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MARYLAND DEPARTMENT OF TRANSPORTATION
STATE HIGHWAY ADMINISTRATION

INTEGRATING EXTREME WEATHER AND CLIMATE RISK INTO MDOT SHA ASSET MANAGEMENT AND PLANNING

A final report from the FHWA *Asset Management, Extreme Weather, and Proxy Indicators* pilot program

FINAL REPORT

February 2019

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This project was carried out in support of 23 U.S.C. § 503(b)(3)(B)(viii), which directs DOT "to carry out research and development activities … to study vulnerabilities of the transportation system to … extreme events and methods to reduce those vulnerabilities."

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16. Abstract This report summarizes the methods and results of the 2018 Maryland Department of Transportation State Highway Administration (MDOT SHA) Federal Highway Administration pilot project: Asset Management, Extreme Weather, and Proxy Indicators. This MDOT SHA pilot project aimed to 1) refine and expand a vulnerability assessment of state assets to climate hazards, and 2) identify and implement specific opportunities to integrate the vulnerability assessment results—and other information about climate risks—into existing MDOT SHA asset management, planning, and other processes. This report describes the vulnerability assessment methodology and results, which identified 33 bridges highly vulnerable (i.e., scoring at least 3 out of 4) to sea level change, 172 bridges are highly vulnerable to storm surge, and 102 bridges highly vulnerable to precipitation change on MDOT SHA's network. This report also summarizes several actions identified through this project to integrate the findings into existing MDOT SHA decision-making processes, as well as overall lessons learned. For example, MDOT SHA has taken steps to ensure these climate risks are factored into lifecycle planning processes for both roads and bridges.			
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Acronyms and Abbreviations

ADT	Average Daily Traffic
BMS	Bridge Management System
CCVV	MDOT SHA’s Climate Change Vulnerability Viewer
CFR	Code of Federal Regulations
CHART	MDOT SHA Coordinated Highways Action Response Team
CMIP	Coupled Model Intercomparison Project
DOT	Department of Transportation
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
HAZUS	Hazards US
HB	House Bill
HMA	Hot Mix Asphalt
HVI	Hazard Vulnerability Index
MDE	Maryland Department of the Environment
MDOT SHA	Maryland Department of Transportation State Highway Administration
MEPDG	Mechanistic-Empirical Pavement Design Guide
MHHW	Mean Higher High Water (i.e., the average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch)
MPO	Metropolitan Planning Organization
MOSAIC	Model of Sustainability and Integrated Corridors
NAVD88	North American Vertical Datum of 1988
NEPA	National Environmental Policy Act
NOAA	National Oceanographic and Atmospheric Administration
OHD	MDOT SHA Office of Highway Development
OMT	MDOT SHA Office of Materials Technology
OOS	MDOT SHA Office of Structures
OPPE	MDOT SHA Office of Planning and Preliminary Engineering
PMS	Pavement Management System
SB	Senate Bill
SLC	Sea level change
TAMP	Transportation Asset Management Plan
TAP	Transportation Alternatives Program
USGS	U.S. Geological Survey
VAST	Vulnerability Assessment Scoring Tool

EXECUTIVE SUMMARY

As of 2019, the Maryland Department of Transportation State Highway Administration (MDOT SHA) manages over 73,000 lane miles of road and over 5,300 bridges. Several of these assets experience flooding, whether from extreme rain events (such as the devastating floods in Ellicott City in 2016 and 2018) or from extreme high tides or storm surge in Maryland's low-lying coastal areas. As these events persist and potentially worsen into the future, MDOT SHA is seeking to ensure the resilience of Maryland's transportation system through, among other means, an asset management program that minimizes risk and optimizes state resources.

In 2014, MDOT SHA completed a pilot climate change vulnerability assessment to identify specific roads and bridges most vulnerable to flooding in Anne Arundel and Somerset counties.

In 2018, MDOT SHA received a Federal Highway Administration (FHWA) grant to build on this work, including:

- Refining the vulnerability assessment approach and expanding the assessment to cover bridge structures statewide.[1]
- Identifying and implementing specific opportunities to integrate the vulnerability assessment results—and other information about climate risks—into existing MDOT SHA asset management, planning, and other processes.

This report documents the processes, findings, and outcomes of the project. In addition, it summarizes key lessons learned that may be relevant to other agencies seeking to integrate climate risk into their ongoing asset management and planning practices.

Vulnerability Assessment

The bridge vulnerability assessment conducted under this project applies an indicator-based approach based on the FHWA Vulnerability Assessment Scoring Tool (VAST). The approach uses data on asset location and other key attributes to serve as indicators of each of the components of vulnerability: exposure, sensitivity, and adaptive capacity. The assessment approach uses scores assigned to each indicator to develop a vulnerability score for each asset across three climate hazards: sea level change, storm surge, and precipitation change.

The assessment identified that, of the 8,588 structures evaluated, 33 are highly vulnerable to sea level change, 172 are highly vulnerable to storm surge, and 102 are highly vulnerable to precipitation change.

Assets with high vulnerability to sea level change are concentrated in MDOT SHA Districts 1, 2, and 5. Those same districts share vulnerability to storm surge, with the addition of District 4. Assets with high vulnerability to precipitation change are spread across all Districts, with the highest concentration in MDOT SHA Districts 4 and 7 (see Figure 2, Figure 4, and Figure 6).

[1] The original scope of the project was to refine the approach and expand the assessment to Queen Anne's county, but the project team was able to expand the assessment statewide within available resources.

Integrating Results into MDOT SHA Practice

The project team conducted a series of working sessions with MDOT SHA staff to discuss opportunities and strategies for integrating this vulnerability assessment information into existing asset management systems and processes, including pavement asset management, bridge asset management, planning, and operations.

The working sessions resulted in a set of specific actions MDOT SHA or the project team are taking to ensure that future sea level rise and extreme weather risks are systematically managed within existing processes. These actions and their statuses are summarized in Table 1. All items currently "In Progress" are expected to be completed by mid-2019.

Table 1. Summary of integration actions identified

Status	Action
Pavement Asset Management	
Complete	Calculate and provide the percentage of time different road segments may be inundated (to inform pavement performance modeling).
Complete	Provide information on the impacts of inundation on pavement performance (to inform pavement performance modeling).
Complete	Make coastal risk information available to District, Operations, metropolitan planning organizations (MPOs), counties and municipalities, as well as other state agencies.
In Progress	Office of Materials Technology (OMT) to add climate risk fields (e.g., pavement inundation frequency, Hazard Vulnerability Index (HVI)) into the Pavement Management System (PMS) to inform lifecycle planning.
In Progress	OMT to update PMS performance models to reflect current and expected inundation frequency. This will ensure risk of inundation is captured in expected deterioration rates and proactively factored into maintenance and other investment priorities.
In Progress	MDOT SHA to systematize collection of road and bridge closure information associated with flooding or other damage during a natural disaster.
Bridge Asset Management	
Complete	Include a field for the HVI score in bridge vulnerability results in the Climate Change Vulnerability Viewer (CCVV) to indicate vulnerability of the bridge approach.
Complete	Develop screening process for considering risks related to future environmental conditions in project planning.
In Progress	MDOT SHA to review structures prior to design and identify any climate or physical risks nearby.
In Progress	Office of Planning and Preliminary Engineering (OPPE) to incorporate bridge vulnerability results into interactive CCVV.
In Progress	Office of Structures (OOS) to consult CCVV in project planning process.
In Progress	MDOT SHA to improve modeling of precipitation change effects on flood zones.

Status	Action
In Progress	MDOT SHA to systematize collection of road and bridge closure information associated with flooding or other damage during a natural disaster.
To Do (long-term)	Develop development strategies for various sub-categories of assets that take climate risk information into account.
Planning	
Complete	Review CCVV and document project adaptation in environmental review (e.g., National Environmental Policy Act (NEPA) processes).
In Progress	OPPE to finalize CCVV and share with counties.
In Progress	Share CCVV at standing Office of Highway Development (OHD) coordination meetings.
In Progress	OPPE to share CCVV with all Districts.
In Progress	Hold a "lunch and learn" series to share CCVV, availability of climate risk information. Participants may include Bridge Hydraulics and Highway Hydraulics, among others.
In Progress	Incorporate climate risk into Purpose and Need template, which is completed to justify all new projects.
In Progress	Update project management manuals or checklists to include the climate risk results as resource materials for consideration during project development and management.
To Do (long-term)	Integrate climate risks into the Model of Sustainability and Integrated Corridors (MOSAIC), a quantitative tool used to estimate the impact of multimodal highway corridor improvement options on sustainability in the transportation planning process.[2].
To Do (long-term)	OPPE to provide climate risk data to discretionary grant applicants.
To Do (long-term)	Develop decision trees and other guidance on climate risk management.
Operations	
Complete	Provide Coordinated Highways Action Response Team (CHART) with a "cheat sheet" for how to interpret the different flood extent layers.
In Progress	CHART, District Maintenance, and Office of Maintenance to consult CCVV to inform preparations for flood events.
Transportation Asset Management Plan	
Complete	MDOT to continue to include climate-related risks in the overall Transportation Asset Management Plan (TAMP) risk register.
In Progress	OPPE to share statewide climate risk statistics with OMT and OOS related to TAMP risk register items.

[2] MDOT SHA. 2015. MOSAIC: Model of Sustainability and Integrated Corridors. Research Project: SP309B4H. Available at: https://www.roads.maryland.gov/OPR_Research/MD-15-SHA-UM-3-7_MOSAIC-Phase3_Summary.pdf

Status	Action
In Progress	MDOT to incorporate climate risk considerations throughout TAMP.

Next Steps

MDOT SHA has taken and will continue to take steps to integrate findings from this pilot project. Cross-cutting next steps include:

- Improve and finalize the online interactive CCVV, which includes HVI data, bridge vulnerability data, and related future flooding information.
- Implement a process for tracking flood-related road closures (e.g., road closure reporter).
- Continue to disseminate climate risk information through coordination meetings, lunch and learn meetings, and other venues (bridge and pavement hydraulics).
- Complete implementation of all "In Progress" strategies and begin longer-term "To Do" items from Table 1.

Summary and Lessons Learned

Overall, this project demonstrated that there are several practical actions DOTs can take to incorporate climate risk into their asset management and other systems. Furthermore, this project demonstrated several key lessons about the process of integrating climate risk into asset management. These include:

- There are practical strategies DOTs can use to incorporate climate risk into decision-making processes.
- Working sessions are effective in focusing attention and generating ideas for climate risk integration into planning, asset management, and other decision-making processes.
- It is important to meet staff where they are with regards to existing concerns, understanding of climate risk, time available to devote to the topic, and data used/required for decision-making.
- Having an internal "champion" with decision-making authority or influence within MDOT SHA helped to facilitate meaningful discussion and change.
- Different offices and individuals will have different data needs. It is therefore important to be flexible and able to develop customized datasets for different users.
- It is not always possible to know what the most useful data will be at the outset.
- It is important for potential users of the climate vulnerability results to understand and accept the assessment methodology.
- In an indicator-based vulnerability assessment, users need to be able to understand not just the final vulnerability ratings but also their constituent parts.
- Capturing data on past experiences with flooding is critical to contextualizing and understanding future potential vulnerability. Capturing data is more effective using a simple spatial (map-based) format.

- Historical flooding events have typically not been comprehensively documented in a format that is accessible, leaving a data gap.
- Climate change prompts difficult decisions, some of which may require high-level guidance or other adaptation actions that go beyond individual asset management decisions.

1 INTRODUCTION

The Maryland Department of Transportation State Highway Administration (MDOT SHA) manages over 73,000 lane miles of road and over 5,300 bridges. Several of these assets experience flooding, whether from extreme rain events (such as the devastating floods in Ellicott City in 2016 and 2018) or from extreme high tides or storm surge in Maryland's low-lying coastal areas. As these events persist and potentially worsen into the future, MDOT SHA is seeking to ensure the physical and economic health of Maryland's transportation system through, among other means, an asset management program that minimizes risk and optimizes state resources.[3]

In 2014, the MDOT SHA completed a pilot climate change vulnerability assessment to identify specific roads and bridges most vulnerable to flooding in Anne Arundel and Somerset counties. In 2018, MDOT SHA received a Federal Highway Administration (FHWA) grant to build on this work, including:

- Refining the vulnerability assessment approach and expanding the assessment to cover bridge structures statewide.[4]
- Identifying and implementing specific opportunities to integrate the vulnerability assessment results—and other information about climate risks—into existing MDOT SHA asset management, planning, lifecycle planning, and other processes.

This project is a part of the FHWA Asset Management, Extreme Weather, and Proxy Indicators pilot program.[5] This program seeks to

Why Integrate Climate Risk Into Asset Management?

Considering expected future conditions in asset management processes can ensure responsible use of taxpayer resources.

In addition, federal and state policymakers are increasingly realizing the benefits of planning for climate change and requiring MDOT SHA to take action, including:

- **Federal Regulation 25 CFR parts 515 and 667***: these regulations mandate that state DOTs must develop risk-based asset management plans that account for risks from climate change and extreme weather.
- **Maryland General Assembly 2018 Regular Session SB 1006 (HB 1350)†**: this legislation requires the development of "Coast Smart" siting and design criteria for new construction of structures or highway facilities.

* FHWA. 2016b. Asset Management Plans and Periodic Evaluations of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events.

† General Assembly of Maryland. 2018. Sea Level Rise Inundation and Coastal Flooding – Construction, Adaptation, and Mitigation.

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[3] MDOT. 2018. Maryland Transportation Asset Management Plan. Maryland Department of Transportation.

[4] The original scope of the project was to refine the approach and expand the assessment to Queen Anne's county, but the project team was able to expand the assessment statewide within available resources.

[5] FHWA. 2019. Asset Management, Extreme Weather, and Proxy Indicators Pilot Program (2017-2019). Federal Highway Administration. Available at: https://www.fhwa.dot.gov/asset/resources/pilot.pdf

create case studies for integrating extreme weather and climate risk into asset management practices and for developing a whole lifecycle cost management plan for assets that are subject to these risks. Through this pilot project, MDOT SHA is working to identify potential risks from extreme weather and future environmental conditions and incorporate information on resilience into asset management programs and lifecycle planning. MDOT SHA identified potential risks from extreme weather and future environmental conditions by performing a statewide climate change vulnerability assessment to identify bridge structures most vulnerable to flooding from sea level change, storm surge, and precipitation change under projected futures. The project team then worked with MDOT SHA staff across the agency to identify opportunities for incorporating this climate change vulnerability information into asset management programs and lifecycle planning processes, such as the Pavement Management System, project management manuals, and screening to inform project development.

This report documents the process and findings of the pilot study project. In addition, it summarizes key lessons learned that may be relevant to other agencies seeking to integrate climate risk into their ongoing asset management and planning practices.

Lifecycle Planning

Lifecycle planning aims to identify a strategy of maintenance, preservation, repair, rehabilitation, and replacement actions to achieve and maintain a desired state of good repair over the asset lifecycle while optimizing cost.*

This project considered how best to integrate climate risk considerations into MDOT SHA's existing lifecycle planning processes, using categories of assets to develop investment strategies. Options range from including climate risk information during project development on a case-by-case basis to systematically considering climate risk in asset condition forecasts and for use in investment planning. See Section 3 for details.

* FHWA. 2017b. Using a Life Cycle Planning Process to Support Asset Management. Available at: https://www.fhwa.dot.gov/asset/pubs/life_cycle_planning.pdf.

2 VULNERABILITY ASSESSMENT

The bridge vulnerability assessment conducted under this project, like the 2014 pilot assessment for Anne Arundel and Somerset counties[6], applies an indicator-based approach based on the FHWA Vulnerability Assessment Scoring Tool (VAST). The approach uses data on asset location and other key attributes to serve as indicators of each of the components of vulnerability[7]:

- Exposure – the nature and degree to which an asset is exposed to significant climate variations (i.e., asset location relative to a stressor).
- Sensitivity – the degree to which an asset is affected, either adversely or beneficially, by climate related stimuli (i.e., if all assets were equally exposed, which assets would experience the greatest damage?).
- Adaptive Capacity – the ability of a system or asset to adjust to the impacts of climate change to minimize potential damages, to take advantage of opportunities, or to cope with consequences.

The approach uses the scores assigned to each indicator to develop a vulnerability score for each asset across three climate hazards: sea level change, storm surge, and precipitation change.

Road Vulnerability Assessment: Hazard Vulnerability Index

Separate from this project effort, MDOT SHA has completed a statewide road vulnerability assessment, the results of which include a hazard vulnerability index (HVI). HVI provides a comparative risk value for road segments to climate change variables including sea level rise and subsequent storm events. HVI was also included in the integration activities described in Section 3: Integrating Results into MDOT SHA Practice.

