1.20
55	MD 450	#N/A	1.84	#N/A	1.84	#N/A	1.80
56	IS 595	3.50	1.20	1.66	1.20	1.66	1.60
57	MD 450	#N/A	1.80	#N/A	1.80	#N/A	2.00
58	MD 70	2.00	1.15	1.32	1.15	1.32	1.60
59	MD 436	2.00	1.15	1.32	1.15	1.32	1.60
60	MD 450	2.00	1.35	1.48	1.35	1.48	1.40
61	MD 3	#N/A	1.80	#N/A	1.80	#N/A	1.80
62	MD 3	#N/A	1.84	#N/A	1.84	#N/A	1.80
65	IS 97	3.50	1.18	1.64	1.18	1.64	1.20
66	US 50	3.50	1.40	1.82	1.40	1.82	1.40
67	MD 179	1.75	2.05	1.99	2.95	2.71	4.00
68	MD 908D	2.50	0.63	1.01	0.63	1.01	2.80
69	US 50	#N/A	1.35	#N/A	1.35	#N/A	1.20
72	MD 908C & RAMP A	#N/A	1.35	#N/A	1.35	#N/A	1.20
73	MD 3 NBR	#N/A	1.23	#N/A	1.23	#N/A	1.00
74	MD 3 SBR	#N/A	1.13	#N/A	1.13	#N/A	1.00
81	IS 97 SBR	3.50	1.08	1.56	1.08	1.56	1.20
84	MD 648AA	#N/A	1.36	#N/A	1.36	#N/A	2.20
85	MD 648H	2.00	1.45	1.56	1.45	1.56	1.20
86	MD 32	2.75	1.18	1.49	1.18	1.49	1.00
87	MD 32	2.75	1.00	1.35	1.00	1.35	1.00
88	MD 198 WB	2.25	1.33	1.51	1.33	1.51	1.00
92	MD 648H	#N/A	1.23	#N/A	1.23	#N/A	1.20
93	MD 10	2.25	1.13	1.35	1.13	1.35	1.20
94	MD 174	#N/A	1.23	#N/A	1.23	#N/A	1.00
95	MD 2	#N/A	1.90	#N/A	1.90	#N/A	1.80
96	MD 32	2.75	1.03	1.37	1.03	1.37	1.00
102	MD 100	3.50	1.10	1.58	1.10	1.58	1.20
104	MD 173	2.25	1.85	1.93	3.20	3.01	4.00
106	MD 2	3.00	1.25	1.60	1.25	1.60	1.20
108	MD 100	3.00	0.55	1.04	0.55	1.04	2.60
109	MD 100 EBR	3.25	1.00	1.45	1.00	1.45	1.00
110	MD 10 NBR	2.50	1.23	1.48	1.23	1.48	1.60
111	MD 10 SBR	2.50	1.18	1.44	1.18	1.44	1.60

Asset ID	Asset Name	Sea Level Rise_ Adaptive Capacity	Sea Level Rise_ "Damage" _Scenario1	Sea Level Rise_ Vulnerability_ Scenario1	Sea Level Rise_ "Damage"_S cenario2	Sea Level Rise_ Vulnerability _ Scenario2	Storm Surge_ Exposure _Scenario1
112	MD 648E	2.00	1.48	1.58	1.48	1.58	1.60
113	MD 100 & RPS A & D	3.25	1.08	1.51	1.08	1.51	1.00
114	MD 100	#N/A	1.08	#N/A	1.08	#N/A	1.00
116	IS 97 & RAMP F(2)	#N/A	1.08	#N/A	1.08	#N/A	1.00
118	MD 173	2.25	1.25	1.45	1.25	1.45	1.60
119	MD 100	3.50	1.00	1.50	1.00	1.50	1.00
120	MD 176	1.75	1.20	1.31	1.20	1.31	1.00
121	MD 648E	#N/A	1.40	#N/A	1.40	#N/A	1.20
122	MD 173	2.25	1.23	1.43	1.23	1.43	3.00
124	MD 270 & RAMP 2	2.00	1.18	1.34	1.18	1.34	1.20
128	WBR	3.50	1.03	1.52	1.03	1.52	1.00
131	MD 10 SBR	2.50	1.25	1.50	1.25	1.50	1.60
134	MD 3 BU	2.75	2.35	2.43	2.35	2.43	3.60
136	MD 170	2.25	1.13	1.35	1.13	1.35	1.00
140	'A'	2.50	1.00	1.30	1.00	1.30	1.00
143	MD 2	3.00	1.15	1.52	1.15	1.52	1.20
144	MD 695	3.50	1.25	1.70	1.25	1.70	1.20
146	MD 295	#N/A	1.13	#N/A	1.13	#N/A	1.00
148	MD 648E	2.00	2.05	2.04	2.05	2.04	1.20
149	MD 295 NBR	3.50	1.15	1.62	1.15	1.62	1.20

Asset ID	Asset Name	Storm Surge_ Exposure _Scenario1	Storm Surge_ Sensitivity	Storm Surge_ Adaptive Capacity	Storm Surge_ "Damage"_ Scenario1	Storm Surge_ Vulnerability_ Scenario1	Storm Surge_ "Damage"_ Scenario2
1	MD 423	4.00	1.70	1.75	2.85	2.63	2.85
4	MD 256	2.40	1.35	1.75	1.88	1.85	1.88
5	MD 258	1.00	1.85	#N/A	1.43	#N/A	1.43
6	MD 256	1.60	1.10	1.75	1.35	1.43	1.35
7	MD 258	1.20	1.10	#N/A	1.15	#N/A	1.15
8	MD 258	2.00	1.70	2.00	1.85	1.88	1.85
10	MD 258	1.60	1.10	2.00	1.35	1.48	1.35
12	MD 4 EBR	1.00	2.10	3.50	1.55	1.94	1.55
13	MD 4 WB	1.00	2.10	3.50	1.55	1.94	1.55
15	MD 468	3.60	1.95	#N/A	1.57	#N/A	2.77
17	MD 468	3.60	1.95	#N/A	1.97	#N/A	2.77
19	MD 255	1.20	2.10	#N/A	1.65	#N/A	1.65
21	MD 468	2.80	1.20	#N/A	1.20	#N/A	2.00
22	MD 468	2.80	1.85	#N/A	1.53	#N/A	2.33
25	MD 468	2.00	1.60	#N/A	1.80	#N/A	1.80
26	MD 468	1.20	1.25	#N/A	1.23	#N/A	1.23
27	MD 468	1.20	1.45	#N/A	1.33	#N/A	1.33
29	MD 214	1.20	1.25	#N/A	1.23	#N/A	1.23
30	MD 214	3.60	2.70	#N/A	1.95	#N/A	3.15
31	MD 2	1.40	1.20	#N/A	1.30	#N/A	1.30
34	MD 665 EB	1.40	1.15	#N/A	1.28	#N/A	1.28
35	MD 665 WB	1.40	1.15	2.75	1.28	1.57	1.28
37	181(SIXTH	2.40	1.45	2.00	1.93	1.94	1.93
38	IS 595	1.60	1.95	4.00	1.78	2.22	1.78
39	MD 70	1.60	1.05	2.00	1.33	1.46	1.33
40	IS 595 &	1.20	1.20	#N/A	1.20	#N/A	1.20
41	MD 450	4.00	1.25	2.00	2.63	2.50	2.63
42	MD 450	2.40	2.10	2.25	2.25	2.25	2.25
43	MD 450	2.00	2.74	#N/A	2.37	#N/A	2.37
44	MD 450	1.20	2.70	2.25	1.95	2.01	1.95
45	MD 450	2.80	2.74	#N/A	2.77	#N/A	2.77
46	MD 450	1.20	2.74	#N/A	1.97	#N/A	1.97
47	MD 3 SB	1.00	1.05	3.00	1.03	1.42	1.03
48	MD 450	1.20	1.60	#N/A	1.40	#N/A	1.40
49	MD 450	2.00	3.05	#N/A	2.53	#N/A	2.53
51	MD 450	1.20	1.53	#N/A	1.36	#N/A	1.36
52	MD 450	1.20	1.53	#N/A	1.36	#N/A	1.36

Asset ID	Asset Name	Storm Surge_ _Exposure _Scenario1	Storm Surge_ Sensitivity	Storm Surge_ Adaptive Capacity	Storm Surge_ "Damage"_ Scenario1	Storm Surge_ Vulnerability_ Scenario1	Storm Surge_ "Damage"_ Scenario2
54	MD 450	1.20	1.79	#N/A	1.49	#N/A	1.49
55	MD 450	1.80	1.79	#N/A	1.79	#N/A	1.79
56	IS 595	1.60	1.10	3.50	1.35	1.78	1.35
57	MD 450	2.00	1.60	#N/A	1.80	#N/A	1.80
58	MD 70	1.60	1.00	2.00	1.30	1.44	1.30
59	MD 436	1.60	1.00	2.00	1.30	1.44	1.30
60	MD 450	1.40	1.50	2.00	1.45	1.56	1.45
61	MD 3	1.80	1.70	#N/A	1.75	#N/A	1.75
62	MD 3	1.80	1.79	#N/A	1.79	#N/A	1.79
65	IS 97	1.20	1.25	3.50	1.23	1.68	1.23
66	US 50	1.40	1.60	3.50	1.50	1.90	1.50
67	MD 179	4.00	1.90	1.75	2.95	2.71	2.95
68	MD 908D	2.80	1.06	2.50	1.93	2.05	1.93
69	US 50	1.20	1.60	#N/A	1.40	#N/A	1.40
72	MD 908C & RAMP A	1.20	1.60	#N/A	1.40	#N/A	1.40
73	MD 3 NBR	1.00	1.45	#N/A	1.23	#N/A	1.23
74	MD 3 SBR	1.00	1.25	#N/A	1.13	#N/A	1.13
81	IS 97 SBR	1.20	1.05	3.50	1.13	1.60	1.13
84	MD 648AA	3.00	1.53	#N/A	1.86	#N/A	2.26
85	MD 648H	1.20	1.80	2.00	1.50	1.60	1.50
86	MD 32	1.00	1.35	2.75	1.18	1.49	1.18
87	MD 32	1.00	1.00	2.75	1.00	1.35	1.00
88	MD 198 WB	1.00	1.65	2.25	1.33	1.51	1.33
92	MD 648H	1.20	1.37	#N/A	1.28	#N/A	1.28
93	MD 10	1.20	1.15	2.25	1.18	1.39	1.18
94	MD 174	1.00	1.45	#N/A	1.23	#N/A	1.23
95	MD 2	1.80	1.90	#N/A	1.85	#N/A	1.85
96	MD 32	1.00	1.05	2.75	1.03	1.37	1.03
102	MD 100	1.20	1.10	3.50	1.15	1.62	1.15
104	MD 173	4.00	1.95	2.25	2.98	2.83	2.98
106	MD 2	2.00	1.40	3.00	1.30	1.64	1.70
108	MD 100	2.60	1.00	3.00	1.80	2.04	1.80
109	MD 100	1.00	1.00	3.25	1.00	1.45	1.00
110	MD 10 NBR	1.60	1.15	2.50	1.38	1.60	1.38
111	MD 10 SBR	1.60	1.05	2.50	1.33	1.56	1.33