Key Proxy Indicators

Overall, the key proxy indicators—those that most closely reflect vulnerability and contribute most to each asset's vulnerability score—are:

- Modeled inundation depth
- Past flooding experience/damage
- Underclearance
- Functional classification
- Evacuation route

Additional information on indicator weights is in Appendix A.

2.1 Proxy Indicators

The project team used the following indicators to represent MDOT SHA bridge vulnerability to the three climate hazards. The team selected these indicators based on the 2014 pilot study as a starting point, with refinements to represent best

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[6] MDOT SHA. 2014. Climate Change Adaptation Plan with Detailed Vulnerability Assessment. Final Report. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/maryland/final_report/mdpilot.pdf

[7] U.S. DOT. 2015a. Vulnerability Assessment Scoring Tool. U.S. Department of Transportation. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/adaptation_framework/modules/index.cfm?moduleid=4#tools

practices industry-wide and reflecting additional input from the MDOT SHA Office of Structures (OOS).

The indicators and scoring approach vary for each of the three climate hazards: sea level change, storm surge, and precipitation change (see Table 2). Each indicator received a different weight toward the overall vulnerability score.

Appendix A provides additional details on the specific weights and scoring approaches for the indicators and details specific ways the methodology differs from the 2014 pilot.[8]

Table 2. Vulnerability indicators for sea level change, storm surge, and precipitation change hazards

Component	Sea Level Change (SLC)	Storm Surge	Precipitation Change
Exposure	Modeled SLC Inundation Depth (2050 Mean Higher High Water)	Modeled Surge Inundation Depth (0.2% annual chance storm in 2050)	Location relative to Federal Emergency Management Agency (FEMA) Flood Zones
	Proximity to Coastline	Proximity to Coastline	Percent change in 24-hour, 50-year precipitation
Sensitivity	Past Experience with Tides/SLC	Past Experience with Storm Surge	Past Experience with Precipitation
	Underclearance	Underclearance	Underclearance
	Scour Rating	Scour Rating	Scour Rating
	Bridge Age as of 2018 (from most recent reconstruction)	Bridge Age as of 2018 (from most recent reconstruction)	Bridge Age as of 2018 (from most recent reconstruction)
	Condition of Bridge Substructure	Condition of Bridge Substructure	
	Condition of Bridge Superstructure	Condition of Bridge Superstructure	
	Condition of Bridge Deck	Condition of Bridge Deck	
Adaptive Capacity	Functional Classification	Functional Classification	Functional Classification
	Evacuation Route	Evacuation Route	Evacuation Route
	Detour Length (overall increase in path length due to a detour around a flooded structure)	Detour Length (overall increase in path length due to a detour around a flooded structure)	Detour Length (overall increase in path length due to a detour around a flooded structure)

[8] FHWA. 2016a. 2013-2015 Climate Resilience Pilot Program: Outcomes, Lessons Learned, and Recommendations. U.S. Department of Transportation, Federal Highway Administration (FHWA). FHWA-HEP-16-079. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/final_report/fhwahep16079.pdf

Component	Sea Level Change (SLC)	Storm Surge	Precipitation Change
	Average Daily Traffic (ADT)	Average Daily Traffic (ADT)	Average Daily Traffic (ADT)

2.1.1 Exposure

Sea Level Change: The scoring approach uses two indicators of exposure for sea level change: modeled inundation depth (under 2050 mean higher high water (MHHW)[9]) and proximity to coastline. Data on modeled inundation depth comes from the Salisbury University Eastern Shore Regional GIS Cooperative. Locations expected to experience higher flood depths during high tide are more likely to experience more frequent tidal inundation, including permanent inundation. Further, assets that are located closer to the coastline are more likely to be affected by sea level change. The vast majority (90%) of the exposure score is based on modeled coastal inundation depth from HAZUS models. The Federal Emergency Management Agency's (FEMA) HAZUS model is a decision-support tool that visualizes risk to natural disaster threats.

Storm Surge: Similarly, the storm surge exposure approach accounts for modeled inundation depth (under the 0.2% annual chance storm with 2050 MHHW levels that incorporate expected sea level change) and proximity to coastline. The storm surge inundation data also come from the Salisbury University Eastern Shore Regional GIS Cooperative. Using the most extreme inundation scenario available allows for a conservative identification of assets potentially affected by coastal flooding. Those that experience the highest inundation depths under this scenario are most likely to experience inundation under lesser surge events. The vast majority (80%) of the exposure score is based on modeled inundation depth.[10]

Precipitation Change: The scoring approach uses two indicators of exposure for precipitation change (which, in turn, can cause inland/riverine flooding): location relative to FEMA flood zones and modeled percent change in 24-hour, 50-year precipitation. The FEMA flood zones are currently the best available dataset that defines flood risk spatially. While they do not account for how flood risk may change in the future due to changing rainfall and other conditions, at a minimum, assets located in current flood zones are likely to be exposed in the future. To reflect the fact that precipitation events are changing, the other indicator used is the modeled change in the 24-hour, 50-year rain event, which varies across the state. Additional modeling would be

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[9] Mean Higher High Water (MHHW) is the average of the higher high water height of each tidal day observed over the National Tidal Datum Epoch. For stations with shorter series, comparison of simultaneous observations with a control tide station is made in order to derive the equivalent datum of the National Tidal Datum Epoch. Source: NOAA. 2018b. "Tidal Datums." National Oceanographic and Atmospheric Administration (NOAA). Available at: https://tidesandcurrents.noaa.gov/datum_options.html

[10] Exposure inundation depth weights for sea level change (90%) and storm surge (80%) differ based on approach used in 2014 MDOT SHA Pilot Study approach. Study team determined weights based on expert input from MDOT SHA engineers.

needed to convert changing rainfall amounts into changing flood zones.[11] Therefore, the current FEMA flood zones account for the vast majority (95%) of the exposure score.

2.1.2 Sensitivity

Sensitivity indicators represent which assets may be more likely to experience damage or disruption due to flooding. The scoring approaches for all hazards include three common indicators: past experience (structures that have demonstrated sensitivity in the past are more likely to be sensitive in the future), scour rating (scoured assets are more likely to experience impacts when exposed), and bridge age (older bridges are more likely to be damaged when exposed, since they may have been built to an older design standard).

All hazards incorporate underclearance as a sensitivity indicator. For sea level change and storm surge, assets with a lower underclearance are more likely to experience impacts when exposed since they are more likely to be overtopped and disrupted. For precipitation change and associated riverine flooding, assets with a greater underclearance are more likely to experience impacts when exposed since those assets may experience higher velocities of water and greater scour.[12]

In addition, the approaches for sea level change and storm surge include three additional indicators that are not relevant to precipitation change: condition of bridge substructure, condition of bridge superstructure, and condition of bridge deck. In all cases, bridges in deteriorated condition are more likely to be damaged when exposed due to the exacerbation of pre-existing weaknesses.

2.1.3 Adaptive Capacity

All hazards use four indicators to score adaptive capacity: average daily traffic (bridges with large amounts of traffic are highly significant routes that are difficult to detour and experience the largest disruption when compromised), functional classification (the transportation system may be less able to absorb impacts to assets of higher functional classification), evacuation route (bridges that are part of evacuation routes compromise safety and will cause greater disruption to the system if damaged), and detour length (bridges with long detours are more disruptive to the overall system if damaged).

Appendix A provides additional details on the specific weights, rationales, and scoring methods used in the assessment.

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[11] MDOT SHA is sponsoring a separate study to develop better spatial estimates of future inland flooding, beginning in late 2018.

[12] Based on feedback received in July 2018 working sessions from participants in the bridges asset management session, the project team reversed the scoring bins for underclearance for precipitation change so that assets with a greater underclearance receive a higher exposure score. Participants indicated that assets with greater underclearance are more likely to experience impacts from precipitation due to scour caused by increased velocities of water.

2.2 Results

Across the 8,588 bridges assessed statewide, the assets with a high vulnerability (vulnerability score of at least 3 out of 4) are as follows:

- Sea level change: 33 assets
- Storm surge: 172 assets
- Precipitation change: 102 assets

Bridges missing data for all indicators within a component did not receive a vulnerability score and are not included in the distributions shown in Figure 1, 3, and 5.

Figure 1 depicts the distribution of **sea level change** vulnerability scores. The majority of bridges fall between 1.5 (low) and 2.5 (moderate), since they have low exposure to flooding from sea level change, with just 33 bridges emerging as high vulnerability. Figure 2 maps those bridges with high vulnerability, showing they are concentrated in coastal areas.

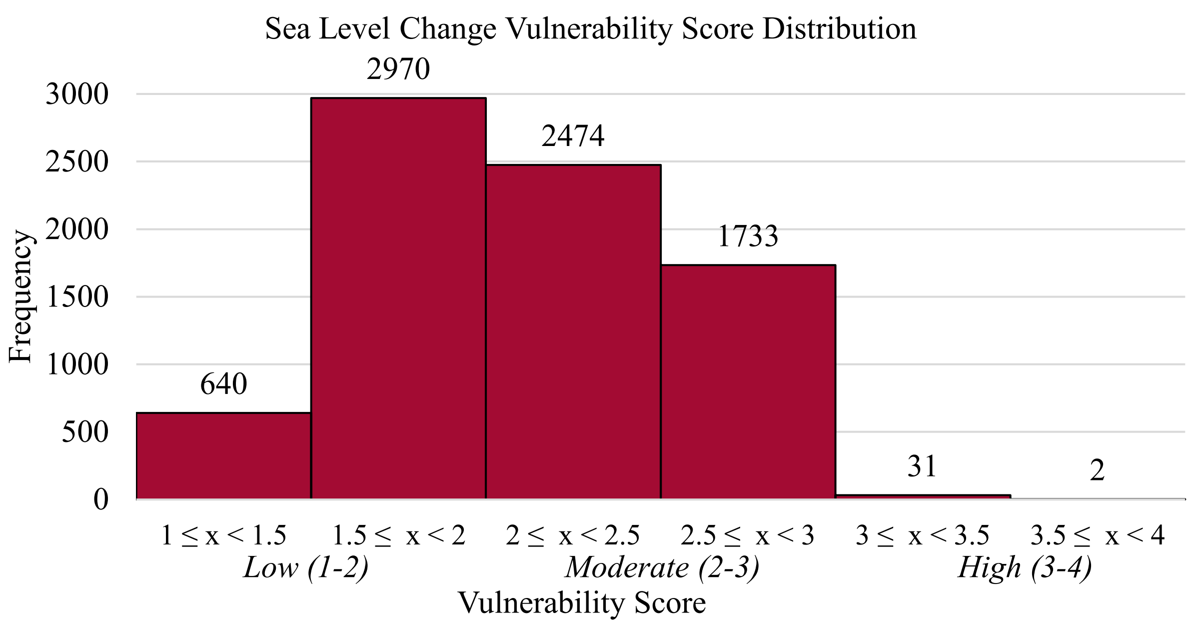

Figure 1. Distribution of bridge sea level change vulnerability scores

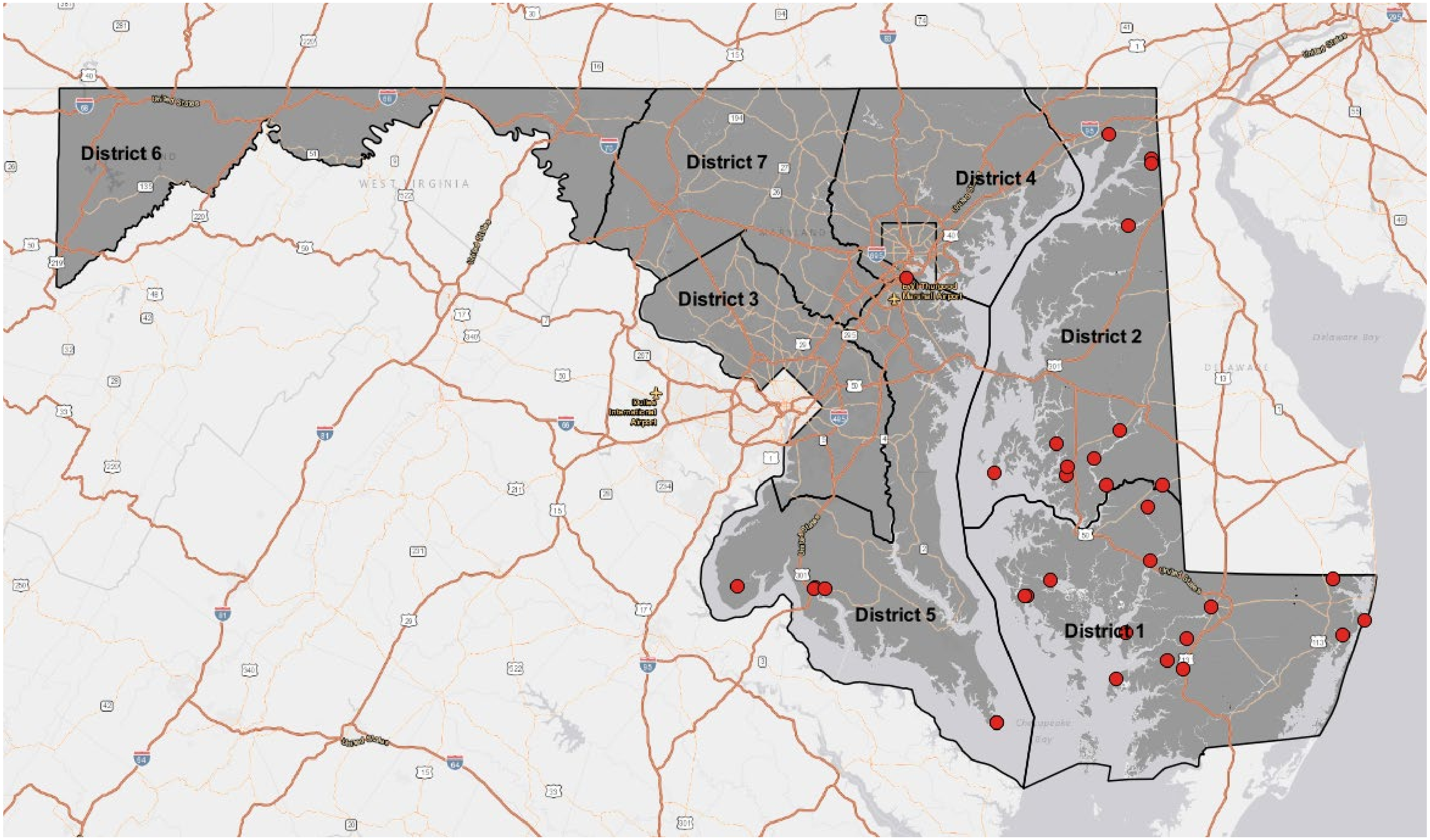

Figure 2. Bridges with high sea level change vulnerability (vulnerability ≥ 3)

Figure 3 depicts the distribution of **storm surge** vulnerability scores. The majority of the bridges fall between 1.5 (low) and 2.5 (moderate), again because exposure to storm surge is limited to coastal areas. Figure 4 maps the 172 bridges with high vulnerability to storm surge, shown to be concentrated in MDOT Districts 1, 2, 4, and 5.