Asset ID	Asset Name	Storm Surge_ _Scenario1 Exposure	Storm Surge_ Sensitivity	Storm Surge_ Adaptive Capacity	Storm Surge_ "Damage"_ Scenario1	Storm Surge_ Vulnerability_ Scenario1	Storm Surge_ "Damage"_ Scenario2
112	MD 648E	1.60	1.65	2.00	1.63	1.70	1.63
113	MD 100 & RPS A & D	1.00	1.15	3.25	1.08	1.51	1.08
114	MD 100	1.00	1.15	#N/A	1.08	#N/A	1.08
116	IS 97 & RAMP F(2)	1.00	1.15	#N/A	1.08	#N/A	1.08
118	MD 173	1.60	1.20	2.25	1.40	1.57	1.40
119	MD 100	1.00	1.00	3.50	1.00	1.50	1.00
120	MD 176	1.00	1.40	1.75	1.20	1.31	1.20
121	MD 648E	1.20	1.70	#N/A	1.45	#N/A	1.45
122	MD 173	3.00	1.25	2.25	2.13	2.15	2.13
124	MD 270 & RAMP 2	1.20	1.25	2.00	1.23	1.38	1.23
128	WBR	1.00	1.05	3.50	1.03	1.52	1.03
131	MD 10 SBR	1.60	1.20	2.50	1.40	1.62	1.40
134	MD 3 BU	3.60	2.25	2.75	2.93	2.89	2.93
136	MD 170	1.00	1.25	2.25	1.13	1.35	1.13
140	RAMP 'A'	1.00	1.00	2.50	1.00	1.30	1.00
143	MD 2	1.20	1.20	3.00	1.20	1.56	1.20
144	MD 695	1.20	1.40	3.50	1.30	1.74	1.30
146	MD 295	1.00	1.25	#N/A	1.13	#N/A	1.13
148	MD 648E	1.20	3.00	2.00	2.10	2.08	2.10
149	MD 295	1.20	1.20	3.50	1.20	1.66	1.20

Asset ID	Asset Name	Storm Surge_ Vulnerability_S cenario2	Latitude	Longitude
1	MD 423	2.63	38.7481	-76.5575
4	MD 256	1.85	38.7781	-76.5632
5	MD 258	#N/A	38.7821	-76.6331
6	MD 256	1.43	38.7825	-76.5593
7	MD 258	#N/A	38.7851	-76.5994
8	MD 258	1.88	38.7911	-76.5794
10	MD 258	1.48	38.7935	-76.5575
12	MD 4 EBR	1.94	38.8112	-76.7122
13	MD 4 WB	1.94	38.8112	-76.7122
15	MD 468	#N/A	38.8386	-76.5615
17	MD 468	#N/A	38.8469	-76.5584
19	MD 255	#N/A	38.853	-76.5669
21	MD 468	#N/A	38.8781	-76.5647
22	MD 468	#N/A	38.8799	-76.5659
25	MD 468	#N/A	38.8892	-76.569
26	MD 468	#N/A	38.8921	-76.5672
27	MD 468	#N/A	38.8965	-76.5635
29	MD 214	#N/A	38.918	-76.5528
30	MD 214	#N/A	38.9276	-76.5893
31	MD 2	#N/A	38.9513	-76.555
34	MD 665 EB	#N/A	38.9713	-76.5379
35	MD 665 WB	1.57	38.9715	-76.5371
37	181(SIXTH	1.94	38.9727	-76.4855
38	IS 595	2.22	38.9814	-76.6049
39	MD 70	1.46	38.9832	-76.4971
40	IS 595 &	#N/A	38.9839	-76.5681
41	MD 450	2.50	38.9851	-76.4944
42	MD 450	2.25	38.9862	-76.6088
43	MD 450	#N/A	38.9867	-76.5695
44	MD 450	2.01	38.9871	-76.6227
45	MD 450	#N/A	38.9874	-76.5709
46	MD 450	#N/A	38.9884	-76.5729
47	MD 3 SB	1.42	38.9893	-76.7054
48	MD 450	#N/A	38.989	-76.5997
49	MD 450	#N/A	38.9891	-76.6008
51	MD 450	#N/A	38.9893	-76.6025
52	MD 450	#N/A	38.9893	-76.6052

Asset ID	Asset Name	Storm Surge_ Vulnerability_Scenario2	Latitude	Longitude
54	MD 450	#N/A	38.9895	-76.5775
55	MD 450	#N/A	38.9899	-76.6502
56	IS 595	1.78	38.9898	-76.5254
57	MD 450	#N/A	38.9907	-76.6368
58	MD 70	1.44	38.9913	-76.5093
59	MD 436	1.44	38.9927	-76.5079
60	MD 450	1.56	38.993	-76.4873
61	MD 3	#N/A	38.9965	-76.7011
62	MD 3	#N/A	39.0004	-76.7002
65	IS 97	1.68	39.0051	-76.6008
66	US 50	1.90	39.006	-76.5041
67	MD 179	2.71	39.0148	-76.4717
68	MD 908D	2.05	39.017	-76.4097
69	US 50	#N/A	39.0188	-76.4812
72	MD 908C & RAMP A	#N/A	39.0256	-76.4472
73	MD 3 NBR	#N/A	39.0285	-76.6866
74	MD 3 SBR	#N/A	39.0289	-76.6875
81	IS 97 SBR	1.60	39.0814	-76.6267
84	MD 648AA	#N/A	39.0863	-76.5493
85	MD 648H	1.60	39.0871	-76.552
86	MD 32	1.49	39.0881	-76.7385
87	MD 32	1.35	39.0965	-76.6894
88	MD 198 WB	1.51	39.0972	-76.8351
92	MD 648H	#N/A	39.1148	-76.5592
93	MD 10	1.39	39.1177	-76.5767
94	MD 174	#N/A	39.1196	-76.714
95	MD 2	#N/A	39.1193	-76.5834
96	MD 32	1.37	39.1199	-76.7824
102	MD 100	1.62	39.1378	-76.6113
104	MD 173	2.83	39.1386	-76.5235
106	MD 2	1.96	39.1449	-76.6065
108	MD 100	2.04	39.1477	-76.6967
109	MD 100 EBR	1.45	39.148	-76.7039
110	MD 10 NBR	1.60	39.1517	-76.5994
111	MD 10 SBR	1.56	39.152	-76.6

Asset ID	Asset Name	Storm Surge_ Vulnerability_Scenario2	Latitude	Longitude
112	MD 648E	1.70	39.1551	-76.5988
113	MD 100 & RPS A & D	1.51	39.1569	-76.6532
114	MD 100	#N/A	39.1571	-76.6537
116	IS 97 & RAMP F(2)	#N/A	39.1595	-76.6449
118	MD 173	1.57	39.1632	-76.5252
119	MD 100	1.50	39.1656	-76.725
120	MD 176	1.31	39.1669	-76.7236
121	MD 648E	#N/A	39.1698	-76.63
122	MD 173	2.15	39.1724	-76.5364
124	MD 270 & RAMP 2	1.38	39.1766	-76.6057
128	WBR	1.52	39.1792	-76.7406
131	MD 10 SBR	1.62	39.1826	-76.605
134	MD 3 BU	2.89	39.1831	-76.6144
136	MD 170	1.35	39.1874	-76.6856
140	'A'	1.30	39.1986	-76.697
143	MD 2	1.56	39.2051	-76.614
144	MD 695	1.74	39.207	-76.6058
146	MD 295	#N/A	39.2157	-76.6688
148	MD 648E	2.08	39.2256	-76.6414
149	MD 295 NBR	1.66	39.2289	-76.6502

Appendix C – Analytical Comparison of TP-40 Vs Atlas 14

Analytical Comparison of TP-40 Vs Atlas 14

For more than a generation, the standard method for performing hydrological computations has been either the *United States Soil Conservation Service (SCS) Hydrograph Method* (TR-55 or Tr-20) for culverts, stormwater management facilities and open channels or the *Rational Method* for closed storm drain systems. The rainfall data which was utilized in each of the three methods was taken from the *National Weather Service (NWS) Technical Paper 40* (TP-40). Utilizing TP-40 data, SCS developed 4 synthetic 24-hour rainfall distributions (I, Ia, II and III). The State of Maryland falls within the region which utilizes Type II rainfall distribution.