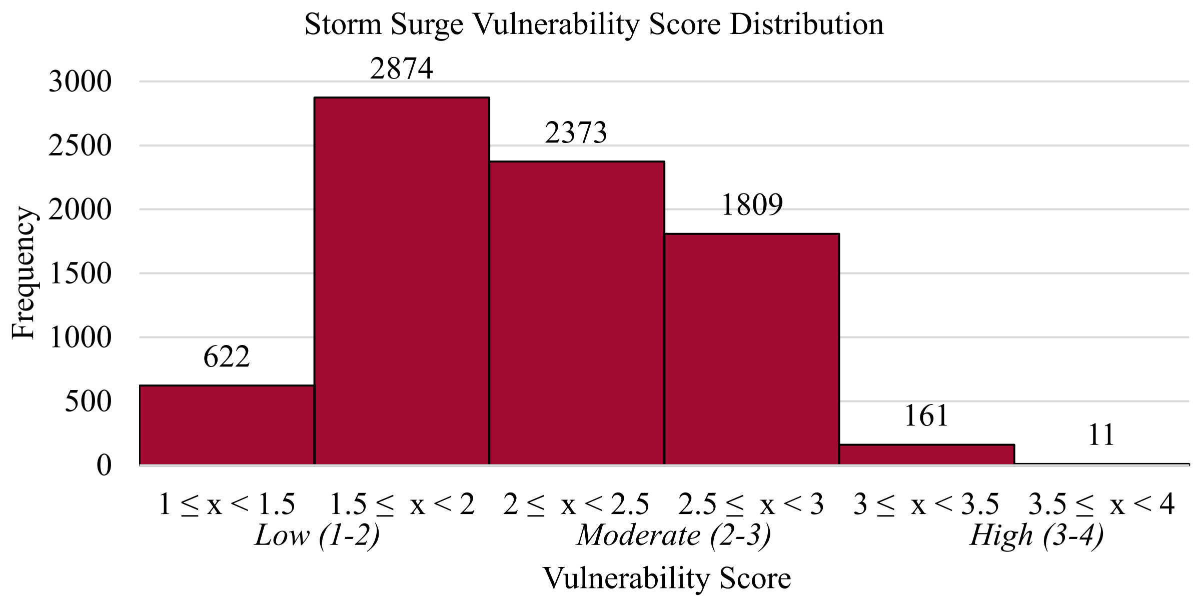

Figure 3. Distribution of bridge storm vulnerability scores

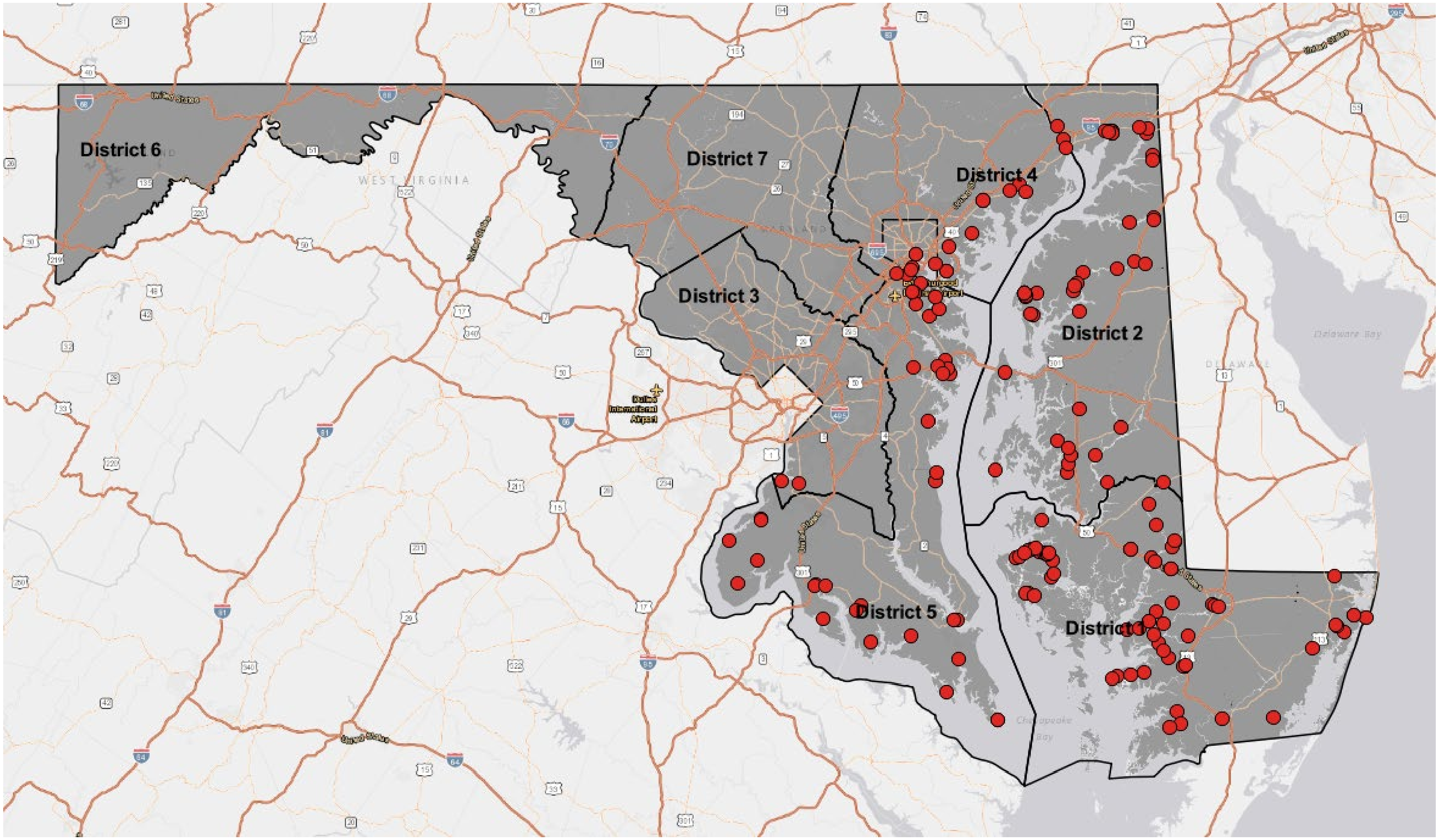

Figure 4. Bridges with high storm surge vulnerability (vulnerability ≥ 3)

Finally, Figure 5 depicts the distribution of **precipitation change** vulnerability scores. Again, most assets have low or moderate vulnerability. The majority of the asset scores fall between 1.5 (low) and 2.5 (moderate). Assets with high vulnerability to precipitation change are spread across all MDOT SHA Districts, with the highest concentration in Districts 4 and 7 (see Figure 6).

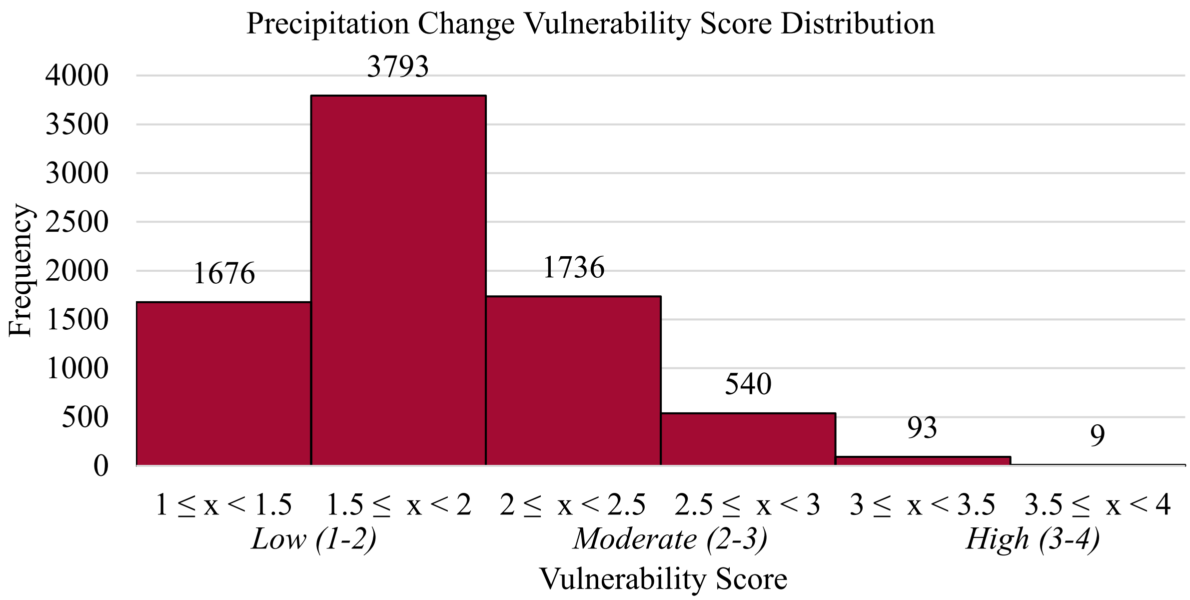

Figure 5. Distribution of precipitation change vulnerability scores

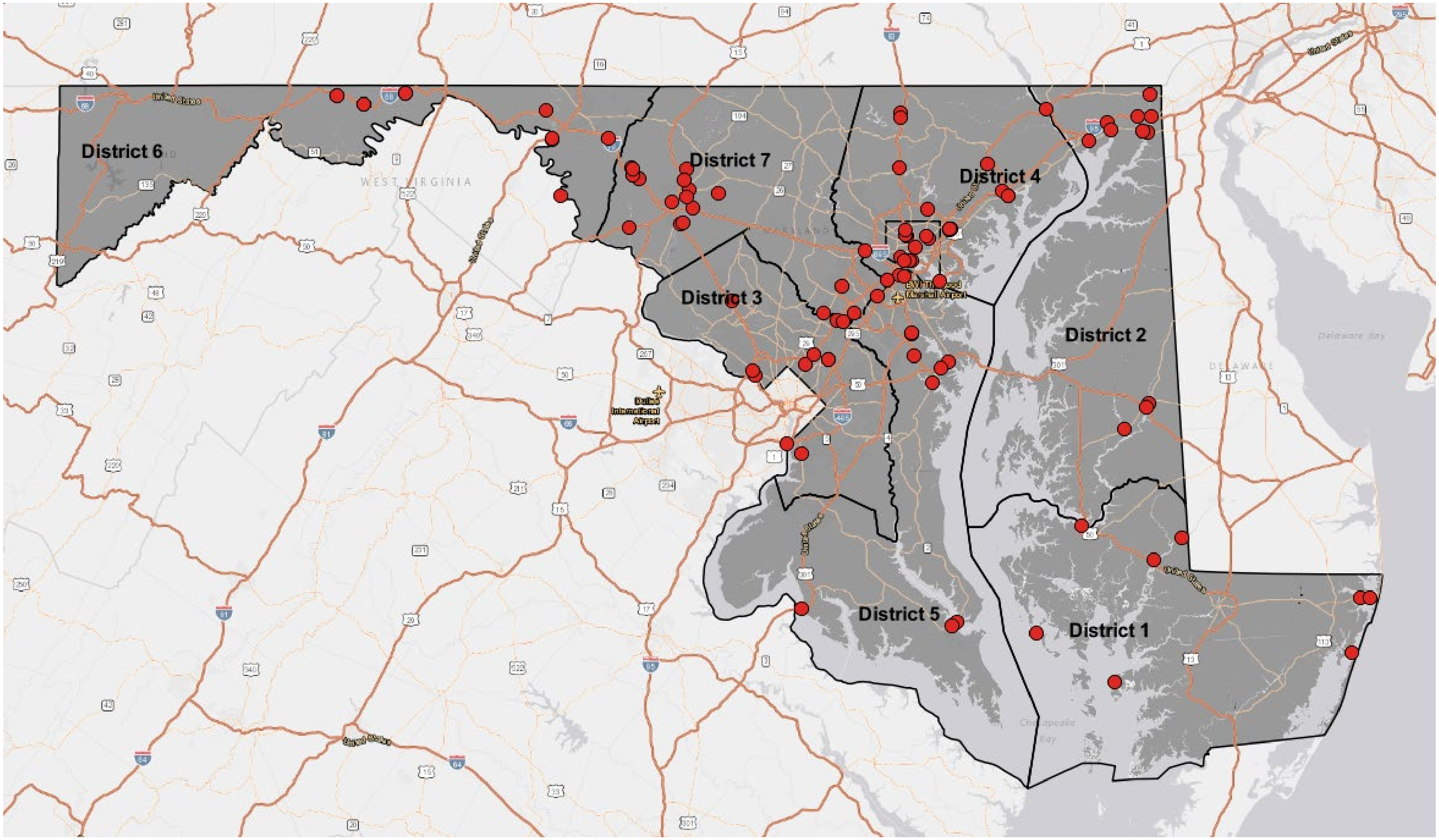

Figure 6. Assets with high precipitation change vulnerability (vulnerability ≥ 3)

Full results are available for exploration in the MDOT SHA Climate Change Vulnerability Viewer (CCVV) at: https://arcg.is/1af8L4. Figure 7 shows an example screen capture of the web viewer showing roads inundated under 2050 Mean Higher High Water from the 2% annual chance storm (also known as the 50-year storm).

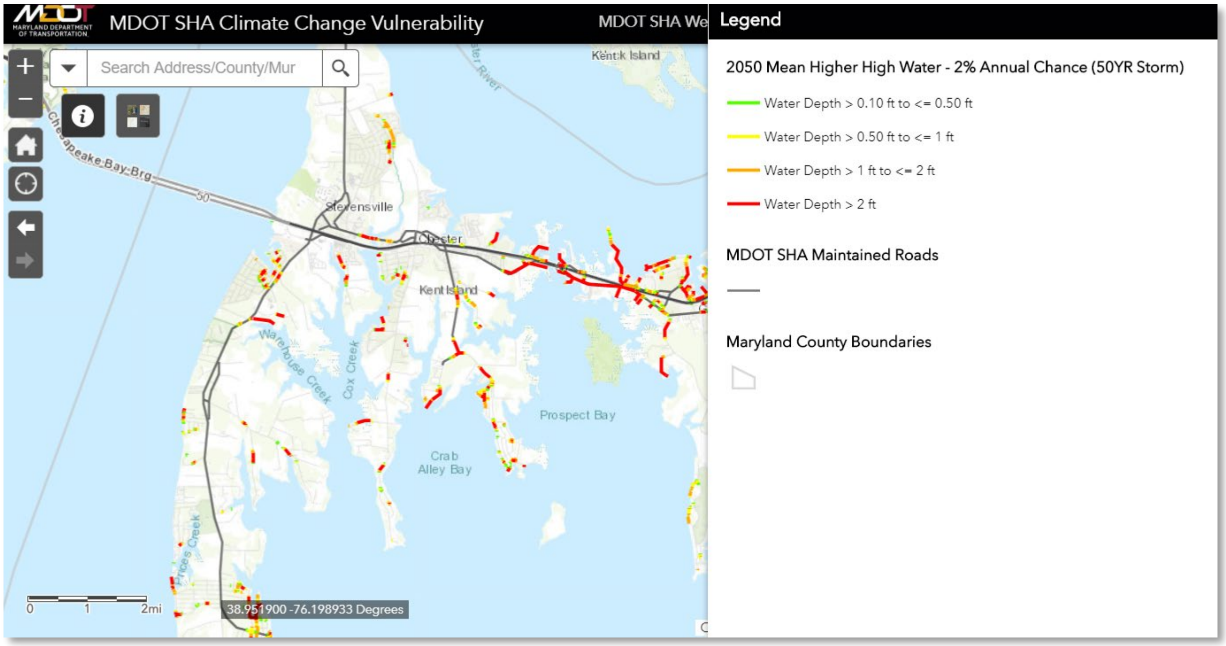

Figure 7. Screen capture of MDOT SHA Climate Change Vulnerability Viewer

3 INTEGRATING RESULTS INTO MDOT SHA PRACTICE

3.1 Approach

The project team conducted a series of four working sessions with MDOT SHA staff to discuss opportunities and strategies for integrating climate risk data (see box) into existing systems and processes for asset management and lifecycle planning, including pavement asset management, bridge asset management, planning, and operations.

During each working session, the project team facilitated a review of the available vulnerability assessment results, discussion of the climate risks in the Transportation Asset Management Plan (TAMP) risk register, and discussion of ways to apply the climate risk information. Guiding questions included:

- How can vulnerability data be most useful?
- Who needs access to what data, and what are the most effective ways to get it to them (e.g., where are they already going for information)?
- Can vulnerability data be integrated into the Pavement Management System (PMS) or Bridge Management System (BMS)? If so, how?
- Is it possible to integrate data into decision support systems? What would need to happen to enable this integration?
- What supplemental information is needed to ensure the data can be acted upon (e.g., guidance, decision trees, policy)?

The working sessions identified several opportunities to use the climate risk

Climate Risk Data

The climate risk data discussed in the working sessions and targeted for integration into agency practices, as applicable, include:

- **Statewide bridge vulnerability assessment results** (described in detail in Section 2.2), including overall vulnerability scores and constituent parts.
- **Inundation depth and extent** under a range of sea level change and storm scenarios (2015, 2050, and 2100 mean sea level and mean higher high water for the 0%, 0.2%, 1%, 2%, 4%, and 10% annual chance storm events).
- **Statewide coastal roadway inundation depth** under each of the sea level change and storm scenarios.
- **Statewide coastal roadway HVI ratings** (developed in 2014 pilot project), reflecting expected inundation depth and system criticality (based on evacuation route and functional classification), under each of the sea level change and storm scenarios.
- **Estimates of the percentage of time** each coastal roadway segment would be inundated in 2015 and 2050 (see description in Appendix B: Pavement Performance Supplement).

The data are available at: https://maryland.maps.arcgis.com/apps/webappviewer/index.html?id=86b5933d2d3e45ee8b9d8a5f03a7030c.

information in asset management and other processes. The actions included specific strategies for using the risk information in decision-making, as well as the smaller, incremental steps necessary to enable those processes. Highlights of the strategies MDOT SHA is taking as the result of this project are in the box below.