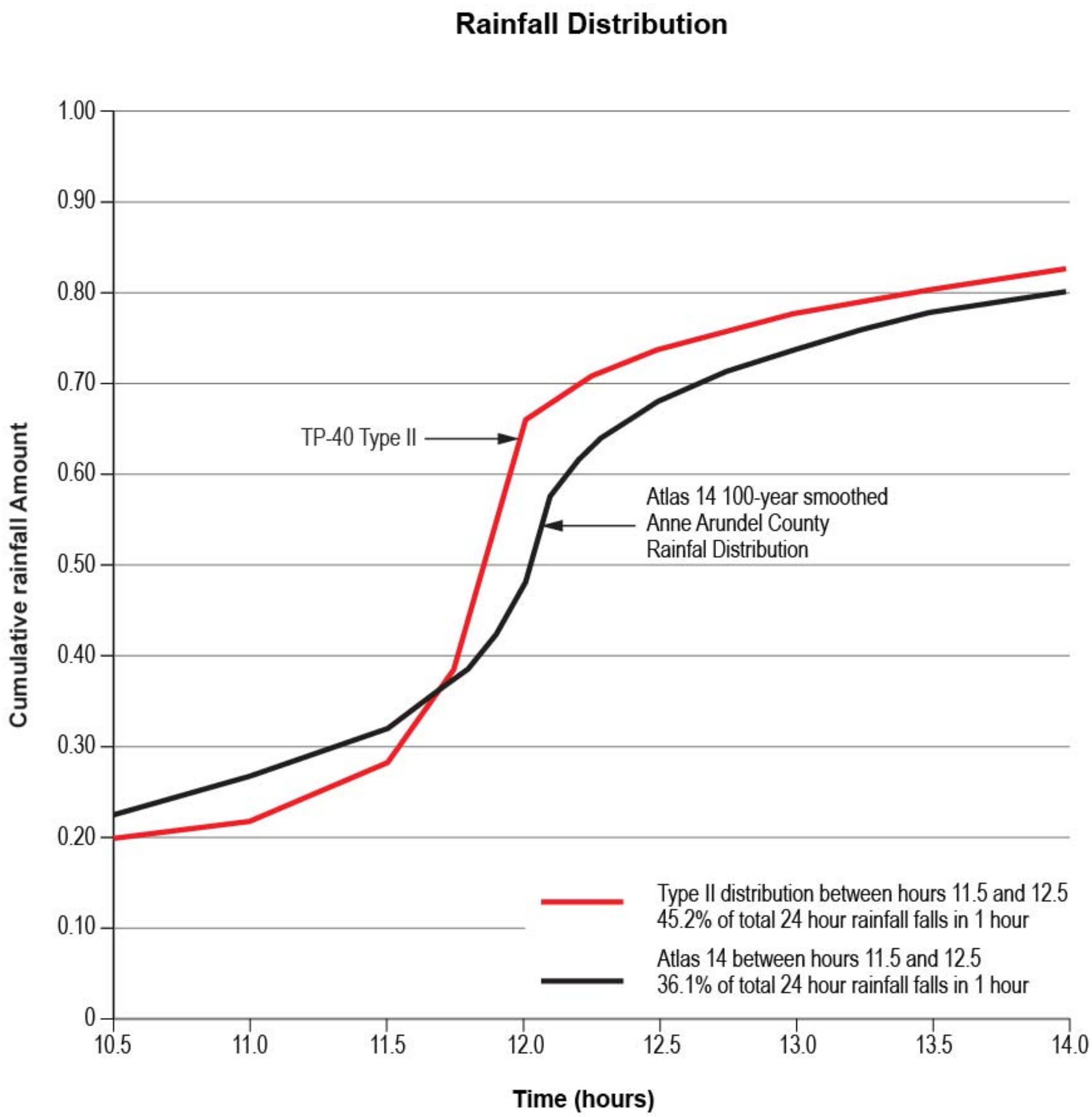
NOAA Atlas 14 Precipitation Frequency Atlas of the United States, Volume 2, Version 3.0, covers the State of Maryland and was published in 2004 (revised 2006). The Atlas supersedes precipitation frequency estimates contained in TP-40 for durations from 30 minutes to 24 hours, and for return periods from 1 to 100 years.

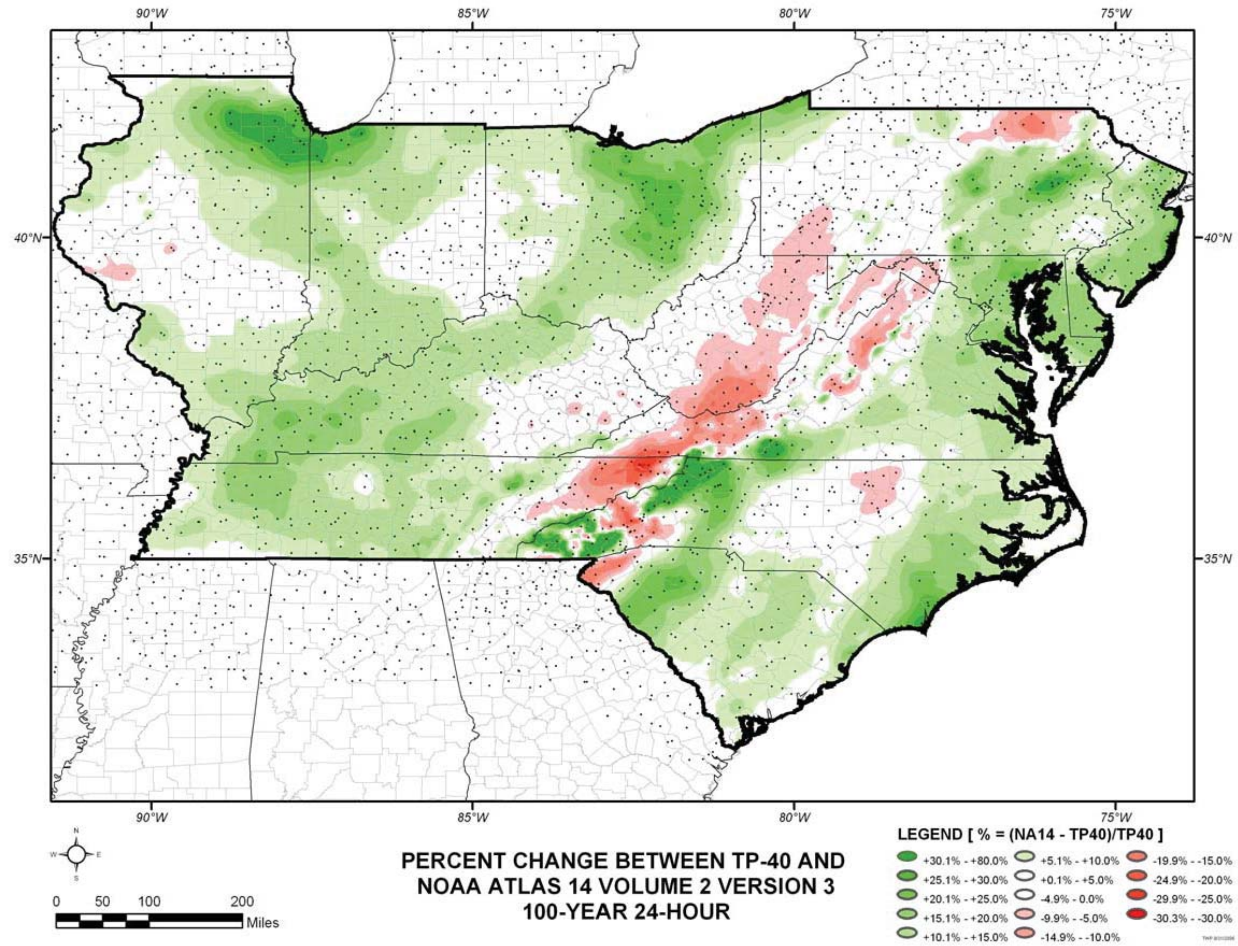
Comparisons of TP-40 and Atlas 14 24-hour rainfall depths in Maryland indicate that for most of the counties, the rainfall depths for the 1 and 2-year storms remain unchanged (within 0.1 inch) or decrease slightly. The majority of the counties have decreased rainfall depths for the 10-year storm and significant increases in the rainfall depths for the 100 year storm.

- 1-2-year 24-hour rainfall depths are nearly the same (within 0.1”). Most Maryland Counties show a slight decrease.
- 10-year 24-hour rainfall depths decrease for nearly all of the Maryland counties.
- 100-year 24-hour rainfall depths increase for all Maryland counties except Allegany and Washington.
- Rainfall distribution tables have been revised and indicate less intensity during peak of storm, In Anne Arundel County the Type II distribution indicates 45% of the total rainfall within the most intense 1 hour period. Atlas 14 indicates only 36% of the total rainfall within the most intense 10hour period.
- Small, flashy watersheds will tend to have smaller peak discharges when utilizing Atlas 14.
- Large watershed with significant storage and long times of concentration, may experience increases in peak discharges for the 100-year storm.
- Increases in rainfall depth will result in increases in runoff volume, even if peak discharges are lower.
- Rational Method rainfall intensities for the 10-year and 25-year storms are lower when using Atlas 14.

Atlas 14 also reviews the rainfall distribution tables for each county. This study did not compare each of the counties; however those that were compared indicated that the steepest portion of the rainfall distribution curve (most intense period of rainfall) was flatter for Atlas 14.

As part of this study we analyzed 6 scenarios (3 each in Anne Arundel and Somerset counties). The scenarios were for small (60 acre), medium (200 acre) and large (4000 acre) watershed. In addition, the small and medium sized watersheds were modeled to account for SWM storage. . Generally peak discharges are expected to be lower for all watersheds except for the 100-year storm for large watersheds and where significant SWM features are in place.




90°W
85°W
80°W
75°W
40°N
35°N
N
W
E
S
0 50 100 200
Miles
PERCENT CHANGE BETWEEN TP-40 AND
NOAA ATLAS 14 VOLUME 2 VERSION 3
100-YEAR 24-HOUR
LEGEND [% = (NA14 - TP40)/TP40]
+30.1% - +80.0%
+25.1% - +30.0%
+20.1% - +25.0%
+15.1% - +20.0%
+10.1% - +15.0%
+5.1% - +10.0%
+0.1% - +5.0%
-4.9% - 0.0%
-9.9% - -5.0%
-14.9% - -10.0%
-19.9% - -15.0%
-24.9% - -20.0%
-29.9% - -25.0%
-30.3% - -30.0%

			1-year (cfs)	2-year (cfs)	100-year (cfs)	100-year (cfs)
Scenario 1	60 acre in Anne Arundel County	TP-40	55.4	86.2	198.2	339.8
		Atlas 14	49.9	75.8	153.5	278.2
			90%	88%	77%	82%
Scenario 2	200 acres in Anne Arundel County	TP-40	79.1	146.9	421.3	792.4
		Atlas 14	67.7	124.1	316.1	670.1
			86%	84%	75%	85%
Scenario 3	60 acres in Somerset County	TP-40	35.2	57.8	153.3	282.6
		Atlas 14	26.1	45.7	107.8	219.2
			74%	79%	70%	78%
Scenario 4	200 acres in Somerset County	TP-40	35.8	72.7	258.8	536.9
		Atlas 14	26.1	57.1	184.4	456.5
			73%	79%	71%	85%
Scenario 5	4000 acres in Anne Arundel County	TP-40	664	1234	3642	6986
		Atlas 14	636	1160	3099	7042
			96%	94%	85%	101%
Scenario 6	4000 acres in Somerset County	TP-40	301	572	1957	4089
		Atlas 14	254	504	1584	4209
			84%	88%	81%	103%

			1-year (cfs)	2-year (cfs)	100-year (cfs)	100-year (cfs)
Scenario 1	60 acre w/storage in Anne Arundel County	TP-40	47.8	75.1	155.8	222.4
		Atlas 14	42.2	64.8	133.2	193.3
			88%	86%	85%	87%
Scenario 2	200 acres w/storage in Anne Arundel County	TP-40	69.7	130.8	264.2	360.2
		Atlas 14	60.8	111.9	223.3	349.7
			87%	86%	85%	97%
Scenario 3	60 acres w/storage in Somerset County	TP-40	28.9	47.9	109.2	166.3
		Atlas 14	21.9	38.5	92.3	144
			76%	80%	85%	87%
Scenario 4	200 acres w/ storage in Somerset County	TP-40	32.8	66.2	172	245.8
		Atlas 14	24.2	52.8	137.9	239.2
			74%	80%	80%	97%

Supporting Data

C:\Users\ghayes\Desktop\Rand TR20 Project\TP40\Scenario1.inp

```
WinTR-20: Version 1.11                  0         0          1.         0
Scenario 1

SUB-AREA:
          Watershed 1                  .094      75.         .24     60Ac Anne Arundel

STREAM REACH:
          1          outlet             Cul       1300.

STORM ANALYSIS:
          1 year               0.       2.7       Type II   2
          2 year               0.       3.3       Type II   2
          10 year              0.       5.2       Type II   2
          100 year             0.       7.4       Type II   2

STRUCTURE RATING:
          Cul        300.
                     300.      0.       0.
                     302.      144.     1.
                     304.      250.     4.
                     306.      323.     8.
                     308.      382.     16.
                     310.      433.     37.

GLOBAL OUTPUT:
                               .1       YNNNN     NNNNNN
```

WinTR-20 Printed Page File   End of Input Data List

Scenario 1

Name of printed page file:
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STORM 1 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	0.094		0.767		12.06	55.4	589.06
OUTLET	0.094		0.765		12.12	47.8	508.87

STORM 2 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	0.094		1.157		12.05	86.2	916.55
OUTLET	0.094		1.154		12.11	75.1	798.99

STORM 10 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	0.094		2.602		12.04	198.2	2108.56
OUTLET	0.094		2.600		12.13	155.8	1657.58

STORM 100 year

Area or Reach	Drainage Area	Rain Gage ID or	Runoff Amount	Peak Flow Elevation	Peak Flow Time	Peak Flow Rate	Peak Flow Rate

Area or Reach Identifier	Drainage Area (sq mi)	Alternate	Peak Flow by Storm 1 year (cfs)	2 year (cfs)	10 year (cfs)	100 year (cfs)	(cfs)
Watershed	0.094		55.4	86.2	198.2	339.8	
1	0.094		55.4	86.2	198.2	339.8	
DOWNSTREAM			47.8	75.1	155.8	222.4	
OUTLET	0.094		47.8	75.1	155.8	222.4	

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WinTR-20: Version 1.11                  0          0                   0
NOAA Atlas 14 Smoothed Precipitation tables and values (inches) - Scenario 1
State, Maryland         Station, Anne Arundel

SUB-AREA:
          Watershed 1                    .094       75.         .24    60Ac Anne Arundel

STREAM REACH:
          1         outlet               Cul        1300.


STORM ANALYSIS:
          1_yr_sm                         2.64      1_yr_sm    2           3.20
          2_yr_sm                         3.20      2_yr_sm    2
          5_yr_sm                         4.13      5_yr_sm    2
          10_yr_sm                        4.94      10_yr_sm   2
          25_yr_sm                        6.19      25_yr_sm   2
          50_yr_sm                        7.29      50_yr_sm   2
          100_yr_sm                       8.53      100_yr_sm  2
          200_yr_sm                       9.94      200_yr_sm  2
          500_yr_sm                      12.10      500_yr_sm  2


STRUCTURE RATING:
          Cul       300.
                    300.      0.         0.
                    302.      144.       1.
                    304.      250.       4.
                    306.      323.       8.
                    308.      382.       16.
                    310.      433.       37.


RAINFALL DISTRIBUTION:
          1_yr_sm             0.1
                         0.0  0.000440   0.000903  0.0014    0.0019
                    0.0024    0.0030     0.0035    0.0041    0.0048
                    0.0054    0.0061     0.0068    0.0075    0.0082
                    0.0089    0.0097     0.0105    0.0113    0.0122
                    0.0130    0.0139     0.0148    0.0157    0.0167
                    0.0177    0.0187     0.0197    0.0207    0.0218
                    0.0229    0.0240     0.0251    0.0263    0.0274
                    0.0286    0.0298     0.0311    0.0323    0.0336
                    0.0349    0.0363     0.0376    0.0390    0.0404
                    0.0418    0.0432     0.0447    0.0462    0.0477
                    0.0492    0.0508     0.0524    0.0539    0.0556
                    0.0572    0.0589     0.0605    0.0623    0.0640
                    0.0657    0.0675     0.0693    0.0711    0.0730
                    0.0748    0.0767     0.0786    0.0805    0.0825
                    0.0845    0.0865     0.0885    0.0905    0.0926
                    0.0947    0.0968     0.0989    0.1010    0.1032
                    0.1054    0.1076     0.1099    0.1121    0.1144
                    0.1167    0.1191     0.1214    0.1238    0.1262
                    0.1286    0.1322     0.1358    0.1395    0.1432
                    0.1470    0.1508     0.1547    0.1586    0.1625
                    0.1665    0.1706     0.1747    0.1788    0.1830
                    0.1873    0.1946     0.2019    0.2092    0.2165
                    0.2238    0.2344     0.2449    0.2554    0.2660
                    0.2765    0.2964     0.3164    0.3440    0.3862
                    0.4664    0.6138     0.6560    0.6836    0.7036
                    0.7235    0.7340     0.7446    0.7551    0.7656
                    0.7762    0.7835     0.7908    0.7981    0.8054
                    0.8127    0.8170     0.8212    0.8253    0.8294
                    0.8335    0.8375     0.8414    0.8453    0.8492
                    0.8530    0.8568     0.8605    0.8642    0.8678
                    0.8714    0.8738     0.8762    0.8786    0.8809
                    0.8833    0.8856     0.8879    0.8901    0.8924
                    0.8946    0.8968     0.8990    0.9011    0.9032
                    0.9053    0.9074     0.9095    0.9115    0.9135
                    0.9155    0.9175     0.9195    0.9214    0.9233
                    0.9252    0.9270     0.9289    0.9307    0.9325
                    0.9343    0.9360     0.9377    0.9395    0.9411
                    0.9428    0.9444     0.9461    0.9476    0.9492
                    0.9508    0.9523     0.9538    0.9553    0.9568
```

...\Desktop\Rand TR20 Project\TP40\Scenario2.inp

WinTR-20: Version 1.11	0	0	1.	0
Scenario 2				

SUB-AREA:

Watershed 1	.313	68.	.36	200 Ac Anne Arundel

STREAM REACH:

1	outlet	Cul	3100.

STORM ANALYSIS:

1 year	0.	2.7	Type II	2
2 year	0.	3.3	Type II	2
10 year	0.	5.2	Type II	2
100 year	0.	7.4	Type II	2

STRUCTURE RATING:

Cul	300.		
	300.	0.	0.
	302.	144.	1.
	304.	250.	4.
	306.	323.	8.
	308.	382.	16.
	310.	433.	37.

GLOBAL OUTPUT:

.1	YNNNN	NNNNNN

WinTR-20 Printed Page File End of Input Data List

Scenario 2

Name of printed page file:
C:\Users\ghayes\Desktop\Rand TR20 Project\TP40\Scenario2.out

STORM 1 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Time (hr)	Rate (cfs)	Rate (csm)
Watershed	0.313		0.478		12.14	79.1	252.69
OUTLET	0.313		0.477		12.23	69.7	222.77

STORM 2 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Time (hr)	Rate (cfs)	Rate (csm)
Watershed	0.313		0.787		12.12	146.9	469.36
OUTLET	0.313		0.786		12.21	130.8	417.83

STORM 10 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Time (hr)	Rate (cfs)	Rate (csm)
Watershed	0.313		2.022		12.11	421.3	1346.02
OUTLET	0.313		2.021		12.30	264.2	843.95

STORM 100 year

Area or Reach	Drainage Area	Rain Gage ID or	Runoff Amount	Peak Flow Elevation	Time	Rate	Rate

Area or Reach Identifier	Drainage Area (sq mi)	Alternate	Peak Flow by Storm 1 year (cfs)	2 year (cfs)	10 year (cfs)	100 year (cfs)	(cfs)
Watershed	0.313		79.1	146.9	421.3	792.4	
1	0.313		79.1	146.9	421.3	792.4	
DOWNSTREAM			69.7	130.8	264.2	360.2	
OUTLET	0.313		69.7	130.8	264.2	360.2	

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WinTR-20: Version 1.11                   0          0                   0
NOAA Atlas 14 Smoothed Precipitation tables and values (inches) - Scenario 2
State, Maryland        Station, Anne Arundel

SUB-AREA:
         Watershed 1                     .313       68.        .36      200 Ac Anne Arundel

STREAM REACH:
         1         outlet                Cul        3100.


STORM ANALYSIS:
         1_yr_sm                          2.64      1_yr_sm   2           3.20
         2_yr_sm                          3.20      2_yr_sm   2
         5_yr_sm                          4.13      5_yr_sm   2
         10_yr_sm                         4.94      10_yr_sm  2
         25_yr_sm                         6.19      25_yr_sm  2
         50_yr_sm                         7.29      50_yr_sm  2
         100_yr_sm                        8.53      100_yr_sm 2
         200_yr_sm                        9.94      200_yr_sm 2
         500_yr_sm                       12.10      500_yr_sm 2


STRUCTURE RATING:
         Cul       300.
                   300.      0.        0.
                   302.      144.      1.
                   304.      250.      4.
                   306.      323.      8.
                   308.      382.      16.
                   310.      433.      37.


RAINFALL DISTRIBUTION:
         1_yr_sm             0.1
                        0.0  0.000440  0.000903  0.0014    0.0019
                   0.0024    0.0030    0.0035    0.0041    0.0048
                   0.0054    0.0061    0.0068    0.0075    0.0082
                   0.0089    0.0097    0.0105    0.0113    0.0122
                   0.0130    0.0139    0.0148    0.0157    0.0167
                   0.0177    0.0187    0.0197    0.0207    0.0218
                   0.0229    0.0240    0.0251    0.0263    0.0274
                   0.0286    0.0298    0.0311    0.0323    0.0336
                   0.0349    0.0363    0.0376    0.0390    0.0404
                   0.0418    0.0432    0.0447    0.0462    0.0477
                   0.0492    0.0508    0.0524    0.0539    0.0556
                   0.0572    0.0589    0.0605    0.0623    0.0640
                   0.0657    0.0675    0.0693    0.0711    0.0730
                   0.0748    0.0767    0.0786    0.0805    0.0825
                   0.0845    0.0865    0.0885    0.0905    0.0926
                   0.0947    0.0968    0.0989    0.1010    0.1032
                   0.1054    0.1076    0.1099    0.1121    0.1144
                   0.1167    0.1191    0.1214    0.1238    0.1262
                   0.1286    0.1322    0.1358    0.1395    0.1432
                   0.1470    0.1508    0.1547    0.1586    0.1625
                   0.1665    0.1706    0.1747    0.1788    0.1830
                   0.1873    0.1946    0.2019    0.2092    0.2165
                   0.2238    0.2344    0.2449    0.2554    0.2660
                   0.2765    0.2964    0.3164    0.3440    0.3862
                   0.4664    0.6138    0.6560    0.6836    0.7036
                   0.7235    0.7340    0.7446    0.7551    0.7656
                   0.7762    0.7835    0.7908    0.7981    0.8054
                   0.8127    0.8170    0.8212    0.8253    0.8294
                   0.8335    0.8375    0.8414    0.8453    0.8492
                   0.8530    0.8568    0.8605    0.8642    0.8678
                   0.8714    0.8738    0.8762    0.8786    0.8809
                   0.8833    0.8856    0.8879    0.8901    0.8924
                   0.8946    0.8968    0.8990    0.9011    0.9032
                   0.9053    0.9074    0.9095    0.9115    0.9135
                   0.9155    0.9175    0.9195    0.9214    0.9233
                   0.9252    0.9270    0.9289    0.9307    0.9325
                   0.9343    0.9360    0.9377    0.9395    0.9411
                   0.9428    0.9444    0.9461    0.9476    0.9492
                   0.9508    0.9523    0.9538    0.9553    0.9568
```