Integrating Climate Risk Data into Practice: Key Actions Identified

- **Update pavement performance models to reflect current and expected inundation frequency.** This will ensure inundation is captured in expected deterioration rates and automatically factored into existing processes for prioritizing and financing maintenance and other investment priorities.
- **Create and implement a process to screen any new structures projects for climate risk.** This will ensure the agency takes advantage of existing repairs or replacement projects to address climate risks as appropriate.
- **Incorporate climate risk into the project Purpose and Need.**
- **Create a climate risk data viewer and disseminate climate risk data throughout the agency and its partners** to ensure all are aware of the information and its applications to decision-making. Where possible, creating formal processes to ensure people consult it at relevant junctures.

All of these strategies—and the supporting actions necessary to achieve them—will help MDOT reduce lifecycle costs of their infrastructure. Additional details are provided in Sections 3.2, 3.3, 3.4, and 3.5.

These opportunities and other outcomes of the working sessions are described below in Sections 3.2, 3.3, 3.4, and 3.5.

3.2 Pavement Asset Management

The project team held an in-person working session with staff from the MDOT SHA Office of Materials Technology (OMT) to discuss ways to integrate data on potential pavement risks related to sea-level change and other climate hazards into PMS at MDOT SHA. The goal of the discussion was to find entry points to integrate climate risks into pavement asset management and lifecycle planning processes (see the asset management process in Figure 8).

Figure 8. Diagram of the Maryland pavement asset management cycle

Two primary opportunities emerged from this working session:

1. MDOT SHA could incorporate data on pavement vulnerabilities into PMS.
2. MDOT SHA could update the PMS performance models to account for accelerated deterioration due to flooding, based on the percentage of time each pavement is expected to be inundated.

These actions would enable OMT to systematically factor climate-related flood risk into ongoing asset management and lifecycle planning decisions. For example, incorporating flood frequency into the performance modeling step will ensure that MDOT SHA can proactively address flood-related pavement damage, rather than make reactionary repairs. Including pavement risk data in the PMS will further ensure this information is considered alongside other relevant factors when making asset-by-asset decisions, which will affect life cycle optimization (including cost optimization). For example, road segments that are likely to be flooded more frequently into the future may experience accelerated deterioration that may require more frequent preventive maintenance, which may have a lower cost than reactionary repairs. The PMS is the key to the lifecycle planning process for pavements; the system develops investment strategies based on asset condition. By integrating climate risk information into the PMS, MDOT SHA will be able to sub-categorize assets based on current and future climate risk information and develop lifecycle strategies that consider changing environmental conditions.

In order to update the PMS performance model, OMT staff identified that, while HVI and expected inundation depth under different flood scenarios were useful, the following information would even more directly inform expected pavement deterioration:

- Frequency/percentage of time any given segment is likely to be inundated
- Relationship between sea level change and water table elevation change

Therefore, the project team developed an approach to calculate this information and provided it to OMT (see details in Appendix B).

Finally, the discussion revealed that, while there are key actions OMT can take to understand and manage risks to pavements, flooding will also affect operations as well as local transportation agencies. The climate risk information should therefore also be accessible to districts, local governments, and operations staff. Over time, it will be helpful to collect better data on road closures related to flooding to understand impacts on operations over time.

Table 3 summarizes the key actions that emerged from the working session and follow-up discussions, as well as the status of those actions (as of the date of this report). All items currently 'In Progress' are expected to be completed by mid-2019.

Table 3. Pavement asset management integration actions identified

Status	Action
Complete	Calculate and provide the percentage of time different road segments may be inundated (to inform pavement performance modeling).
Complete	Provide information on the impacts of inundation on pavement performance (to inform pavement performance modeling).
Complete	Make climate risk information available to District, Operations, MPOs, counties and municipalities, as well as other state agencies.
In Progress	Add climate risk fields (e.g., pavement inundation frequency, HVI) into the PMS to inform lifecycle planning.
In Progress	Update PMS performance models to reflect current and expected inundation frequency. This will ensure inundation is captured in modeled deterioration rates and proactively factored into maintenance and other investment priorities.
In Progress	Systematize collection of road and bridge closure information associated with flooding.

3.3 Bridge Asset Management

Similar to the pavement session above, the project team held an in-person working session with staff from the MDOT SHA Office of Structures (OOS) to discuss ways to integrate data on potential pavement risks related to sea level change and other climate hazards into BMS and structure lifecycle planning processes.

Participants acknowledged that the vulnerability assessment results will be useful, particularly to inform decisions as bridges are up for replacement. To ensure OOS staff have access to the data, they recommended the data be included in an interactive online web viewer that would allow OOS to view the overall vulnerability score as well as its constituent parts (e.g., exposure vs. sensitivity vs. adaptive capacity, as well as individual indicators).

Through additional discussions, the project team ultimately developed a "climate risk screening" process for Planning to complete as structures enter the project pipeline (e.g., for replacement or rehabilitation). If assets have been identified in the vulnerability assessment results as both exposed to climate hazards and sensitive to those hazards, then the screening process prompts MDOT SHA to gather additional information about the project context and flooding risk factors to ultimately inform whether and how changing risks should be factored into project development. See Appendix C for a working draft of this screening process.

This process will ensure that climate risks are considered proactively as structures come up for rehabilitation or replacement, often the most cost-effective time to account for sea level change or other future environmental conditions and reduce their effect over the lifetime of the asset.

Participants also noted several anticipated challenges and needs associated with being able to manage climate risks identified through the assessment. For example:

- Data currently available about inland flooding/precipitation change risk is not sufficient to understand how expected precipitation changes will affect flood risk for structures.
- It would be helpful to have a database of frequently flooded locations to inform and validate the results. The project team developed a survey to collect this information from District maintenance staff as a baseline (See Figure 11). MDOT SHA is actively working to improve active tracking of flood issues for both roads and structures.
- Climate risk data would need to be considered alongside all other factors when an asset is up for repair or replacement. In many cases, MDOT SHA may be limited in its ability to reduce the vulnerabilities (more details on these constraints in the following bullet) but could consider options and document the decisions. This will have to be considered on a case-by-case basis. Some cases may require public involvement (e.g., decisions about whether to reduce maintenance on a road).
- MDOT SHA may be constrained in its ability to adapt highly vulnerable assets. Barriers include:
    - Budgetary constraints to implementing retrofits for projected changes.
    - Permitting and environmental compliance challenges limiting what can be changed due to potential impacts on surrounding land and downstream urban areas. For example, MDOT SHA may be unable to upsize a bridge or culvert to accommodate projected higher flows because it would increase flood depth elevations on adjacent property. Coordination with MDOT SHA's Office of Environmental Design (OED) may be required.
- OOS would like guidance or processes for adaptation considerations, including a strategy for communicating these decisions to the public and coordinating with individual communities. For example, what are some key steps or considerations for investments in assets expected to be under water in 50 years or less?

Table 4 summarizes the key actions that emerged from the working session and follow-up discussions, as well as the status of those actions (as of the date of this report). All items currently 'In Progress' are expected to be completed by mid-2019.

Table 4. Bridge asset management integration actions identified

Status	Action
Complete	Include a field for the HVI score in bridge vulnerability results in CCVV to indicate vulnerability of the bridge approach.
Complete	Develop a review process for considering risks related to future environmental conditions in project planning (see Appendix C).
In Progress	MDOT SHA to apply review process for considering risks related to future environmental conditions in project planning.
In Progress	Office of Planning and Preliminary Engineering (OPPE) to incorporate bridge vulnerability results into CCVV.
In Progress	OOS to consult CCVV in project planning process.
In Progress	Improve modeling of precipitation change effects on flood zones.
In Progress	MDOT SHA to systematize collection of bridge closure information associated with flooding.
To Do (long-term)	Develop guidance regarding project development strategies for various sub-categories of assets that take climate risk information into account.

3.4 Planning

The project team held an in-person working session with the MDOT SHA Office of Planning and Preliminary Engineering (OPPE) to discuss ways to integrate data on potential climate change risks into planning practices and databases. The vulnerability assessment results can inform decisions about identification and evaluation of capital projects through activities undertaken by OPPE. To start, MDOT SHA can take steps to raise awareness about climate risks and existing data within OPPE, OED, and the Office of Highway Development (OHD) by presenting the vulnerability assessment results in coordination meetings and holding lunch and learn events with staff. Through this process, planners will become more familiar with the climate data available and study results. As planners and engineers become aware of the issues, climate risks can be integrated into project development processes. Some processes are already structured to enable the integration of the vulnerability assessment results. For example, as part of the National Environmental Protection Act (NEPA) review process, MDOT SHA staff prepared Programmatic Categorical Exclusion documentation that includes a section on climate change impact areas (see Figure 9).

Climate Change Impact Areas

Is this Project within an area potentially affected by Sea Level Change? Yes — Project must consider sea level change.

- ☒ Mean Sea Level 2050
- ☒ Mean Sea Level 2100
- ☒ Mean High High Water 2050
- ☒ Mean High High Water 2100

See attached Sea Level Change Map, if applicable

Is this a non-state Project located on State lands? No

Is this project involving construction of a new road or bridge, or reconstructing an existing road or bridge due to a storm event? No

Is this project involving construction of a new building/facility or reconstructing an existing building/facility due to a storm event? No

Notes: The hydraulics analysis determined that up to 100-year storm flooding events would not overtop the bridge. The roadway approaches to the bridge are being raised between 1 to 2.5 feet. Additional roadway improvements may be needed to address future flooding.

Figure 9. MDOT SHA Programmatic Categorical Exclusion document section on climate change impact areas[13]

In addition, the climate risk results can also be rolled into Purpose and Need for projects if climate risks are present. Because each project is required to develop a Purpose and Need, incorporating climate risk information could be a consistent way to consider and address risks across all new projects. Table 5 details specific actions to ensure that climate risk results begin to inform project development.

In the longer-term (once the awareness raising phase is complete), the results could also be used in a variety of ways to more systematically account for climate risks in project planning across the agency. For example:

- **Include climate risks in MOSAIC.** MOSAIC (Model of Sustainability and Integrated Corridors) is a quantitative tool MDOT SHA uses to estimate the impact of multimodal highway corridor improvement options on sustainability in the transportation planning process.[14] MOSAIC uses sustainability indicators (e.g., mobility, safety, environmental

[13] MDOT SHA. 2016. Memorandum: Replacement of Bridge No. S-0019 Bryan Hall Road over Marumsco Creek, Somerset County, Maryland. Programmatic Categorical Exclusion.

[14] MDOT SHA. 2015. MOSAIC: Model of Sustainability and Integrated Corridors. Research Project: SP309B4H. Available at: https://www.roads.maryland.gov/OPR_Research/MD-15-SHA-UM-3-7_MOSAIC-Phase3_Summary.pdf

impact) that help determine which solution offers the best balance. Integrating climate risk information into these indicators or in other elements of MOSAIC will allow MDOT SHA to consider climate resilience in corridor improvement planning.

- **Make climate risk data available to discretionary grant applicants such as the Transportation Alternatives Program (TAP).**[15] The TAP is a Federal aid program that MDOT SHA administers for transportation-related community projects that strengthen the intermodal transportation system in Maryland.[16] MDOT SHA will make the climate risk results available as a data source for consideration to ensure resources are funding projects that will be robust into the future.
- **Develop decision trees or other guidance on how to manage climate risks.** As more and more projects go through climate risk reviews (such as described under Section 3.3) and MDOT SHA gains more experience making case-by-case decisions, patterns or "rules of thumb" for making such decisions may emerge. Over time, it would be useful to establish agency-wide guidance, such as in the form of decision trees or other resources, to quickly determine the best risk management strategy in a given scenario (e.g., high risk coastal asset, already in poor condition due for replacement vs. high risk coastal assets in good condition).

Table 5 summarizes the key actions that emerged from the working session and follow-up discussions, as well as the status of those actions (as of the date of this report). All items currently 'In Progress' are expected to be completed by mid-2019.

Table 5. Planning integration actions identified

Status	Action
Complete	OPPE to review CCVV and document project adaptation in environmental review (e.g., National Environmental Policy Act (NEPA) processes).
In Progress	OPPE to finalize CCVV and share with counties.
In Progress	OPPE to share CCVV at standing OHD and OPPE coordination meetings.
In Progress	OPPE to share CCVV with all Districts.
In Progress	OPPE to hold a "lunch and learn" series to share CCVV, availability of climate risk information. Participants may include Bridge Hydraulics and Highway Hydraulics, among others.

[15] The FAST Act replaced the Transportation Alternatives Program (TAP) with a set-aside of funds under the Surface Transportation Block Grant Program. The new set-aside, which is referred to as the Transportation Alternatives (TA) Set-Aside, provides funding through 2020 for all of the projects and activities previously eligible under the TAP.

[16] MDOT SHA. 2019. Transportation Alternatives Program. Available at: https://www.roads.maryland.gov/index.aspx?PageId=144.

Status	Action
In Progress	OPPE to incorporate climate risk into Purpose and Need template, which is completed to justify all new projects.
In Progress	OPPE to update project management manuals or checklists to include the climate risk results as resource materials for consideration during project development and management.
To Do (long-term)	OPPE to integrate climate risks into MOSAIC, a quantitative tool used to estimate the impact of multimodal highway corridor improvement options on sustainability in the transportation planning process.[17]
To Do (long-term)	OPPE to provide climate risk data to discretionary grant applicants.
To Do (long-term)	MDOT SHA to develop decision trees and other guidance on climate risk management.

3.5 Operations

The project team held a teleconference with the Coordinated Highways Action Response Team (CHART) to discuss opportunities to integrate climate risk data into operations processes. The vulnerability assessment results can inform operations decisions surrounding evacuation planning as well as post-event planning, staging, and access decision-making. More specifically, the climate risk data can inform the CHART's understanding of what populations will be at risk to flooding in the future and how accessible existing or planned evacuation shelters might be under various future flood scenarios. Integrating climate risk data into evacuation planning decisions can help the Operations team determine the best routes for evacuation and ensure evacuation shelters are accessible to vulnerable populations.

In addition, CHART can support efforts to collect and share information on how frequently different roads and structures are flooded, and its effects on operations.

Table 6 summarizes the key actions that emerged from the working session and follow-up discussions, as well as the status of those actions (as of the date of this report). All items currently 'In Progress' are expected to be completed by mid-2019.

[17] MDOT SHA. 2015. MOSAIC: Model of Sustainability and Integrated Corridors. Research Project: SP309B4H. Available at: https://www.roads.maryland.gov/OPR_Research/MD-15-SHA-UM-3-7_MOSAIC-Phase3_Summary.pdf

Table 6. Operations integration actions identified

Status	Action
Complete	Provide CHART with a "cheat sheet" for how to interpret the different flood extent layers.
In Progress	CHART, District Maintenance, and Office of Maintenance to consult CCVV to inform preparations for flood events.

3.6 Transportation Asset Management Plan

During the working sessions on Pavement Asset Management, Bridge Asset Management, and Planning, the project team also discussed options for integrating climate and extreme weather risks into the MDOT TAMP. One required element of a TAMP is a "risk register," a simple table that identifies and prioritizes risks to the agency's ability to meet its objectives.[18] The initial Maryland TAMP (submitted for FHWA review on May 4, 2018) risk register includes several climate-related risks alongside financial, compliance, and other risks. This existing risk register is a good starting point for consideration of climate risks within the TAMP. Table 7 summarizes the climate change-influenced risks to transportation assets included in the initial TAMP.

Table 7. Climate change-related risks to MDOT assets identified in the preliminary TAMP[19]

Asset	Risk Identified	Likelihood Rating	Impact Rating	Consequence Rating
Bridges	If predictive models are not accurate, projections may not be correct.*	4	2	Medium
	If an Act of God impacts a fracture critical bridge, there may be failure.*	5	1	Medium
Pavement	If climate effects result in floods or inundations, it will have a negative effect on the pavement conditions.	3	2	Low
	If climate effects result in severe freeze or heat, it will have a negative effect on the pavement conditions.	3	1	Low

*Neither of these are explicitly climate-related, but climate change increases their likelihood. These ratings will be reviewed with climate risk considerations prior to the final TAMP submittal.

The project team provided additional suggestions for more detailed climate-related risk items based on the vulnerability assessment results, including:

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[18] FHWA. 2017a. Incorporating Risk Management into Transportation Asset Management Plans. Federal Highway Administration. Available at: https://www.fhwa.dot.gov/asset/pubs/incorporating_rm.pdf

[19] Derived from Figure 5.2 and 5.3 of the MDOT TAMP (MDOT 2018).