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WinTR-20: Version 1.11 0 0 1. 0
Scenario 3

SUB-AREA:
Watershed 1 .094 70. .38 60 Ac Somerset

STREAM REACH:
1 outlet Cul 1700.

STORM ANALYSIS:

1 year	0.	2.9	Type II	2
2 year	0.	3.5	Type II	2
10 year	0.	5.6	Type II	2
100 year	0.	8.1	Type II	2

STRUCTURE RATING:

Cul	100.		
	100.	0.	0.
	102.	96.	1.
	104.	167.	4.
	106.	215.	8.
	108.	255.	16.
	110.	289.	37.

GLOBAL OUTPUT:
.1 YNNNN NNNNNN

WinTR-20 Printed Page File End of Input Data List

Scenario 3

Name of printed page file:
C:\Users\ghayes\Desktop\Rand TR20 Project\TP40\Scenario3.out

STORM 1 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	0.094		0.655		12.15	35.2	374.33
OUTLET	0.094		0.653		12.25	28.9	307.93

STORM 2 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	0.094		1.004		12.13	57.8	615.28
OUTLET	0.094		1.002		12.23	47.9	510.02

STORM 10 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	0.094		2.483		12.12	153.3	1630.65
OUTLET	0.094		2.479		12.26	109.2	1161.51

STORM 100 year

Area or Reach	Drainage Area	Rain Gage ID or	Runoff Amount	Peak Flow Elevation	Peak Flow Time	Peak Flow Rate	Peak Flow Rate

Area or Reach Identifier	Drainage Area (sq mi)	Alternate	1 year (cfs)	2 year (cfs)	10 year (cfs)	100 year (cfs)	(cfs)
Watershed	0.094		35.2	57.8	153.3	282.6	
1	0.094		35.2	57.8	153.3	282.6	
DOWNSTREAM			28.9	47.9	109.2	166.3	
OUTLET	0.094		28.9	47.9	109.2	166.3	

Peak Flow by Storm

```
C:\Users\ghayes\Desktop\Rand TR20 Project\Atlas14\Scenario3.inp

WinTR-20: Version 1.11                0         0          0
NOAA Atlas 14 Smoothed Precipitation tables and values (inches) - Scenario 3
State, Maryland         Station, Somerset

SUB-AREA:
          Watershed 1                  .094      70.       .38      60 Ac Somerset

STREAM REACH:
          1          outlet            cul       1700.


STORM ANALYSIS:
          1_yr_sm                       2.65     1_yr_sm   2          3.22
          2_yr_sm                       3.22     2_yr_sm   2
          5_yr_sm                       4.18     5_yr_sm   2
          10_yr_sm                      5.01     10_yr_sm  2
          25_yr_sm                      6.28     25_yr_sm  2
          50_yr_sm                      7.40     50_yr_sm  2
          100_yr_sm                     8.64     100_yr_sm 2
          200_yr_sm                    10.05     200_yr_sm 2
          500_yr_sm                    12.20     500_yr_sm 2


STRUCTURE RATING:
          cul        100.
                     100.       0.        0.
                     102.       96.       1.
                     104.       167.      4.
                     106.       215.      8.
                     108.       255.      16.
                     110.       289.      37.



RAINFALL DISTRIBUTION:
          1_yr_sm               0.1
                          0.0   0.000328  0.000677  0.0010    0.0014
                     0.0019     0.0023    0.0027    0.0032    0.0037
                     0.0042     0.0048    0.0054    0.0059    0.0065
                     0.0072     0.0078    0.0085    0.0092    0.0099
                     0.0106     0.0114    0.0122    0.0130    0.0138
                     0.0146     0.0155    0.0164    0.0173    0.0182
                     0.0192     0.0202    0.0212    0.0222    0.0232
                     0.0243     0.0253    0.0264    0.0276    0.0287
                     0.0299     0.0311    0.0323    0.0335    0.0348
                     0.0360     0.0373    0.0386    0.0400    0.0413
                     0.0427     0.0441    0.0456    0.0470    0.0485
                     0.0500     0.0515    0.0530    0.0546    0.0561
                     0.0577     0.0593    0.0610    0.0626    0.0643
                     0.0660     0.0678    0.0695    0.0713    0.0731
                     0.0749     0.0767    0.0786    0.0804    0.0823
                     0.0842     0.0862    0.0882    0.0901    0.0921
                     0.0942     0.0962    0.0983    0.1004    0.1025
                     0.1046     0.1068    0.1090    0.1112    0.1134
                     0.1156     0.1191    0.1226    0.1261    0.1297
                     0.1333     0.1370    0.1407    0.1445    0.1483
                     0.1522     0.1561    0.1601    0.1641    0.1682
                     0.1723     0.1797    0.1871    0.1945    0.2019
                     0.2093     0.2203    0.2312    0.2422    0.2532
                     0.2642     0.2859    0.3076    0.3374    0.3824
                     0.4663     0.6176    0.6626    0.6924    0.7141
                     0.7358     0.7468    0.7578    0.7688    0.7797
                     0.7907     0.7981    0.8055    0.8129    0.8203
                     0.8277     0.8318    0.8359    0.8399    0.8439
                     0.8478     0.8517    0.8555    0.8593    0.8630
                     0.8667     0.8703    0.8739    0.8774    0.8809
                     0.8844     0.8866    0.8888    0.8910    0.8932
                     0.8954     0.8975    0.8996    0.9017    0.9038
                     0.9058     0.9079    0.9099    0.9118    0.9138
                     0.9158     0.9177    0.9196    0.9214    0.9233
                     0.9251     0.9269    0.9287    0.9305    0.9322
                     0.9340     0.9357    0.9374    0.9390    0.9407
                     0.9423     0.9439    0.9454    0.9470    0.9485
                     0.9500     0.9515    0.9530    0.9544    0.9559
                     0.9573     0.9587    0.9600    0.9614    0.9627
```

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WinTR-20: Version 1.11 0 0 1. 0
Scenario 4

SUB-AREA:
Watershed 1 .313 63. .68 200 Ac. Somerset

STREAM REACH:
1 outlet Cul 3700.

STORM ANALYSIS:

1 year	0.	2.9	Type II	2
2 year	0.	3.5	Type II	2
10 year	0.	5.6	Type II	2
100 year	0.	8.1	Type II	2

STRUCTURE RATING:

Cul	100.		
	100.	0.	0.
	102.	96.	1.
	104.	167.	4.
	106.	215.	8.
	108.	255.	16.
	110.	289.	37.

GLOBAL OUTPUT:
.1 YNNNN NNNNNN

WinTR-20 Printed Page File End of Input Data List

Scenario 4

Name of printed page file:
C:\Users\ghayes\Desktop\Rand TR20 Project\TP40\Scenario4.out

STORM 1 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Time (hr)	Rate (cfs)	Rate (csm)
Watershed	0.313		0.390		12.41	35.8	114.47
OUTLET	0.313		0.390		12.54	32.8	104.75

STORM 2 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Time (hr)	Rate (cfs)	Rate (csm)
Watershed	0.313		0.658		12.35	72.7	232.36
OUTLET	0.313		0.658		12.48	66.2	211.49

STORM 10 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Time (hr)	Rate (cfs)	Rate (csm)
Watershed	0.313		1.900		12.32	258.8	826.91
OUTLET	0.313		1.899		12.62	172.0	549.50

STORM 100 year

Area or Reach	Drainage Area	Rain Gage ID or	Runoff Amount	Peak Flow Elevation	Time	Rate	Rate

Area or Reach Identifier	Drainage Area (sq mi)	Alternate	----------- Peak Flow by Storm ----------- 1 year (cfs)	2 year (cfs)	10 year (cfs)	100 year (cfs)	(cfs)
Watershed	0.313		35.8	72.7	258.8	536.9	
1	0.313		35.8	72.7	258.8	536.9	
DOWNSTREAM			32.8	66.2	172.0	245.8	
OUTLET	0.313		32.8	66.2	172.0	245.8	

WinTR-20 Version 1.11 Page 2 07/17/2014 14:16

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C:\Users\ghayes\Desktop\Rand TR20 Project\Atlas14\Scenario4.inp

WinTR-20: Version 1.11                    0         0                   0
NOAA Atlas 14 Smoothed Precipitation tables and values (inches) - Scenario 4
State, Maryland         Station, Somerset

SUB-AREA:
          Watershed 1                     .313      63.       .68          200 Ac Somerset

STREAM REACH:
          1          outlet               cul       3700.


STORM ANALYSIS:
          1_yr_sm                          2.65     1_yr_sm   2             3.22
          2_yr_sm                          3.22     2_yr_sm   2
          5_yr_sm                          4.18     5_yr_sm   2
          10_yr_sm                         5.01     10_yr_sm  2
          25_yr_sm                         6.28     25_yr_sm  2
          50_yr_sm                         7.40     50_yr_sm  2
          100_yr_sm                        8.64     100_yr_sm 2
          200_yr_sm                       10.05     200_yr_sm 2
          500_yr_sm                       12.20     500_yr_sm 2


STRUCTURE RATING:
          cul        100.
                     100.       0.        0.
                     102.       96.       1.
                     104.       167.      4.
                     106.       215.      8.
                     108.       255.      16.
                     110.       289.      37.



RAINFALL DISTRIBUTION:
          1_yr_sm               0.1
                           0.0  0.000328  0.000677  0.0010    0.0014
                     0.0019     0.0023    0.0027    0.0032    0.0037
                     0.0042     0.0048    0.0054    0.0059    0.0065
                     0.0072     0.0078    0.0085    0.0092    0.0099
                     0.0106     0.0114    0.0122    0.0130    0.0138
                     0.0146     0.0155    0.0164    0.0173    0.0182
                     0.0192     0.0202    0.0212    0.0222    0.0232
                     0.0243     0.0253    0.0264    0.0276    0.0287
                     0.0299     0.0311    0.0323    0.0335    0.0348
                     0.0360     0.0373    0.0386    0.0400    0.0413
                     0.0427     0.0441    0.0456    0.0470    0.0485
                     0.0500     0.0515    0.0530    0.0546    0.0561
                     0.0577     0.0593    0.0610    0.0626    0.0643
                     0.0660     0.0678    0.0695    0.0713    0.0731
                     0.0749     0.0767    0.0786    0.0804    0.0823
                     0.0842     0.0862    0.0882    0.0901    0.0921
                     0.0942     0.0962    0.0983    0.1004    0.1025
                     0.1046     0.1068    0.1090    0.1112    0.1134
                     0.1156     0.1191    0.1226    0.1261    0.1297
                     0.1333     0.1370    0.1407    0.1445    0.1483
                     0.1522     0.1561    0.1601    0.1641    0.1682
                     0.1723     0.1797    0.1871    0.1945    0.2019
                     0.2093     0.2203    0.2312    0.2422    0.2532
                     0.2642     0.2859    0.3076    0.3374    0.3824
                     0.4663     0.6176    0.6626    0.6924    0.7141
                     0.7358     0.7468    0.7578    0.7688    0.7797
                     0.7907     0.7981    0.8055    0.8129    0.8203
                     0.8277     0.8318    0.8359    0.8399    0.8439
                     0.8478     0.8517    0.8555    0.8593    0.8630
                     0.8667     0.8703    0.8739    0.8774    0.8809
                     0.8844     0.8866    0.8888    0.8910    0.8932
                     0.8954     0.8975    0.8996    0.9017    0.9038
                     0.9058     0.9079    0.9099    0.9118    0.9138
                     0.9158     0.9177    0.9196    0.9214    0.9233
                     0.9251     0.9269    0.9287    0.9305    0.9322
                     0.9340     0.9357    0.9374    0.9390    0.9407
                     0.9423     0.9439    0.9454    0.9470    0.9485
                     0.9500     0.9515    0.9530    0.9544    0.9559
                     0.9573     0.9587    0.9600    0.9614    0.9627
```

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C:\Users\ghayes\Desktop\Rand TR20 Project\TP40\Scenario5.inp

WinTR-20: Version 1.11              0         0         1.        0
Scenario  5

SUB-AREA:
          Watershed 1               6.25      68.       1.25      4000 A. Ann Arud. 1

STREAM REACH:
          1         outlet          Cul       3100.


STORM ANALYSIS:
          1 year              0.        2.7       Type II   2
          2 year              0.        3.3       Type II   2
          10 year             0.        5.2       Type II   2
          100 year            0.        7.4       Type II   2


STRUCTURE RATING:
          Cul       300.
                    300.      0.        0.
                    302.      4000.     400.




GLOBAL OUTPUT:
                              .1        YNNNN     NNNNNN
```

WinTR-20 Printed Page File End of Input Data List

Scenario 2

Name of printed page file:
C:\Users\ghayes\Desktop\Rand TR20 Project\TP40\Scenario5.out

STORM 1 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	6.250		0.478		12.79	664.3	106.29
OUTLET	6.250		0.478		13.66	355.2	56.83

STORM 2 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	6.250		0.787		12.77	1233.5	197.37
OUTLET	6.250		0.787		13.56	645.3	103.24

STORM 10 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	6.250		2.023		12.68	3642.1	582.74
OUTLET	6.250		2.023		13.39	1890.2	302.43

STORM 100 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	6.250		3.736		12.65	6986.1	1117.78
OUTLET	6.250		3.736		13.36	3659.5	585.52

```
C:\Users\ghayes\Desktop\Rand TR20 Project\Atlas14\Scenario5.inp

WinTR-20: Version 1.11                    0         0               0
NOAA Atlas 14 Smoothed Precipitation tables and values (inches) - Scenario   5
State, Maryland          Station, Anne Arundel

SUB-AREA:
          Watershed 1                    6.25      68.       1.25    4000 Ac Anne Arundel

STREAM REACH:
          1         outlet               Cul       3100.


STORM ANALYSIS:
          1_yr_sm                         2.64     1_yr_sm   2            3.20
          2_yr_sm                         3.20     2_yr_sm   2
          5_yr_sm                         4.13     5_yr_sm   2
          10_yr_sm                        4.94     10_yr_sm  2
          25_yr_sm                        6.19     25_yr_sm  2
          50_yr_sm                        7.29     50_yr_sm  2
          100_yr_sm                       8.53     100_yr_sm 2
          200_yr_sm                       9.94     200_yr_sm 2
          500_yr_sm                      12.10     500_yr_sm 2


STRUCTURE RATING:
          Cul       300.
                    300.      0.         0.
                    302.      8000.      800.



RAINFALL DISTRIBUTION:
          1_yr_sm             0.1
                         0.0  0.000440   0.000903  0.0014    0.0019
                    0.0024    0.0030     0.0035    0.0041    0.0048
                    0.0054    0.0061     0.0068    0.0075    0.0082
                    0.0089    0.0097     0.0105    0.0113    0.0122
                    0.0130    0.0139     0.0148    0.0157    0.0167
                    0.0177    0.0187     0.0197    0.0207    0.0218
                    0.0229    0.0240     0.0251    0.0263    0.0274
                    0.0286    0.0298     0.0311    0.0323    0.0336
                    0.0349    0.0363     0.0376    0.0390    0.0404
                    0.0418    0.0432     0.0447    0.0462    0.0477
                    0.0492    0.0508     0.0524    0.0539    0.0556
                    0.0572    0.0589     0.0605    0.0623    0.0640
                    0.0657    0.0675     0.0693    0.0711    0.0730
                    0.0748    0.0767     0.0786    0.0805    0.0825
                    0.0845    0.0865     0.0885    0.0905    0.0926
                    0.0947    0.0968     0.0989    0.1010    0.1032
                    0.1054    0.1076     0.1099    0.1121    0.1144
                    0.1167    0.1191     0.1214    0.1238    0.1262
                    0.1286    0.1322     0.1358    0.1395    0.1432
                    0.1470    0.1508     0.1547    0.1586    0.1625
                    0.1665    0.1706     0.1747    0.1788    0.1830
                    0.1873    0.1946     0.2019    0.2092    0.2165
                    0.2238    0.2344     0.2449    0.2554    0.2660
                    0.2765    0.2964     0.3164    0.3440    0.3862
                    0.4664    0.6138     0.6560    0.6836    0.7036
                    0.7235    0.7340     0.7446    0.7551    0.7656
                    0.7762    0.7835     0.7908    0.7981    0.8054
                    0.8127    0.8170     0.8212    0.8253    0.8294
                    0.8335    0.8375     0.8414    0.8453    0.8492
                    0.8530    0.8568     0.8605    0.8642    0.8678
                    0.8714    0.8738     0.8762    0.8786    0.8809
                    0.8833    0.8856     0.8879    0.8901    0.8924
                    0.8946    0.8968     0.8990    0.9011    0.9032
                    0.9053    0.9074     0.9095    0.9115    0.9135
                    0.9155    0.9175     0.9195    0.9214    0.9233
                    0.9252    0.9270     0.9289    0.9307    0.9325
                    0.9343    0.9360     0.9377    0.9395    0.9411
                    0.9428    0.9444     0.9461    0.9476    0.9492
                    0.9508    0.9523     0.9538    0.9553    0.9568
                    0.9582    0.9596     0.9610    0.9624    0.9637
                    0.9651    0.9664     0.9677    0.9689    0.9702
                    0.9714    0.9726     0.9737    0.9749    0.9760
                    0.9771    0.9782     0.9793    0.9803    0.9813
```