Pavements:

- If new pavements are designed based on historical climate conditions and those conditions change, then assets would not meet their intended level of service over their lifetime.
- If sea levels change as expected, some low-lying roadways will be permanently inundated.
- If sea levels change as expected, the water table may rise, affecting the sub-base of pavement structure and reducing pavement life.
- If heavy precipitation events become more extreme, more frequent inundation, erosion, and pavement damage may occur, with a negative effect on pavement condition and maintenance costs.
- If roads are flooded more frequently due to sea level change, MDOT may be unable to provide road access to certain locations or would incur additional cost to provide the same level of service.
- If evacuation routes are damaged by extreme weather events or flooded by high tide, then they may be unable to fulfill their function and provide egress and ingress routes to coastal areas before and after a storm.
- If climate change increases coastal and inland flooding, then repair and maintenance costs may escalate.

Bridges:

- If bridge approaches are flooded more frequently due to sea level change or heavy rain, then bridges may be unable to provide intended level of service.
- If climate change increases coastal and inland flooding, then repair and maintenance costs may escalate.
- If new bridges are designed based on historical climate conditions and those conditions change, then assets would not meet their intended level of service over their lifetime.

At working sessions, participants discussed that no changes are needed to the existing TAMP risk-register statements, given the intended level of detail of the TAMP. More detailed consideration of climate risks in asset management should be achieved through the specific system-level integration actions discussed previously.

However, participants determined it would be effective to pair the existing climate-related risk register statements with additional information on the magnitude of risks. For example, including in the TAMP the number of National Highway System roads that are at high risk can communicate the scale of the risk within Maryland. Figure 10, for example, provides a visualization of the relationship between sea level change vulnerability and average substructure, superstructure, and deck condition. This type of visualization can help to identify strategies for the structures asset class generally, as well as identifying specific structures that could be prioritized for improvement (e.g., assets with poor condition and high sea level change vulnerability).

Figure 10. Example of how system-wide statistics can inform the TAMP: Sea level change vulnerability score vs. average bridge condition (based on substructure, superstructure, and deck condition) for MDOT SHA structures

Finally, in addition to the risk register, the project team is integrating climate risk considerations throughout the TAMP. For example, as discussed previously, several of the strategies identified through this project inform the life cycle planning processes for pavements and bridges and, in turn, financial planning. The final TAMP will reflect these considerations.

Table 8 summarizes the key actions that emerged from the working sessions and follow-up discussions, as well as the status of those actions (as of the date of this report). All items currently ‘In Progress’ are expected to be completed by mid-2019.

Table 8. TAMP integration actions identified

Status	Action
Complete	Continue to include climate-related risks in the overall TAMP risk register.
In Progress	OPPE to share statewide climate risk statistics with OMT and OOS related to TAMP risk register items.
In Progress	Incorporate climate risk considerations throughout TAMP.

4 NEXT STEPS

MDOT SHA has taken and will continue to take steps to integrate findings from this pilot project (see Table 3 through Table 8). Cross-cutting next steps include:

- **Improve and finalize the online interactive CCVV, which includes HVI data, bridge vulnerability data, and related future flooding information.** This viewer, which will be widely available within MDOT SHA, will provide access to climate risk information for use in asset management activities. Part of finalizing this update may include creating guidance to determine what layers in the interactive CCVV are most useful for each asset or study. This type of guidance will assist operations and other teams in planning for storm events and anticipating system disruptions.
- **Implement a process for tracking flood-related road closures (e.g., road closure reporter).** The project team will work with existing road closure and damage reporting systems in the Districts, OOM and CHART to ensure data are captured correctly and identify flooding-related causes of road closures.
- **Continue to disseminate climate risk information through coordination meetings, lunch and learn meetings, and other venues.** For example, members of the project team will seek to present findings at OHD and OPPE coordination meetings, environmental planning coordination meetings, and lunch and learn meetings.
- **Complete implementation of all "In Progress" strategies and begin longer-term "To Do" items** identified throughout this report (summarized in Table 1). Further build on these and continue to improve and identify other ways to increase the agency's resilience to climate risks.

5 SUMMARY AND LESSONS LEARNED

Overall, this project demonstrated that there are several practical actions DOTs can take to incorporate climate risk into their asset management and other systems. The actions identified here are specific to MDOT SHA, based on organizational structure, existing practices, and even individual engagement. The actions, even if not directly transferable, can serve as inspiration for other agencies.

Furthermore, this project demonstrated several key lessons about the process of integrating climate risk into asset management. These include:

- **There are practical strategies DOTs can use to incorporate climate risk into decision-making processes.** Through the working sessions and continued conversations, each office identified and took ownership over actions that will ensure climate risks are factored into asset lifecycle planning and investment decisions. The actions included specific strategies for using the risk information in decision-making, as well as the smaller, incremental steps necessary to enable those processes.
- **Working sessions are effective in focusing attention and generating ideas for climate risk integration** into planning, asset management, and other decision-making processes. The two-hour working session format was highly effective and productive. In these sessions, the project team developed and presented a visualization of highway and bridge vulnerability scores that was useful for reviewing results. In addition, the project team came to the working session with initial ideas for integrating vulnerability results into asset management processes, which helped to facilitate discussion and generate new ideas.
- **It is important to meet staff where they are with regards to existing concerns, understanding of climate risk, time available to devote to the topic, and data used.** Another key success of this project was that the project team worked with MDOT SHA

Working Session Discussion Questions

During the working sessions with MDOT SHA staff, the project team used the following guiding questions to facilitate discussion of opportunities and strategies for the integration climate risk information:

- What steps of the Pavement Management System (PMS) or Bridge Management System (BMS) process could the climate risk information be integrated into?
- How will changing conditions strain assets? Are these considerations integrated into performance modeling?
- What are the logistics of adding climate risk data into existing systems or databases (e.g., format, management)?
- What supplemental information is needed to ensure the data can be acted upon (e.g., guidance, decision trees)?
- What are some decision-level goals that the climate risk information could help achieve?
- Are there existing systems or platforms within Planning that support asset level decisions? How could this data fit into that?
- How will potential users access the climate risk data?

staff who will be the end users of the climate risk information and identified actions that would provide data in a format that would fit into existing processes.

- **Having an internal "champion" with decision-making authority or influence within the various agency offices helped to facilitate buy-in.** MDOT SHA has a staff person dedicated to climate resilience. This role was critical for identifying the right staff to participate in the working sessions, helping to communicate the reasons to act on climate risk information, and, ultimately cultivating a network of champions in different parts of the agency with decision-making authority who will oversee actual implementation.
- **Different offices and individuals will have different data needs. It is therefore important to be flexible and able to develop customized datasets for different users.** A key to the project team's success was its ability to be flexible and provide different variables and datasets to different users. For example, participants at the Bridge Asset Management Working Session indicated they would like to access both the overall vulnerability score as well as its constituent parts (e.g., exposure vs. sensitivity vs. adaptive capacity, as well as individual indicators.
- **It is not always possible to know what the most useful data will be at the outset.** Although the project team asked MDOT SHA staff what output data would be most useful to them before conducting the vulnerability assessment, it was much easier for staff to react to existing results and modify from there. Again, it was critical to build in flexibility to the project schedule and budget to accommodate these modifications.
- **It is important for potential users of the climate vulnerability results to understand and accept the assessment methodology.** The working sessions generated discussion and recommended updates for the assessment methodology, which the project team incorporated before finalizing the assessment results. In general, the project team found that results will only be meaningfully used if end users have approved and have a clear understanding of the value added by the results.
- **In an indicator-based vulnerability assessment, users need to be able to understand not just the final vulnerability ratings but also their constituent parts.** By itself, a vulnerability score of 1-4 is difficult to interpret. In response, the project team paired all scores with descriptive meanings, and also provided users easy access to the underlying data behind the scores (e.g., expected inundation depth, age, condition, functional classification, average daily traffic). For some users, certain components (e.g., exposure) may be more useful than others. Providing final vulnerability score results as well as more complete supporting information ensures that users can access the elements of the results that are most meaningful to their decisions.
- **Capturing data on past experience with flooding is critical to contextualizing and understanding future potential vulnerability, and more effective using a simple spatial (map-based) format.** Initially, the project team developed a maintenance survey that listed each asset in a table, and asked staff to populate different columns (whether the asset had flooded, how frequently, etc.). However, this format proved cumbersome and time-consuming for maintenance staff, particularly because typically only a small handful

of assets had past flooding issues. In response to this feedback, the project team developed a simplified, map-based survey (see Figure 11) where respondents could simply print out and annotate a map with this same information. The map-based survey was much more effective at eliciting responses and provided the same information as the tabular survey.

Circle any areas or structures where you have experienced past flooding issues.

For each circled structure, note:

- The cause of the flooding issue:
  - R = rain
  - T = tidal
  - S = storm surge
- The average number of times the structure floods per year
- Whether the structure has been damaged from flooding
  - Leave blank if no damage
  - ✳ = minor damage
  - ✳✳ = moderate-major damage

Use the margins to note any additional information about past flooding issues.

Example:

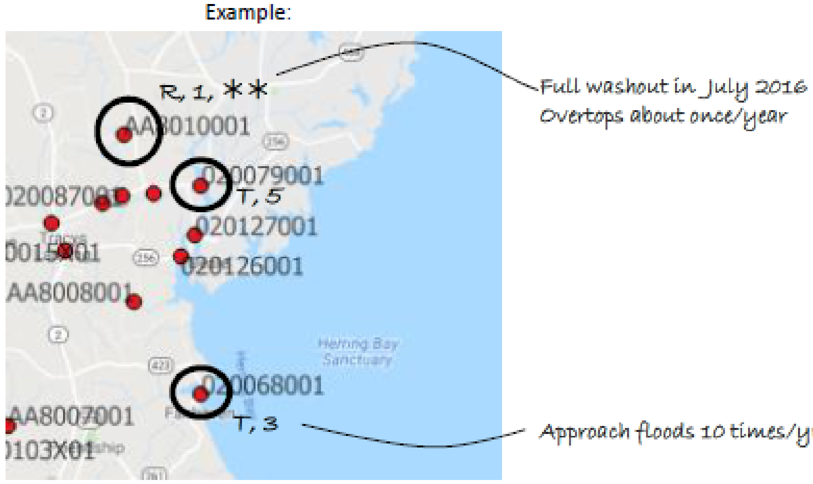

Figure 11. Example map-based maintenance survey instructions

- **Historical flooding events have typically not been comprehensively documented in an accessible manner, leaving a data gap.** Working session participants in all sessions identified the need for more comprehensive historical flooding data collection. MDOT SHA has access to the existing "Road Closure Reporter" app used by some Counties and municipalities, Coordination with current data collection practices in CHART and OOM will be reviewed to develop a comprehensive data collection system.
- **Climate change prompts difficult decisions, some of which may require high-level guidance or other adaptation actions that go beyond individual asset management decisions.** Climate change does not typically threaten transportation infrastructure in isolation. Sea level change can lead to inundation challenges community-wide, and transportation infrastructure provides a critical service to communities. In cases where, for example, entire communities are vulnerable to sea level change, it is important to

make decisions about how to adapt that community as a whole, and not just how to adapt individual pieces of infrastructure.

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APPENDIX A: DETAILED VULNERABILITY ASSESSMENT METHODOLOGY

This appendix describes in detail the methodology used for the vulnerability assessment conducted in this pilot project. It includes the following sections:

- Detailed final scoring approach (indicators, weights, scoring bins, rationales, data sources, etc.).
- Summary of how this approach differs from the 2014 vulnerability assessment pilot approach.
- Discussion of special issues encountered and addressed while conducting this vulnerability assessment related to the past experience and underclearance indicators.

Detailed Scoring Approach

Table 9914, Table 101015, and Table 111116 provide the detailed scoring methodology for this pilot for sea level change, storm surge, and precipitation change, respectively. The scoring methodology is based on the approach used in the 2014 pilot (updates from the 2014 pilot approach are described in the Proxy Indicators section 2.1).

Sea Level Change

Table 9. Sea level change scoring approach

Component		Indicator	Weight	Indicator Value	Score	Justification
Exposure	35%	Modeled SLC Inundation Depth (2050 Mean Higher High Water)	90%	x ≥ 3 Feet of inundation from MHHW	4	Locations with larger projected amounts of sea level change are likely to be impacted by projected changes in climate, including permanent inundation.
				1.4 ≤ x < 3 Feet of inundation from MHHW	3	
				0 < x < 1.4 Feet of inundation from MHHW	2	
				x ≤ 0 feet of inundation from MHHW	1	
		Proximity to Coastline	10%	1 ≤ Feet < 500	4	Assets that are located a shorter distance from the coastline are more likely to be affected by sea level change.
				500 ≤ Feet < 1,000	3	
				1,000 ≤ Feet < 5,000	2	
				5,000 ≤ Feet < 24,576	1	

Component		Indicator	Weight	Indicator Value	Score	Justification
Sensitivity	35%	Past Experience with Tides/SLC	45%	Demonstrated at least moderate damage during past tidal flooding	4	Structures that have demonstrated sensitivity in the past are likely to be sensitive in the future.
				Demonstrated at least minor damage during past tidal flooding	3	
				No experience of damage beyond operational disruption during past tidal flooding	2	
				No experience of prior tidal flooding	1	
		Underclearance	20%	A (< 10')	4	Assets with a lower underclearance are more likely to experience impacts when exposed. For example, coastal flooding is more likely to overtop the structure and cause damage or disruption.
				B (10' to < 20')	3	
				C (20' to < 30')	2	
				D (30' to < 40'), E (> 40')	1	
		Scour Rating	15%	0: Bridge has failed and is closed to traffic	4	Scoured assets are more likely to experience impacts when they are flooded.
				1: Bridge closed; failure of foundation is imminent	4	
				2: Scour critical; extensive scour at a foundation	4	
				3, 3B: Bridge is scour critical; bridge foundations determined to be unstable for assessed or calculated scour conditions	4	
				4: Stable structure. Action required to protect exposed foundation	3	
				5, 5A, 5B, 5C: A detailed scour study has found structure is stable	2	
				7, 7A: Countermeasures installed to correct scour critical condition	2	
				8, 8L: Countermeasures installed to correct scour critical condition	2	
				9, 9P: Foundations well above flood water elevations	1	

Component		Indicator	Weight	Indicator Value	Score	Justification
				T: Bridge over tidal waters that has not been evaluated for scour, but considered low risk	1	
				N: Not over waterway	1	
				U: No data	No data	
				6, 6N, 6R: No data	No data	
				8P: No data	No data	
				Pe: No data	No data	
		Condition of Bridge Substructure	7%	0: Failed Condition, 1: Imminent Failure Condition, 2: Critical Condition	4	Bridges in serious condition are more likely to be damaged when exposed due to the exacerbation of pre-existing weaknesses.
				3: Serious Condition, 4: Poor Condition	3	
				6: Satisfactory Condition, 5: Fair Condition	2	
				7: Good Condition, 8: Very Good Condition, 9: Excellent Condition	1	
		Condition of Bridge Superstructure	4%	0: Failed Condition, 1: Imminent Failure Condition, 2: Critical Condition	4	See above.
				3: Serious Condition, 4: Poor Condition	3	
				6: Satisfactory Condition, 5: Fair Condition	2	
				7: Good Condition, 8: Very Good Condition, 9: Excellent Condition	1	
		Condition of Bridge Deck	4%	0: Failed Condition, 1: Imminent Failure Condition, 2: Critical Condition	4	See above.
				3: Serious Condition, 4: Poor Condition	3	
				6: Satisfactory Condition, 5: Fair Condition	2	
				7: Good Condition, 8: Very Good Condition, 9: Excellent Condition	1	
		Bridge Age as of 2018 from most recent reconstruction	5%	$70 \leq$ Years < 99	4	Older bridges are likely to be damaged when exposed, since they may be built to an older design standard.
				$50 \leq$ Years < 70	3	
				$25 \leq$ Years < 50	2	
				$1 \leq$ Years < 25	1	
Adaptive Capacity	30%	Function Classification	50%	Principal arterial – interstate, other freeways or expressways (01, 11, 12)	4	

Component	Indicator	Weight	Indicator Value	Score	Justification
			Principal arterial (02, 14)	3	The transportation system may be less able to absorb impacts to assets of higher functional classification.
			Major and minor collector, minor arterial (06, 07, 08, 16, 17)	2	
			Local (09, 19)	1	
	Evacuation Route	25%	Yes (within 50 feet of a known evacuation route)	4	Bridges that are part of evacuation routes compromise safety and will cause greater disruption to the system if damaged.
			No	1	
	Detour Length (overall increase in path length due to a detour around a flooded structure)	12.5%	Miles ≥ 10	4	Bridges with long detours are more disruptive to the overall system if damaged.
			5 ≤ Miles < 10	3	
			1 ≤ Miles < 5	2	
			Miles ≤ 1	1	
	Average Daily Traffic (ADT)	12.5%	ADT ≥ 50,000	4	Bridges with large amounts of average daily traffic are highly significant routes that are less able to cope with changes caused by climate impacts.
			5,000 ≤ ADT < 50,000	3	
			1,000 ≤ ADT < 5,000	2	
			0 ≤ ADT < 1,000	1	

Storm Surge

Table 10. Storm surge scoring approach

Component		Indicator	Weight	Indicator Value	Score	Interpretation
Exposure	35%	Modeled Surge Inundation Depth (0.2% annual chance storm[20] with 2050 MHHW)	80%[21]	x ≥ 3 Feet of inundation from surge	4	Locations with higher inundation depth under this extreme scenario are more likely to be inundated under lesser events and affected by projected changes in climate.
				1.4 ≤ x < 3 Feet of inundation from surge	3	
				0 < x < 1.4 Feet of inundation from surge	2	
				x ≤ 0 feet of inundation from surge	1	
		Proximity to Coastline	20%	1 ≤ Feet < 500	4	Assets that are located a closer to the coastline are more likely to be affected by storm surge.
				500 ≤ Feet < 1,000	3	
				1,000 ≤ Feet < 5,000	2	
				5,000 ≤ Feet < 24,576	1	
Sensitivity	35%	Past Experience with Storm Surge	45%	Demonstrated at least moderate damage during past storm surge events	4	Structures that have demonstrated sensitivity in the past are likely to be sensitive in the future.
				Demonstrated at least minor damage during past storm surge events	3	
				No experience of damage beyond operational disruption during past storm surge events	2	
				No experience of prior storm surge	1	
		Underclearance	20%	A (< 10')	4	Assets with a lower underclearance are more likely to experience impacts when exposed. For example, surge is more likely to overtop the structure and cause damage or disruption.
				B (10' to < 20')	3	
				C (20' to < 30')	2	
				D (30' to < 40'), E (> 40')	1	
		Scour Rating	15%	0: Bridge has failed and is closed to traffic	4	Scoured assets are more likely to experience impacts when flooded.
				1: Bridge closed; failure of foundation is imminent	4	

[20] Also known as a "500-year" storm.
[21] Exposure inundation depth weights for sea level change (90%) and storm surge (80%) differ based on approach used in 2014 MDOT SHA Pilot Study, in which weights were based on expert input from MDOT SHA engineers.

Component	Indicator	Weight	Indicator Value	Score	Interpretation
			2: Scour critical; extensive scour at a foundation	4	
			3, 3B: Bridge is scour critical; bridge foundations determined to be unstable for assessed or calculated scour conditions	4	
			4: Stable structure. Action required to protect exposed foundation	3	
			5, 5A, 5B, 5C: A detailed scour study has found structure is stable	2	
			7, 7A: Countermeasures installed to correct scour critical condition	2	
			8, 8L: Countermeasures installed to correct scour critical condition	2	
			9, 9P: Foundations well above flood water elevations	1	
			T: Bridge over tidal waters that has not been evaluated for scour, but considered low risk	1	
			N: Not over waterway	1	
			U: No data	No data	
			6, 6N, 6R: No data	No data	
			8P: No data	No data	
			Pe: No data	No data	
	Condition of Bridge Substructure	7%	0: Failed Condition, 1: Imminent Failure Condition, 2: Critical Condition	4	Bridges in serious condition are more likely to be damaged when exposed due to the exacerbation of pre-existing weaknesses.
			3: Serious Condition, 4: Poor Condition	3	
			6: Satisfactory Condition, 5: Fair Condition	2	
			7: Good Condition, 8: Very Good Condition, 9: Excellent Condition	1	
	Condition of Bridge Superstructure	4%	0: Failed Condition, 1: Imminent Failure Condition, 2: Critical Condition	4	See above.
			3: Serious Condition, 4: Poor Condition	3	

Component		Indicator	Weight	Indicator Value	Score	Interpretation
				6: Satisfactory Condition, 5: Fair Condition	2	
				7: Good Condition, 8: Very Good Condition, 9: Excellent Condition	1	
		Condition of Bridge Deck	4%	0: Failed Condition, 1: Imminent Failure Condition, 2: Critical Condition	4	See above.
				3: Serious Condition, 4: Poor Condition	3	
				6: Satisfactory Condition, 5: Fair Condition	2	
				7: Good Condition, 8: Very Good Condition, 9: Excellent Condition	1	
		Bridge Age as of 2018 from most recent reconstruction	5%	70 ≤ Years < 99	4	Older bridges are likely to be damaged when exposed, since they may be built to an older design standard.
				50 ≤ Years < 70	3	
				25 ≤ Years < 50	2	
				1 ≤ Years < 25	1	
Adaptive Capacity	30%	Function Classification (FC)	50%	Principal arterial – interstate, other freeways or expressways (01, 11, 12)	4	The transportation system may be less able to absorb impacts to assets of higher functional classification.
				Principal arterial (02, 14)	3	
				Major and minor collector, minor arterial (06, 07, 08, 16, 17)	2	
				Local (09, 19)	1	
		Evacuation Route	25%	Yes (within 50 feet of an evacuation route)	4	Bridges that are part of evacuation routes will cause greater disruption to the system if damaged.
				No	1	
		Detour Length (overall increase in path length due to a detour around a flooded structure)	12.5%	Miles ≥ 10	4	Bridges with long detours are most likely to disrupt the overall system if damaged.
				5 ≤ Miles < 10	3	
				1 ≤ Miles < 5	2	
				Miles ≤ 1	1	
		Average Daily Traffic (ADT)	12.5%	ADT ≥ 50,000	4	Bridges with large amounts of average daily traffic are highly significant routes that are less able to cope with changes caused by climate impacts.
				5,000 ≤ ADT < 50,000	3	
				1,000 ≤ ADT < 5,000	2	
				0 ≤ ADT < 1,000	1	

Precipitation Change

Table 11. Precipitation change scoring approach

Component		Indicator	Weight	Indicator Value	Score	Interpretation
Exposure	25%	Location relative to FEMA Flood Zones	95%	1% annual chance flood zone;	4	Assets located in current flood zones are likely to be exposed in the future.
				0.2% annual chance flood zone	2	
				Outside of flood zone	1	
		Percent change in 24-hour, 50-year precipitation (%D)	5%	%D ≥ 10%	4	Additional assets may become exposed as precipitation changes over time.
				%D < 10%	2	
Sensitivity	45%	Past Experience with Precipitation	45%	Demonstrated at least moderate damage during past precipitation events	4	Structures that have demonstrated sensitivity in the past are likely to be sensitive in the future.
				Demonstrated at least minor damage during past precipitation events	3	
				No experience of damage beyond operational disruption during past precipitation events	2	
				No experience of prior precipitation events	1	
		Underclearance	35%	10 ≤ Feet <50	4	Assets with a lower underclearance are less likely to experience impacts when exposed to extreme precipitation events.
				5 ≤ Feet < 10	2	
				0 ≤ Feet < 5	1	
		Scour Rating	15%	0: Bridge has failed and is closed to traffic	4	Scoured assets are more likely to experience impacts when they are exposed.
				1: Bridge closed; failure of foundation is imminent	4	
				2: Scour critical; extensive scour at a foundation	4	
				3, 3B: Bridge is scour critical; bridge foundations determined to be unstable for assessed or calculated scour conditions	4	
				4: Stable structure. Action required to protect exposed foundation	3	

Component		Indicator	Weight	Indicator Value	Score	Interpretation
				5, 5A, 5B, 5C: A detailed scour study has found structure is stable	2	
				7, 7A: Countermeasures installed to correct scour critical condition	2	
				8, 8L: Countermeasures installed to correct scour critical condition	2	
				9, 9P: Foundations well above flood water elevations	1	
				T: Bridge over tidal waters that has not been evaluated for scour, but considered low risk	1	
				N: Not over waterway	1	
				U: No data	No data	
				6, 6N, 6R: No data	No data	
				8P: No data	No data	
				Pe: No data	No data	
		Bridge Age as of 2018 from most recent reconstruction	5%	70 ≤ Years < 99	4	Older bridges are likely to be damaged when exposed, since they may be built to an older design standard.
				50 ≤ Years < 70	3	
				25 ≤ Years < 50	2	
				1 ≤ Years < 25	1	
Adaptive Capacity	30%	Functional Classification	50%	Principal arterial – interstate, other freeways or expressways (01, 11, 12)	4	The transportation system may be less able to absorb impacts to assets of higher functional classification.
				Principal arterial (02, 14)	3	
				Major and minor collector, minor arterial (06, 07, 08, 16, 17)	2	
				Local (09, 19)	1	
		Evacuation Route	25%	Yes (within 50 feet of an evacuation route)	4	Bridges that are part of evacuation routes will cause greater disruption to the system if damaged.
				No	1	
		Detour Length (overall increase in path length due to a detour around a flooded structure)	12.5%	Miles ≥ 10	4	Bridges with long detours are most likely to disrupt the overall system if damaged.
				5 ≤ Miles < 10	3	
				1 ≤ Miles < 5	2	
				Miles ≤ 1	1	
			12.5%	ADT ≥ 50,000	4	

Component		Indicator	Weight	Indicator Value	Score	Interpretation
		Average Daily Traffic (ADT)		5,000 ≤ ADT < 50,000	3	Bridges with large amounts of average daily traffic are highly significant routes that are less able to cope with changes caused by climate impacts.
				1,000 ≤ ADT < 5,000	2	
				0 ≤ ADT < 1,000	1	

Data Sources

The data sources used in the vulnerability assessment are summarized in Table 121217.

Table 12. Data sources for vulnerability assessment

Indicator	Data Source	Processing Notes
Exposure Indicators		
Modeled SLC Inundation Depth (2050 MHHW)	Salisbury University Eastern Shore Regional GIS Cooperative Sea Level Change (SLC) mapping Depth Grids (created using US Army Corps of Engineers Sea Level Change Methodology). Data: MD_MeanHigherHighWater_2050/DepthGrid_00_PercentAnnualChance available at: https://geoservices.salisbury.edu/arcgis/rest/services/MD_MeanHigherHighWater_2050/DepthGrid_00_PercentAnnualChance/ImageServer	ICF extracted values from the ArcGIS online raster.
Proximity to Coastline	The distances of each asset from the coastline was calculated using a Maryland Geological Survey shoreline map for tidewater Maryland. Data available at: http://www.mgs.md.gov/coastal_geology/hi%20res%20shoreline.html	For each asset, ICF calculated the distance to the coastline in miles using GIS software.
Modeled Surge Inundation Depth (0.2% annual chance storm with 2050 MHHW)	ESRGC Storm Event Depth Grids. Data MD_MeanHigherHighWater_2050/DepthGrid_0_2_PercentAnnualChance available at: https://geoservices.salisbury.edu/arcgis/rest/services/MD_MeanHigherHighWater_2050/DepthGrid_0_2_PercentAnnualChance/ImageServer	ICF extracted values from the ArcGIS online raster.
Location in FEMA Flood Zone	FEMA National Flood Hazard Layers (NFHL), available at: https://www.fema.gov/national-flood-hazard-layer-nfhl	ICF compared structures against an open water layer that ICF created to avoid confusion where the NFHL may indicate a point is in a floodplain but it is really in the middle of a river or bay. ICF's open water layer is based on the NFHL open water flood

		zone type. ICF then compared assets that are not within the open water layer to the NFHL dataset. If an asset is somehow within a flood zone that indicates Open Water but it didn't get caught by the open water layer, we mark it as such. Asset is a flood zone that starts with "A" or "V", are marked as in the 100-year floodplain. Assets with a zone subtype of "0.2 PCT ANNUAL CHANCE FLOOD HAZARD", are marked as in the 500-year floodplain. Assets in a flood zone of "X", are marked as in the minimal flood hazard area.
Change in 24-hour, 50-year precipitation for 2050	North American Regional Climate Change Assessment Program (NARCCAP); analysis from Brubaker, K., Moglen, G., Feng, Y., Davis, B., and Belaia, V. 2017. Incorporating Future Precipitation Estimates into SHA Design.	The vulnerability analysis uses percent change data sent directly from Kaye Brubaker for the 25-hour precipitation amounts, by return interval (from 1971-2000 to 2041-2070). The data are of 50 km resolution. ICF assigned the value from the nearest point in either Regional/Global Climate Model pair for use in the scoring of each asset (either ECP2/GFDL or CRCM/CGCM3)
Sensitivity Indicators		
Underclearance	Data sent by from Michel Sheffer (MDOT SHA GIS) to ICF on April 17, 2018 from the MDOT SHA Office of Structures database (2013). Structure_UnderClearance.gdb file included bridge point locations and attribute data on underclearance, condition of bridge substructure, condition of bridge superstructure, condition of deck, year build, year reconstructed, and average daily traffic. Underclearance attribute comes from a Maryland Department of the Environment dataset.	
Scour Criticality	Data sent by Pat Meinecke (MDOT SHA) to ICF on May 2, 2018. Data included Scour criticality, functional class, and detour length.	ICF appended data from Pat Meinecke to data from Structure_UnderClearance.gdb.
Past Experience with Tides/SLC	Data gathered from a survey sent to maintenance points of contact using map-based survey.	Points of contact identified bridges that had experienced flooding issues in the past, noting

Past Experience with Storm Surge	Data gathered from a survey sent to maintenance points of contact using map-based survey.	whether it had flooded previously, the cause of flooding (e.g., tidal, surge, or rain), how frequently it floods, and whether it had experienced minor or moderate flood damage.
Past Experience with Precipitation	Data gathered from a survey sent to maintenance points of contact using map-based survey.	
Condition of Bridge Substructure	Data sent by Michel Sheffer (MDOT SHA) to ICF on April 17, 2018. Structure_UnderClearance.gdb file includes bridge point locations and attribute data on underclearance, condition of bridge substructure, condition of bridge superstructure, condition of deck, year build, year reconstructed, and average daily traffic.	
Condition of Bridge Superstructure	Data sent by Michel Sheffer (MDOT SHA) to ICF on April 17, 2018. Structure_UnderClearance.gdb file includes bridge point locations and attribute data on underclearance, condition of bridge substructure, condition of bridge superstructure, condition of deck, year build, year reconstructed, and average daily traffic.	
Condition of Bridge Deck	Data sent by Michel Sheffer (MDOT SHA) to ICF on April 17, 2018. Structure_UnderClearance.gdb file includes bridge point locations and attribute data on underclearance, condition of bridge substructure, condition of bridge superstructure, condition of deck, year build, year reconstructed, and average daily traffic.	
Bridge Age	Data sent by Michel Sheffer (MDOT SHA) to ICF on April 17, 2018. Structure_UnderClearance.gdb file includes bridge point locations and attribute data on underclearance, condition of bridge substructure, condition of bridge superstructure, condition of deck, year build, year reconstructed, and average daily traffic.	ICF calculated the bridge age based on two possible fields: year built and year reconstructed. If a structure had a value for the year reconstructed, ICF calculated the bridge age by subtracting the year reconstructed from 2018. If a structure did not have a value, or was designated "UNK" for year reconstructed, ICF calculated the bridge age by subtracting the year built from 2018.
Adaptive Capacity Indicators		

FHWA Roadway Functional Classification	Data sent by Pat Meinecke (MDOT SHA) to ICF on May 2, 2018. Data included Scour criticality, functional class, and detour length.	ICF appended data from Pat Meinecke to data from Structure_UnderClearance.gdb.
Evacuation Routes	Data sent by Michel Sheffer (MDOT SHA) to ICF on April 17, 2018. RITIS_Evacuation Data folder sent by Michel Sheffer includes routes_md shapefile with evacuation routes for Maryland.	ICF intersected the bridge point locations with the evacuation data line segments. Only two of the bridge points actually intersected the evacuation routes. In some cases, this was because the point was slightly offset from the line. ICF calculated the distance from each bridge point to the nearest evacuation route. ICF considered bridges with evacuation routes within 50 feet to be evacuation routes.
Detour Length	Data sent by Pat Meinecke (MDOT SHA) to ICF on May 2, 2018. Data included Scour criticality, functional class, and detour length. Detour length data from the National Bridge Inventory represent the total additional travel for a vehicle would result from closing of the bridge.[22]	ICF appended data from Pat Meinecke to data from Structure_UnderClearance.gdb.
Annual Average Daily Traffic	Data sent by Michel Sheffer (MDOT SHA) to ICF on April 17, 2018. Structure_UnderClearance.gdb file includes bridge point locations and attribute data on underclearance, condition of bridge substructure, condition of bridge superstructure, condition of deck, year build, year reconstructed, and average daily traffic.	ICF appended data from Pat Meinecke to data from Structure_UnderClearance.gdb.