C:\Users\ghayes\Desktop\Rand TR20 Project\TP40\Scenario6.inp

```
WinTR-20: Version 1.11                    0          0          1.         0
Scenario 6

SUB-AREA:
          Watershed 1                     6.25       63.        2.5        4000 Ac Somerset

STREAM REACH:
          1          outlet               Cul        3700.

STORM ANALYSIS:
          1 year               0.         2.9        Type II    2
          2 year               0.         3.5        Type II    2
          10 year              0.         5.6        Type II    2
          100 year             0.         8.1        Type II    2

STRUCTURE RATING:
          Cul        100.
                     100.      0.         0.
                     102.      4000.      400.

GLOBAL OUTPUT:
                               .1         YNNNN      NNNNNN
```

WinTR-20 Printed Page File   End of Input Data List

Scenario 4

Name of printed page file:
C:\Users\ghayes\Desktop\Rand TR20 Project\TP40\Scenario6.out

STORM 1 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	6.250		0.392		13.82	301.2	48.19
OUTLET	6.250		0.391		14.92	221.2	35.39

STORM 2 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	6.250		0.659		13.71	572.3	91.57
OUTLET	6.250		0.659		14.66	410.5	65.68

STORM 10 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	6.250		1.902		13.61	1957.3	313.17
OUTLET	6.250		1.901		14.55	1372.2	219.56

STORM 100 year

Area or Reach Identifier	Drainage Area (sq mi)	Rain Gage ID or Location	Runoff Amount (in)	Peak Flow Elevation (ft)	Peak Flow Time (hr)	Peak Flow Rate (cfs)	Peak Flow Rate (csm)
Watershed	6.250		3.747		13.52	4089.0	654.24
OUTLET	6.250		3.747		14.46	2865.1	458.42

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```
WinTR-20: Version 1.11                   0          0                       0
NOAA Atlas 14 Smoothed Precipitation tables and values (inches) - Scenario  6
State, Maryland         Station, Somerset

SUB-AREA:
          Watershed 1                    6.25       63.        2.5    4000 Ac Somerset

STREAM REACH:
          1          outlet              cul        3700.


STORM ANALYSIS:
          1_yr_sm                         2.65      1_yr_sm    2            3.22
          2_yr_sm                         3.22      2_yr_sm    2
          5_yr_sm                         4.18      5_yr_sm    2
          10_yr_sm                        5.01      10_yr_sm   2
          25_yr_sm                        6.28      25_yr_sm   2
          50_yr_sm                        7.40      50_yr_sm   2
          100_yr_sm                       8.64      100_yr_sm 2
          200_yr_sm                      10.05      200_yr_sm 2
          500_yr_sm                      12.20      500_yr_sm 2


STRUCTURE RATING:
          cul        100.
                     100.       0.         0.
                     102.       8000.      800.