[22] FHWA. 1995. Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. Federal Highway Administration. Available at: https://www.fhwa.dot.gov/bridge/mtguide.pdf.

Summary of Updates from 2014 Vulnerability Assessment

MDOT SHA completed a pilot climate change vulnerability assessment for transportation assets in Anne Arundel and Somerset counties in 2014. The statewide bridge vulnerability assessment approach conducted under this project uses a similar methodology but with some updates based on:

- the scoring approach and indicator evaluation workshops conducted for the Anne Arundel and Somerset County vulnerability assessments,[23]
- lessons learned through indicator-based vulnerability assessments in other projects,[24]
- discussion at the project kickoff workshop, and
- discussion at the project working session meetings with MDOT SHA staff members from pavement asset management, bridge asset management, and planning.

The statewide vulnerability assessment described in this report includes the following updates from the pilot approach used for Anne Arundel and Somerset Counties:

Addition of scoring interpretation aids: The statewide assessments adds qualitative descriptions of the exposure, sensitivity, and adaptive capacity scores (scored on a scale of 1-4) to help MDOT staff more readily interpret the results. These interpretations are provided in Table 13-Table 15 below.

Table 13. Exposure score interpretation guide

Exposure Score	Meaning
Sea Level Change	
1	Asset is unlikely to experience inundation from sea level change. Asset is not expected to be inundated under 2050 MHWW and is located more than 5,000 feet from the shoreline.
2	Asset is expected to be inundated by up to 1.4 feet under 2050 MHHW and is located 1,000 to 5,000 feet from the shoreline. Asset may experience inundation under severe conditions.
3	Asset is expected to be inundated by 1.4 to 3 feet under 2050 MHHW and is located 500 to 1,000 feet from the shoreline. Asset may experience inundation under some conditions.
4	Asset is expected to be inundated by greater than 3 feet under 2050 MHHW and is located less than 500 feet from the shoreline. Asset would be flooded about half of the days of the year.

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[23] MDOT SHA. 2014. Climate Change Adaptation Plan with Detailed Vulnerability Assessment. Final Report. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/maryland/final_report/mdpilot.pdf

[24] FHWA. 2016a. 2013-2015 Climate Resilience Pilot Program: Outcomes, Lessons Learned, and Recommendations. U.S. Department of Transportation, Federal Highway Administration (FHWA). FHWA-HEP-16-079. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/final_report/fhwahep16079.pdf

Exposure Score	Meaning
Storm Surge	
1	Asset is unlikely to experience inundation from storm surge. Asset is not expected to be inundated by the 2050 0.2% annual chance storm surge event and is located more than 5,000 feet from the shoreline.
2	Asset is expected to be inundated by up to 1.4 feet by the 2050 0.2% annual chance storm surge event and is located 1,000 to 5,000 feet from the shoreline. Asset may experience inundation under severe conditions.
3	Asset is expected be inundated by 1.4 to 3 feet by the 2050 0.2% annual chance storm surge event and is located 500 to 1,000 feet from the shoreline. Asset may experience inundation under some conditions.
4	Asset is expected to be inundated by greater than 3 feet under the 2050 0.2% annual chance storm surge event and is located less than 500 feet from the shoreline.
Precipitation Change	
1	Asset is located outside of FEMA flood zones.
2	Asset is located in the current FEMA 0.2% annual chance flood zone and 24-hour, 50-year precipitation is expected to increase by greater than 10% by 2050.
4	Asset is located in the current FEMA 1% annual chance flood zone and 24-hour, 50-year precipitation is expected to increase by greater than 10% by 2050.

Table 14. Sensitivity score interpretation guide

Sensitivity Score	Meaning
1	Flooding would lead to negligible damage and temporary operational disruption (hours).
2	Flooding would lead to minor damage or major operational disruption (days).
3	Flooding would lead to moderate damage to the asset or major operational disruption (weeks).
4	Flooding would lead to severe damage to the asset or long-term operational disruption (months).

Table 15. Adaptive capacity score interpretation guide

Adaptive Capacity Score	Meaning
1	Damage/disruption would lead to minimal network or social effects (e.g., not an evacuation route, alternate routes available, minor collector or local road, less than 1,000 ADT).
2	Damage/disruption would lead to moderate network or social effects (e.g., some alternate routes available, minor arterial or major collector, 1,000-5,000 ADT).
3	Damage/disruption would lead to major network or social effects (e.g., limited alternate routes, principal arterial, 5,000-50,000 ADT).
4	Damage/disruption would lead to severe network or social effects (e.g., evacuation route, no alternate routes, interstate, more than 50,000 ADT).

Updates to "underclearance" indicator scoring: In the previous approach, underclearance was included as an indicator of both exposure and sensitivity for precipitation. For simplicity, we are including it only as a sensitivity indicator (this is consistent with how underclearance is treated for the other hazards) but increasing the weight to be consistent with the weight it carried in the previous approach. Based on feedback received in July 2018 working sessions from participants in the bridges asset management session, we reversed the scoring bins for underclearance for precipitation change so that assets with a greater underclearance receive a higher exposure score. Participants indicated that assets with greater underclearance are more likely to experience impacts from precipitation due to scour caused by increased velocities of water.

Removal of "proximity to shoreline" as a precipitation change vulnerability indicator: In the previous approach (as recorded in the VAST spreadsheets), proximity to coastline was used as a sensitivity indicator for precipitation. This indicator is not mentioned as an indicator of sensitivity in the Final Report document. This indicator will be removed from the set of precipitation indicators as it is not strongly indicative of precipitation change sensitivity.

Updates to precipitation change exposure scoring: The previous methodology used "location in FEMA 100-year floodplain" and "change in total annual precipitation" to assess exposure to precipitation change. The 2014 approach explained the rationale behind using change in total annual precipitation as follows:

- 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.
- Percentage of change in total annual precipitation is an indicator that the engineering working group ranked as "low significance." However, because of limited data available, it was incorporated in the analysis to identify a structure's vulnerability to changes in precipitation.

However, instead of total annual precipitation, the updated methodology uses percent change in 24-hour, 50-year precipitation as an indicator. The 50-year precipitation event is linked to the design standard for bridges in Maryland. The project team made this methodology change based on discussion with the MDOT SHA Hydrology and Hydraulics panel. During this discussion, the project team asked the panel to consider the following guiding questions:

- Are there additional existing data sources that provide information on projected changes in runoff volume, peak discharge, flow velocity, or other related indicators that could be used in this analysis instead of variables from the U.S. DOT Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool?
- What type of precipitation events cause the most damage (single-day, multi-day, etc.)?
- Which indicator(s) would provide the most meaningful spatial differentiation between assets?

Precipitation Change Exposure Indicator

The project team engaged the MDOT SHA Hydrology and Hydraulics Panel to determine the relevant precipitation indicators for the analysis. Options included:

- 95^{th} percentile 24-hour precipitation amount (“very heavy”)
- 99^{th} percentile 24-hour precipitation amount (“extremely heavy”)
- Future annual number of today’s “very heavy” 24-hour precipitation events
- Future annual number of today’s “extremely heavy” 24-hour precipitation events
- Maximum 3-day precipitation total, by season
- Annual days with precipitation above 25 mm (1 inch)
- Time series of annual maximum precipitation, 1950-2099

As an outcome of this discussion, the panel identified existing data available from Dr. Kaye Brubaker of the University of Maryland that provides future precipitation intensity-duration-frequency curves for Maryland based on climate model data. The project team opted to include this data with a very low weight to capture that precipitation change is a component of future flood exposure but recognizing that precipitation change alone is not sufficient to inform future flooding.

Updates to precipitation indicator weighting: Compared to sea level change and storm surge, there is much more uncertainty about future exposure for heavy precipitation. In the absence of hydraulic modeling, the current sensitivity indicators, especially past experience with flooding and underclearance, are the strongest indicators of whether an individual asset is likely to experience flooding issues in the future. Therefore, the updated exposure methodology for precipitation weights location in the FEMA flood zone at 95% and percent change in 50-year 24-hour precipitation amount in the 2050s at 5%. In addition, the methodology decreases the weight of exposure (decreased to 25%) relative to sensitivity (increased to 45%) for precipitation scoring. This way, the three strongest indicators (past experience, underclearance, and flood zone) account for about 60% of the overall vulnerability score. A side-by-side comparison of the previous and updated precipitation exposure scoring approaches is provided in Table 16.

Table 16. Comparison of pilot and statewide precipitation exposure scoring approaches

Pilot Approach	
0.1	Unlikely to experience inland flooding (not located in a current FEMA flood zone).
2.5	At least a 1% annual chance of inland flooding; located in the current FEMA flood zone and expected to experience an increase in annual precipitation.

Statewide Approach	
1	Asset is located outside of FEMA flood zones.
2	Asset is located in the current FEMA 0.2% annual chance flood zone and 24-hour, 50-year precipitation is expected to increase by greater than 10% by 2050.
4	Asset is located in the current FEMA 1% annual chance flood zone and 24-hour, 50-year precipitation is expected to increase by greater than 10% by 2050.

In summary, the project team updated the precipitation exposure scoring as follows:

- Location relative to FEMA Flood Zones: 95%
- Percent change in 24-hour, 50-year precipitation: 5%

Updates to adaptive capacity indicator weighting: Based on feedback received during July 2018 working sessions, we adjusted the weights for the adaptive capacity components to place greater emphasis on functional classification. In addition, working session participants recommended that evacuation route receive a higher weight. However, due to the limitations of the evacuation route dataset, the project team limited the weight to 25%. The evacuation route dataset is not comprehensive or official, rather it is drawn from a number of unofficial sources for the state. The project team adjusted the weights as follows:

- Functional classification: 50%
- Evacuation Route: 25%
- Average Daily Traffic: 12.5%
- Detour Length: 12.5%

Application of statewide scoring consistency: For several indicators used for Anne Arundel and Somerset Counties, the scoring thresholds vary by county (e.g., the threshold for a “4” in Average Daily Traffic is different). The updated methodology applies a consistent scoring rubric statewide to ensure that results are comparable across the state. This affects scoring bins for modeled sea level change inundation depth, modeled surge inundation depth, past experience with tides/storm surge/precipitation, scour rating, bridge age, average daily traffic, and detour length.

Updates to bridge condition sensitivity weighting: In the pilot for Anne Arundel and Somerset Counties, the three sensitivity indicators of bridge condition for sea level change and storm surge (condition of bridge substructure, condition of bridge superstructure, and condition of bridge deck) are weighted equally at 5% each. The updated methodology applies a slightly higher weighting to bridge substructure condition (7%) and lower weightings to bridge superstructure condition and bridge deck condition (4% each). These changes were the result of feedback from the MDOT SHA OOS that assets with substructures in poor condition may be more susceptible to damage from flooding, potentially resulting in bridge wash out.

Updates to adaptive capacity component weighting: In the pilot for Anne Arundel and Somerset Counties, adaptive capacity is weighted at 20% of the overall vulnerability score, while exposure and sensitivity are each weighted at 40%. Adaptive capacity is the component of vulnerability scoring with the most diverse approaches for scoring. Because of the various approaches to scoring, MDOT SHA wanted to consider the range of options undertaken by other DOT and Metropolitan Planning Organization (MPO) projects. Table 17 summarizes how other DOT and MPO projects have addressed adaptive capacity in their transportation infrastructure vulnerability assessments. The four primary approaches used by other DOTs and MPOs for adaptive capacity include:

- Weighted equally with exposure (E) and sensitivity (S).
- Weighted differently than exposure and/or sensitivity (table shows exposure, sensitivity, and adaptive capacity (AC) weights, respectively).
- Disaggregated from a single vulnerability score (often used as part of a risk matrix).
- Excluded from the vulnerability assessment.

Based on this information, MDOT SHA elected to increase the adaptive capacity weighting. For sea level change and storm surge, the updated methodology weights exposure and sensitivity at 35% each and adaptive capacity at 30% (see above for details on precipitation scoring).

Table 17. Summary of how adaptive capacity is incorporated in existing transportation infrastructure vulnerability assessment studies

Study	**Treatment of Adaptive Capacity**			
	Weighted Equally	***Weighted Differently (E / S / AC)***	***Disaggregated)***	***AC Excluded***
2014 MDOT SHA pilot[25]		X 40% / 40% / 20%		
MnDOT pilot[26]	X (bridges)	X (roads paralleling streams) 43.3% / 23.3% / 33.3%		
CAMPO pilot[27]			X* (into E vs S & AC)	

[25] MDOT SHA. 2014. Climate Change Adaptation Plan with Detailed Vulnerability Assessment. Final Report. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/maryland/final_report/mdpilot.pdf

[26] Minnesota Department of Transportation. 2014. Flash Flood Vulnerability and Adaptation Assessment Pilot Project. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/minnesota/final_report/index.cfm

[27] Capital Area Metropolitan Planning Organization. 2016. Central Texas Extreme Weather and Climate Change Vulnerability Assessment of Regional Transportation Infrastructure. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/campo/final_report/index.cfm

Study	Treatment of Adaptive Capacity			
	Weighted Equally	*Weighted Differently (E / S / AC)*	*Disaggregated)*	*AC Excluded*
South Florida pilot[28]		X (roads) 70% / 20% / 10%		
Maine DOT pilot[29]				X
NYSDOT pilot[30]			X* (into E & S vs. AC)**	
Michigan DOT pilot[31]			X* (into E vs. AC)**	
Gulf Coast Study, Phase 2[32]		X 40% / 40% / 20%		
VAST default[33]	X		X (into E & S vs. AC)	
National Park Service[34]				X
2018 MDOT SHA statewiede assessment (this report)		X 35% / 35% / 30%		

*Used in a risk matrix
**Called "Criticality" but based on comparable indicators (Functional Class, ADT, detour length, etc.)

[28] Broward Metropolitan Planning Organization. 2015. South Florida Climate Change Vulnerability Assessment and Adaptation Pilot Project. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/south_florida/final_report/index.cfm

[29] Maine DOT. 2014. Integrating Storm Surge and Sea Level Rise Vulnerability Assessments and Criticality Analyses into Asset Management at Maine DOT. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/maine/final_report/index.cfm

[30] New York State Department of Transportation. 2015. Climate Vulnerability and Economic Assessment for At-Risk Transportation Infrastructure in the Lake Champlain Basin, New York. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/new_york/final_report/index.cfm

[31] Michigan DOT. 2014. Michigan DOT Climate Vulnerability Assessment Pilot Project. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/michigan/final_report/index.cfm

[32] FHWA. 2015. U.S. DOT Gulf Coast Study, Phase 2. U.S. Department of Transportation, Federal Highway Administration. FHWA-HEP-15-019. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/case_studies/gulf_coast_study/engineering_and_tasks/case14.cfm

[33] U.S. DOT. 2015b. U.S. DOT Vulnerability Assessment Scoring Tool User's Guide. U.S. Department of Transportation. Available at: https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/scoring_tools_guide/

[34] Western Carolina University. No date. Coastal Hazards & Sea-Level Rise Asset Vulnerability Assessment Protocol. Program for the Study of Developed Shorelines. Available at: https://psds.wcu.edu/current-research/nps-vulnerabilityprotocol/

Special Issues

Impact of Maintenance Survey on Results

MDOT maintenance staff completed a survey ("maintenance survey") to report the historical sensitivity of assets to flooding. If the maintenance survey indicated that an asset had experienced flooding in the past, that asset received a higher rating that increased the overall vulnerability score. The converse is also true. By design, the maintenance survey has a large influence on the final vulnerability scores.

Table 18 demonstrates how the maintenance survey changed the overall vulnerability scores for Queen Anne's County.

Table 18. Change in vulnerability scores based on maintenance survey results

	Sea Level Change			**Storm Surge**			**Precipitation**		
Change Direction	Number of bridges	Averag e % change	Averag e score change	Number of bridges	Average % change	Average score change	Number of bridges	Average % change	Average score change
Increase	0	--	--	0	--	--	9	13%	0.20
Decrease	157	-22%	-0.53	157	-21%	-0.53	90	-5%	-0.10
No Change	1	0%	0.00	1	0%	0.00	59	0%	0.00
Total	**158**	**-21%**	**-0.5**	**158**	**-21%**	**-0.5**	**158**	**-2%**	**0.0**

The results show that for all assets the results of the maintenance survey reduced the vulnerability scores for sea level change and storm surge by approximately 21%. This means that the assets have not experienced sensitivity in the past due to tidal flooding and storm surge, which indicates a lower overall vulnerability. For the nine assets where the maintenance survey showed past flooding issues, the vulnerability scores increased by an average of 13%. For the other 149 assets, staff reported low historical sensitivity, which resulted in vulnerability scores that decreased or remained the same due to the maintenance survey results.