RAINFALL DISTRIBUTION:
          1_yr_sm               0.1
```

0.0	0.000328	0.000677	0.0010	0.0014
0.0019	0.0023	0.0027	0.0032	0.0037
0.0042	0.0048	0.0054	0.0059	0.0065
0.0072	0.0078	0.0085	0.0092	0.0099
0.0106	0.0114	0.0122	0.0130	0.0138
0.0146	0.0155	0.0164	0.0173	0.0182
0.0192	0.0202	0.0212	0.0222	0.0232
0.0243	0.0253	0.0264	0.0276	0.0287
0.0299	0.0311	0.0323	0.0335	0.0348
0.0360	0.0373	0.0386	0.0400	0.0413
0.0427	0.0441	0.0456	0.0470	0.0485
0.0500	0.0515	0.0530	0.0546	0.0561
0.0577	0.0593	0.0610	0.0626	0.0643
0.0660	0.0678	0.0695	0.0713	0.0731
0.0749	0.0767	0.0786	0.0804	0.0823
0.0842	0.0862	0.0882	0.0901	0.0921
0.0942	0.0962	0.0983	0.1004	0.1025
0.1046	0.1068	0.1090	0.1112	0.1134
0.1156	0.1191	0.1226	0.1261	0.1297
0.1333	0.1370	0.1407	0.1445	0.1483
0.1522	0.1561	0.1601	0.1641	0.1682
0.1723	0.1797	0.1871	0.1945	0.2019
0.2093	0.2203	0.2312	0.2422	0.2532
0.2642	0.2859	0.3076	0.3374	0.3824
0.4663	0.6176	0.6626	0.6924	0.7141
0.7358	0.7468	0.7578	0.7688	0.7797
0.7907	0.7981	0.8055	0.8129	0.8203
0.8277	0.8318	0.8359	0.8399	0.8439
0.8478	0.8517	0.8555	0.8593	0.8630
0.8667	0.8703	0.8739	0.8774	0.8809
0.8844	0.8866	0.8888	0.8910	0.8932
0.8954	0.8975	0.8996	0.9017	0.9038
0.9058	0.9079	0.9099	0.9118	0.9138
0.9158	0.9177	0.9196	0.9214	0.9233
0.9251	0.9269	0.9287	0.9305	0.9322
0.9340	0.9357	0.9374	0.9390	0.9407
0.9423	0.9439	0.9454	0.9470	0.9485
0.9500	0.9515	0.9530	0.9544	0.9559
0.9573	0.9587	0.9600	0.9614	0.9627
0.9640	0.9652	0.9665	0.9677	0.9689
0.9701	0.9713	0.9724	0.9736	0.9747
0.9757	0.9768	0.9778	0.9788	0.9798
0.9808	0.9818	0.9827	0.9836	0.9845

Table 2.2 Rainfall Depths Associated with the 1,2,10 and 100-year, 24-hour Storm Events

County	Rainfall Depth			
	1 yr - 24 hr	2 yr-24 hr	10 yr-24 hr	100 yr-24 hr
Allegany	2.4 inches	2.9 inches	4.5 inches	6.2 inches
Anne Arundel	2.7	3.3	5.2	7.4
Baltimore	2.6	3.2	5.1	7.1
Calvert	2.8	3.4	5.3	7.6
Caroline	2.8	3.4	5.3	7.6
Carroll	2.5	3.1	5.0	7.1
Cecil	2.7	3.3	5.1	7.3
Charles	2.7	3.3	5.3	7.5
Dorchester	2.8	3.4	5.4	7.8
Frederick	2.5	3.1	5.0	7.0
Garrett	2.4	2.8	4.3	5.9
Harford	2.6	3.2	5.1	7.2
Howard	2.6	3.2	5.1	7.2
Kent	2.7	3.3	5.2	7.4
Montgomery	2.6	3.2	5.1	7.2
Prince George's	2.7	3.3	5.3	7.4
Queen Anne's	2.7	3.3	5.3	7.5
St. Mary's	2.8	3.4	5.4	7.7
Somerset	2.9	3.5	5.6	8.1
Talbot	2.8	3.4	5.3	7.6
Washington	2.5	3.0	4.8	6.7
Wicomico	2.9	3.5	5.6	7.9
Worcester	3.0	3.6	5.6	8.1

__I. **MARYLAND AVERAGE RAINFALL FROM NOAA ATLAS 14**

County		Rainfall Depth					
		1 yr 24 hr	2 yr 24 hr	10 yr 24 hr	25 yr 24 hr	50 yr 24 hr	100 yr 24 hr
Allegany		2.07	2.47	3.64	4.45	5.16	5.96
Anne Arundel		2.64	3.20	4.94	6.19	7.29	8.53
Baltimore		2.70	3.27	5.01	6.27	7.38	8.65
Calvert		2.73	3.32	5.17	6.48	7.63	8.93
Caroline		2.70	3.29	5.13	6.42	7.56	8.84
Carroll		2.54	3.07	4.69	5.85	6.88	8.06
Cecil		2.66	3.22	4.87	6.01	7.00	8.10
Charles		2.67	3.24	5.04	6.31	7.44	8.70
Dorchester		2.77	3.38	5.27	6.60	7.77	9.08
Frederick	Catoctin	2.54	3.05	4.51	5.54	6.43	7.44
	Frederick	2.54	3.07	4.63	5.77	6.78	7.94
Garrett		2.13	2.55	3.69	4.50	5.20	5.99
Harford		2.70	3.26	5.00	6.24	7.34	8.57
Howard		2.64	3.19	4.91	6.14	7.23	8.47
Kent		2.66	3.23	5.01	6.27	7.38	8.63
Montgomery		2.57	3.10	4.77	5.97	7.03	8.23
Prince George's		2.63	3.19	4.92	6.16	7.26	8.49
Queen Anne's		2.67	3.24	5.06	6.33	7.46	8.72
St. Mary's		2.77	3.37	5.24	6.57	7.73	9.04
Somerset		2.65	3.22	5.01	6.28	7.40	8.64
Talbot		2.74	3.33	5.19	6.51	7.67	8.97
Washington	East	2.52	3.03	4.41	5.40	6.29	7.30
	West	2.37	2.84	4.11	4.94	5.64	6.40
Wicomico		2.81	3.42	5.34	6.69	7.88	9.22
Worcester		2.81	3.42	5.34	6.70	7.89	9.23
Minimum		2.07	2.47	3.64	4.45	5.16	5.96
Median		2.66	3.22	5.00	6.24	7.34	8.57
Maximum		2.81	3.42	5.34	6.70	7.89	9.23
Standard Deviation		0.18	0.24	0.46	0.62	0.77	0.94

This chart can only be used with proper NRCS software programs converted for NOAA 14 rainfall data. See below:

(WinTR-55) Small Watershed Hydrology. WinTR-55 is a tool for urban hydrology for small watersheds. This version includes the NOAA 14 rainfall data and will run in the Windows 7 environment. ftp://ftp-fc.sc.egov.usda.gov/NDCSMC/Software/WinTR-55 installwindows7.exe

APPENDIX 4-2

PRINCE GEORGE'S COUNTY MARYLAND RAINFALL INTENSITY
(Inches/Hour)

Duration	Return Period (Years)					
(Minutes)	2	5	10	25	50	100
5	5.53	6.49	7.08	8.05	8.89	9.72
6	5.23	6.19	6.80	7.76	8.58	9.39
7	4.97	5.93	6.54	7.50	8.30	9.09
8	4.73	5.68	6.30	7.25	8.04	8.80
9	4.52	5.46	6.07	7.03	7.79	8.53
10	4.33	5.26	5.87	6.81	7.55	8.28
11	4.15	5.07	5.67	6.61	7.33	8.04
12	4.00	4.90	5.49	6.42	7.17	7.31
13	3.85	4.73	5.32	6.23	6.92	7.59
14	3.71	4.58	5.17	6.06	6.73	7.39
15	3.59	4.44	5.02	5.90	6.56	7.20
16	3.48	4.31	4.88	5.75	6.39	7.01
17	3.37	4.19	4.75	5.60	6.23	6.84
18	3.27	4.07	4.62	5.46	6.07	6.67
19	3.17	3.96	4.50	5.33	6.93	6.51
20	3.09	3.86	4.39	5.20	5.79	6.36
21	3.00	3.76	4.28	5.08	5.66	6.22
22	3.67	3.67	4.18	4.96	5.53	6.08
23	2.85	3.58	4.09	4.85	5.41	5.95
24	2.78	3.50	4.00	4.75	5.29	5.82
25	2.72	3.42	3.91	4.64	5.18	5.70
26	2.66	3.34	3.82	4.55	5.07	5.58
27	2.60	3.27	3.41	4.45	4.97	5.47
28	2.54	3.20	3.67	4.36	4.87	5.36
29	2.49	3.14	3.59	4.28	4.77	5.26
30	2.44	3.08	3.52	4.19	4.68	5.16
31	2.39	3.02	3.46	4.11	4.59	5.06
32	2.34	2.96	3.39	4.04	4.51	4.97
33	2.29	2.90	3.33	3.96	4.43	4.88
34	2.25	2.85	3.27	3.86	4.35	4.79
35	2.21	2.80	3.21	3.82	4.27	4.71
36	2.17	2.75	3.15	3.75	4.20	4.63
37	2.13	2.70	3.10	3.69	4.12	4.55
38	2.10	2.66	3.05	3.62	4.06	4.48
39	2.06	2.61	3.00	3.56	3.99	4.40
40	2.03	2.57	2.95	3.50	3.92	4.33
41	2.00	2.53	2.90	3.45	3.86	4.26
42	1.96	2.49	2.86	3.39	3.80	4.20
43	1.93	2.45	2.81	3.34	3.74	4.13
44	1.91	2.42	2.77	3.29	3.68	4.07
45	1.88	2.38	2.73	3.24	3.63	4.01
46	1.85	2.35	2.69	3.19	3.57	3.95

RATIONAL METHOD RAINFALL INTENSITY

NOAA 14-2004: Intermediate Values from Interpolation
(Upper Marlboro 3 NNW: 18-9070)
PRINCE GEORGE'S COUNTY MARYLAND RAINFALL INTENSITY
(INCHES/HOUR)

DURATION	RETURN PERIOD (YEARS)						
(MINUTES)	1	2	5	10	25	50	100
5.00	4.20	5.04	6.00	6.72	7.56	8.28	8.88
6.00	4.03	4.84	5.76	6.44	7.26	7.93	8.51
7.00	3.86	4.63	5.52	6.17	6.96	7.58	8.14
8.00	3.70	4.43	5.28	5.89	6.66	7.24	7.76
9.00	3.53	4.22	5.04	5.62	6.36	6.89	7.39
10.00	3.36	4.02	4.80	5.34	6.06	6.54	7.02
11.00	3.25	3.89	4.65	5.18	5.86	6.34	6.80
12.00	3.14	3.76	4.50	5.01	5.67	6.13	6.58
13.00	3.02	3.62	4.34	4.85	5.47	5.93	6.36
14.00	2.91	3.49	4.19	4.68	5.28	5.72	6.14
15.00	2.80	3.36	4.04	4.52	5.08	5.52	5.92
16.00	2.74	3.29	3.96	4.44	4.99	5.43	5.83
17.00	2.68	3.22	3.89	4.35	4.91	5.34	5.74
18.00	2.62	3.16	3.81	4.27	4.82	5.25	5.64
19.00	2.57	3.09	3.73	4.19	4.73	5.16	5.55
20.00	2.51	3.02	3.65	4.11	4.65	5.07	5.46
21.00	2.45	2.95	3.58	4.02	4.56	4.98	5.37
22.00	2.39	2.88	3.50	3.94	4.47	4.89	5.28
23.00	2.33	2.82	3.42	3.86	4.39	4.79	5.18
24.00	2.27	2.75	3.34	3.78	4.30	4.70	5.09
25.00	2.21	2.68	3.27	3.69	4.21	4.61	5.00
26.00	2.15	2.61	3.19	3.61	4.13	4.52	4.91
27.00	2.10	2.54	3.11	3.53	4.04	4.43	4.82
28.00	2.04	2.48	3.03	3.45	3.95	4.34	4.72
29.00	1.98	2.41	2.96	3.36	3.87	4.25	4.63
30.00	1.92	2.34	2.88	3.28	3.78	4.16	4.54
31.00	1.90	2.31	2.85	3.24	3.74	4.12	4.49
32.00	1.87	2.28	2.81	3.20	3.70	4.07	4.45
33.00	1.85	2.25	2.78	3.17	3.65	4.03	4.40
34.00	1.82	2.22	2.74	3.13	3.61	3.98	4.35
35.00	1.80	2.19	2.71	3.09	3.57	3.94	4.31
36.00	1.78	2.16	2.67	3.05	3.53	3.89	4.26
37.00	1.75	2.13	2.64	3.01	3.48	3.85	4.21
38.00	1.73	2.11	2.60	2.97	3.44	3.80	4.16
39.00	1.70	2.08	2.57	2.94	3.40	3.76	4.12
40.00	1.68	2.05	2.53	2.90	3.36	3.71	4.07
41.00	1.66	2.02	2.50	2.86	3.31	3.67	4.02
42.00	1.63	1.99	2.46	2.82	3.27	3.62	3.98
43.00	1.61	1.96	2.43	2.78	3.23	3.58	3.93
44.00	1.58	1.93	2.39	2.74	3.19	3.53	3.88
45.00	1.56	1.90	2.36	2.71	3.15	3.49	3.84
60.00	1.20	1.46	1.84	2.13	2.51	2.82	3.13

RATIONAL METHOD RAINFALL INTENSITY

NOAA 14-2004: Intermediate Values from Interpolation
(Upper Marlboro 3 NNW: 18-9070)
PRINCE GEORGE'S COUNTY MARYLAND RAINFALL INTENSITY
(INCHES/HOUR)

DURATION	RETURN PERIOD (YEARS)						
(MINUTES)	1	2	5	10	25	50	100
5.00	4.20	5.04	6.00	6.72	7.56	8.28	8.88
6.00	4.03	4.84	5.76	6.44	7.26	7.93	8.51
7.00	3.86	4.63	5.52	6.17	6.96	7.58	8.14
8.00	3.70	4.43	5.28	5.89	6.66	7.24	7.76
9.00	3.53	4.22	5.04	5.62	6.36	6.89	7.39
10.00	3.36	4.02	4.80	5.34	6.06	6.54	7.02
11.00	3.25	3.89	4.65	5.18	5.86	6.34	6.80
12.00	3.14	3.76	4.50	5.01	5.67	6.13	6.58
13.00	3.02	3.62	4.34	4.85	5.47	5.93	6.36
14.00	2.91	3.49	4.19	4.68	5.28	5.72	6.14
15.00	2.80	3.36	4.04	4.52	5.08	5.52	5.92
16.00	2.74	3.29	3.96	4.44	4.99	5.43	5.83
17.00	2.68	3.22	3.89	4.35	4.91	5.34	5.74
18.00	2.62	3.16	3.81	4.27	4.82	5.25	5.64
19.00	2.57	3.09	3.73	4.19	4.73	5.16	5.55
20.00	2.51	3.02	3.65	4.11	4.65	5.07	5.46
21.00	2.45	2.95	3.58	4.02	4.56	4.98	5.37
22.00	2.39	2.88	3.50	3.94	4.47	4.89	5.28
23.00	2.33	2.82	3.42	3.86	4.39	4.79	5.18
24.00	2.27	2.75	3.34	3.78	4.30	4.70	5.09
25.00	2.21	2.68	3.27	3.69	4.21	4.61	5.00
26.00	2.15	2.61	3.19	3.61	4.13	4.52	4.91
27.00	2.10	2.54	3.11	3.53	4.04	4.43	4.82
28.00	2.04	2.48	3.03	3.45	3.95	4.34	4.72
29.00	1.98	2.41	2.96	3.36	3.87	4.25	4.63
30.00	1.92	2.34	2.88	3.28	3.78	4.16	4.54
31.00	1.90	2.31	2.85	3.24	3.74	4.12	4.49
32.00	1.87	2.28	2.81	3.20	3.70	4.07	4.45
33.00	1.85	2.25	2.78	3.17	3.65	4.03	4.40
34.00	1.82	2.22	2.74	3.13	3.61	3.98	4.35
35.00	1.80	2.19	2.71	3.09	3.57	3.94	4.31
36.00	1.78	2.16	2.67	3.05	3.53	3.89	4.26
37.00	1.75	2.13	2.64	3.01	3.48	3.85	4.21
38.00	1.73	2.11	2.60	2.97	3.44	3.80	4.16
39.00	1.70	2.08	2.57	2.94	3.40	3.76	4.12
40.00	1.68	2.05	2.53	2.90	3.36	3.71	4.07
41.00	1.66	2.02	2.50	2.86	3.31	3.67	4.02
42.00	1.63	1.99	2.46	2.82	3.27	3.62	3.98
43.00	1.61	1.96	2.43	2.78	3.23	3.58	3.93
44.00	1.58	1.93	2.39	2.74	3.19	3.53	3.88
45.00	1.56	1.90	2.36	2.71	3.15	3.49	3.84
60.00	1.20	1.46	1.84	2.13	2.51	2.82	3.13