Overall, the maintenance survey results decreased the overall vulnerability scores for most assets. However, for those assets that were sensitive to inland flooding historically, the maintenance survey resulted in a relatively large increase in the vulnerability scores of those assets.

Underclearance Data

The available dataset on bridge underclearance comes from the Maryland Department of the Environment (MDE), and, for each structure, identifies whether the underclearance falls into one of five categories:

- A (< 10')
- B (10' to < 20')
- C (20' to < 30')
- D (30' to < 40')
- E (> 40')

During the Bridge Asset Management working session, staff from OOS expressed concern regarding the accuracy of the data source compared with as-builts due to several factors such as age of data. As a result, the project team selected a sample of structures to test the MDE underclearance information against the low chord elevation from OOS design files and planning documents. ICF selected a sample of structures in Queen Anne's county with high exposure to storm surge, and OOS provided the low chord elevations for each structure from design documents.

Table 19 provides a comparison of the underclearance values. Structures with cells shaded red do not match between data sources. Structures with cells shaded gray are not comparable between the two datasets. For eight of the nine applicable structures, the design files verified the accuracy of the MDE dataset. A dataset of bridge low chord elevations based on design files would certainly be preferred to the MDE dataset, but this assessment demonstrated that the MDE dataset is adequate for the screening purposes of this assessment.

Table 19. Comparison of vulnerability assessment underclearance data source and design file underclearance

Structure Number	Facility Carried	Feature Crossed	Location	Storm Surge Inundation Depth (ft.)	FEMA Flood Zone	Average Precipitation Change (%)	Underclearance Indicator Data Source	Underclearance Design files (ft.)
170029X01	MD 544	FOREMAN BRANCH	0.04 M E OF EWINGTOWN RD	6.65	Flood Zone 100yr	1.60%	A (<10 ft.)	24.06
170029001	MD 304	CORSICA CREEK	0.88 MILE WEST OF MD 213	6.65	Flood Zone 100yr	1.60%	A (<10 ft.)	4.75
170046001	US 50/301	KENT ISLAND NARROW	0.59 MILE WEST OF MD 835	5.85	Flood Zone 100yr	8.20%	3401 (not over water)	*44.06, 61.55, 37.04
170006001	MD 18B	KENT ISLAND NARROW	0.59 MILE WEST OF MD 835	5.85	Flood Zone 100yr	8.20%	B (10 to < 20 ft.)	18.13
170004001	US 50/301	COX CREEK	1.02 MILES WEST OF MD 18B	5.55	Open Water	8.20%	A (<10 ft.)	6.89
170001001	MD 18A	COX CREEK	0.6 MILE EAST OF MD 835C	5.55	Open Water	8.20%	A (<10 ft.)	5.77
170005031	US 50/301 EB	PINEY CREEK	1.21 MILES EAST OF MD 552	3.9	Open Water	8.20%	A (<10 ft.)	5.95
170005041	US 50/301 WB	PINEY CREEK	1.21 MILES EAST OF MD 552	3.02	Open Water	8.20%	A (<10 ft.)	5.95
170013021	US 301 SB	UNICORN BRANCH	0.48 M S OF KENT CO LINE	5.08	Flood Zone 500yr	-7.20%	B (10 to < 20 ft.)	13.38
170108X01	MD 18B	MARSHY CREEK	0.23 M E OF WELLS COVE RD	4.97	Open Water	8.20%	A (<10 ft.)	Not Found
170013011	US 301 NB	UNICORN BRANCH	0.48 M S OF KENT CO LINE	8	Minimal Flood Hazard	-7.20%	B (10 to < 20 ft.)	12.46

*East Abutment, Center of the span, West Abutment

APPENDIX B: PAVEMENT PERFORMANCE SUPPLEMENT

The project team hosted a working session with the MDOT SHA Office of Materials Technology (OMT) on July 23, 2018 to discuss ways to integrate data on potential pavement risks related to sea level change and other climate changes into the MDOT SHA Pavement Management System (PMS).

Two primary opportunities emerged from this working session (see Section 3.2 for details):

(1) MDOT SHA could incorporate data on pavement vulnerabilities into PMS.
(2) MDOT SHA could update the PMS performance models to account for accelerated deterioration due to flooding, based on the percentage of time each pavement is expected to be inundated from tidal flooding under sea level rise scenarios.

The project team provided supporting information to inform opportunity (2) above, including:

- A description of methodology for calculating percent of time each segment is inundated.
- A summary of available information on how sea level change could affect water table elevation in Maryland.
- A summary of existing literature on the effects of flood frequency on pavement deterioration.

The project team also provided a dataset of the percent of time each segment of pavement is expected to be inundated and percent of time water levels reach one foot below the centerline elevation in both 2015 and 2050.

Methodology for Flood Frequency Calculations

To inform MDOT SHA's understanding of how sea level change could affect pavement performance over time, the project team calculated and provided data on the average percentage of time that coastal road segments are inundated under baseline (2015) conditions and in 2050 based on projected sea level change. The project team calculated baseline and future inundation frequencies for two metrics:

- **Centerline inundation:** Expressed as the percent of time that water levels exceed the centerline elevation of each segment by any amount.
- **Subbase inundation:** Expressed as the percent of time that water elevations reach at least one foot below the centerline elevation (this value is a proxy for subbase inundation requested by OMT).

The project team calculated the frequency that water levels reach the above thresholds using tidal time series data from relevant stations in Maryland and approximated data on centerline elevations as follows:

1. **Calculate minimum water level necessary for centerline inundation.** For each segment, MDOT SHA provided the projected maximum centerline flood depth for coastal road segments under 2100 mean higher high water (MHHW) levels based on data from the Salisbury University/Eastern Shore Regional GIS Cooperative depth grid, in North American Vertical Datum of 1988 (NAVD88).[35] The depth grid dataset represents projected stillwater depths for use in scenario planning. Salisbury University/The Eastern Shore Regional GIS Cooperative used the U.S. Army Corps of Engineers sea level change estimate, which they localized using water elevations, glacial isostatic adjustments, and land elevations. The project team subtracted the known added water depth for 2100 MHHW for each county to determine the minimum water level necessary for centerline elevation for each segment. Finally, the project team converted these elevations from NAVD88 to mean sea level (MSL) based on datum adjustments for each tidal station.

   For example, modeling shows that a road segment in Worcester County would be inundated under 0.77 feet of water in the 2100 MHHW model. The 2100 MHHW scenario represents water levels 7.05 feet higher than 2015 mean sea level (see Table 20), associated with the Ocean City tidal station. Therefore, we calculate that the minimum water level necessary to inundate this segment is 7.05-0.77 or 6.28 feet above MSL. Further, the water level necessary to inundate one foot below the centerline is 6.28-1 or 5.28 feet above MSL.

[35] Salisbury University. 2018. MD_MeanHigherHighWater_2100/Depth Grid_00_PercentAnnualChange. ArcGIS REST Services Directory. Available at: https://geoservices.salisbury.edu/arcgis/rest/services/MD_MeanHigherHighWater_2100/DepthGrid_00_PercentAnnualChance/ImageServer

Table 20. Sea level change values for Maryland, by county and tidal station[36]

Final Adjusted Sea Level Change Values					
		2050		***2100***	
County	**Tidal Station**	**MSL**	**MHHW**	**MSL**	**MHHW**
Anne Arundel	Annapolis	2.08	2.79	5.7	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	2.1	2.82	5.76	6.48
Caroline	Cambridge	2.11	3.13	5.78	6.8
Cecil	Chesapeake City	1.98	3.63	5.56	7.21
Charles	Washington DC	2.21	3.83	5.78	7.4
Dorchester	Cambridge	2.11	3.13	5.78	6.8
Harford	Baltimore	2.01	2.87	5.59	6.45
Kent	Annapolis	2.08	2.79	5.7	6.41
Prince George's	Washington DC	2.21	3.83	5.78	7.4
Queen Anne's	Annapolis	2.08	2.79	5.7	6.41
Somerset	Cambridge	2.11	3.13	5.78	6.8
St. Mary's	Solomons Island	2.1	2.82	5.76	6.48
Talbot	Cambridge	2.11	3.13	5.78	6.8
Wicomico	Cambridge	2.11	3.13	5.78	6.8
Worcester	Ocean City	2.06	3.25	5.86	7.05

2. **Calculate frequency that the relevant tidal station reaches the critical water levels.** The project team assigned each road segment to its relevant tidal station, based on county (per Table 20).

   For each tidal station, the project team gathered an hourly time series of water elevation data for 2013-2017 in the MSL datum from the National Oceanographic and Atmospheric Administration (NOAA) Tides and Currents Database, to capture the 2015 baseline time period.[37] Note that the Solomon's Island tidal station does not have data available for 10/21/2013 00:00 - 4/22/2014 17:00, so a shorter timeframe is included.

[36] Eastern Shore Regional GIS Cooperative. 2016. GIS Data Products to Support Climate Change Adaptation Planning. Available at: http://www.esrgc.org/mapServices/

[37] NOAA. 2018a. Center for Operational Oceanographic Products and Services. National Oceanic and Atmospheric Administration (NOAA). Available at: https://tidesandcurrents.noaa.gov/

Based on the 2013-2017 time series, the project team also calculated a proxy time series for 2050 water levels.[38] To do so, we added the 2050 MSL sea level change values from Table 20 to the 2015 time series.

Finally, the project team calculated the frequency that each road segment centerline elevation and 1 foot below the centerline elevation is inundated. This calculation counts the number of times that the road segment elevation is at or above the water level in the full 2015 (2013-2017) time series and the 2050 proxy time series, divided by the number of entries in the time series.

The results show that coastal pavements will experience more frequent inundation over the next 35 years. For example, while no road segments experience centerline inundation more than 75 percent of the time under baseline conditions, that number could increase to 63 segments (27 miles) by 2050. See Table 21.

Table 21. Number and length of road segments inundated under different scenarios

Inundation Frequency	**2015**		**2050**	
	Centerline	**1 ft. Below Centerline**	**Centerline**	**1 ft. Below Centerline**
> 0% of time	141 segments (63 miles)	248 segments (69 miles)	1,099 segments (95 miles)	1,944 segments (106 miles)
> 25% of time	37 segments (18 miles)	66 segments (32 miles)	126 segments (60 miles)	190 segments (67 miles)
> 50% of time	25 segment (3.5 miles)	46 segments (20 miles)	95 segments (54 miles)	155 segments (65 miles)
> 75% of time	0 segments (0 miles)	32 segments (7.3 miles)	63 segments (27 miles)	116 segments (56 miles)

Note: Values should not be summed across rows. The number of segments flooded more than 75% of the time are also included in the statistics for the number of segments flooded more than 50% of the time (etc.).

[38] The analysis is concerned with increased frequency of tidal flooding due to sea level rise; it does not take into account extreme events.

Research Summary: Effects of Sea Level Change on Water Table Elevation in Maryland

Groundwater rise impacts on pavement performance

Rising groundwater levels can increase pavement strain.[39] Knott et al. found that for vulnerable roads, groundwater rises could lead to reductions of 5% to 17% in fatigue life, and that reductions increase to 50% as groundwater moves into the base layers of the pavement. Knott et al. also predicted increased reductions in rutting life from 38% to 92% when groundwater moves from the subgrade into the base layers. Depth to groundwater, pavement structure, and subgrade materials all affect variations in the magnitude of service-life reduction.[40]

Groundwater rise projections for Maryland

No specific projections are available for how sea level change will lead to groundwater change in Maryland.

However, a study of New Hampshire's coastline found that groundwater levels near the coast tend to rise along with sea level rise until equilibrium is established.[41] Groundwater modeling was used to project changes in groundwater levels due to sea level rise, finding that three feet of sea level rise would increase groundwater levels along the coast by the same three feet.[42] The impacts on the groundwater were also found within two miles of the coast, although to a lesser degree. The effects of sea level rise on groundwater was also found further inland where original groundwater levels were 17 to 34 feet above mean sea level.[43] Groundwater rises due to sea level rise at all sites in the study, however, the impact on pavements depends on the original depth of groundwater.

Further, there are several sources available to find monitoring data for Maryland's groundwater and soil moisture levels:

- USDA Natural Resources Conservation Service Soils provides soil survey data for Maryland counties in both tabular and spatial form.[44]
- The Maryland Geological Survey, along with the U.S. Geological Survey (USGS), maintains a network of observation wells around the state. The map can be used to find

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[39] Knott, Jayne, Mohamed Elshaer, Jo Sias Daniel, Jennifer Jacobs, and Paul Kirshen. 2016. Assessing the Effects of Rising Groundwater from Sea Level Rise on the Service Life of Pavements in Coastal Road Infrastructure. TRB 2017 Annual Meeting. Available at: https://trrjournalonline.trb.org/doi/pdf/10.3141/2639-01

[40] Knott et al. 2016.

[41] Knott et al. 2016.

[42] Knott et al. 2016.

[43] Knott et al. 2016.

[44] USDA. 2018. Published Soil Surveys for Maryland. U.S. Department of Agriculture (USDA) Natural Resources Conservation Service. Available at: https://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=MD

observation wells, where water level data and hydrographs are accessible. The map has 497 data points/wells that cover 15 aquifers and the water table.[45]

- USGS also provides groundwater levels from real-time data and 5-year hydrographs. These data could be used to assess climatic conditions impact on groundwater. USGS selected the wells because they are not heavily influenced by other factors. Wells have been minimally affected by irrigation, canals, drains, pipelines, and other sources of artificial recharge. These can be viewed at the well level, shown in Figure 121210.[46]

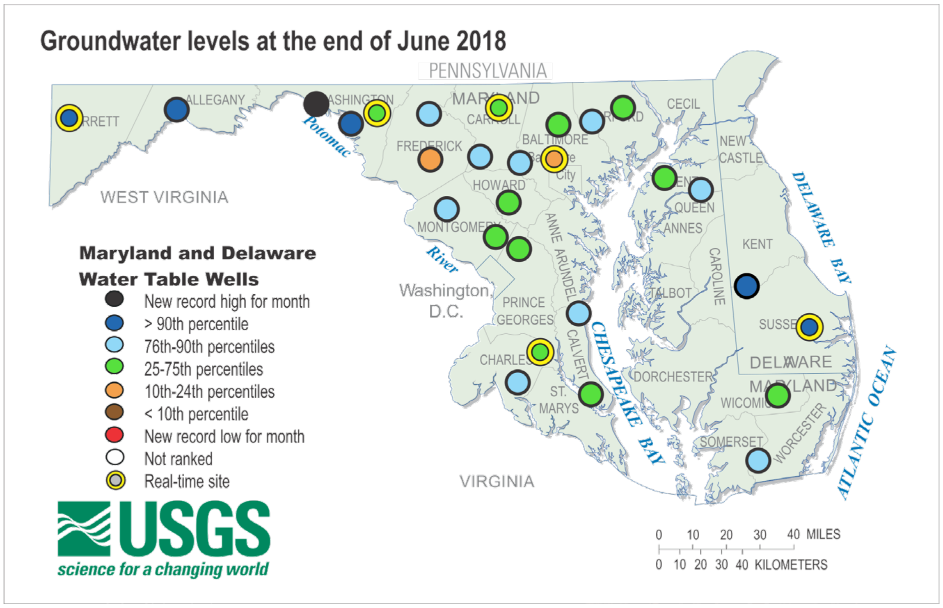

Figure 12. Groundwater levels at the end of June 2018[47]

Research Summary: Flooding Effects on Pavement Performance

There is a growing body of literature on the effects of flooding on pavement performance. Overall, the studies have demonstrated that flooding or saturation can cause pavement deterioration, affecting the performance and maintenance needs of the roads. The studies reviewed here have quantified the impacts of flooding on roadways in terms of the impact on structural strength and capacity, damage ratios due to precipitation, and critical lengths of saturation, the findings of which are discussed below.

Pavement Strength and Capacity

Several studies (including Gaspard et al., Zhang et al., Elshaer and Daniel, Sultana et al., and Lu et al.) provide assessments of the losses in structural strength of pavement under flooded

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[45] Maryland Geological Survey. 2018. Interactive Water-Level Mapper Tool. Available at: http://www.mgs.md.gov/groundwater/water_level_mapper.html

[46] USGS. 2018. Maryland and Delaware–Climate Response–Water Table Wells. U.S. Geological Survey (USGS). Available at: https://md.water.usgs.gov/groundwater/web_wells/current/water_table/counties/

[47] USGS. 2018.

and saturated conditions, represented by reductions in the Structural Number.[48,49,50,51,52] The Structural Number is an index that characterizes the structural strength of pavement given soil conditions, traffic load, and environmental factors. It is a function of the thickness of the pavement surface, base, and subbase, the structural layer coefficients, and the drainage coefficients of the base and subbase.[53] These studies found that flooding reduced pavement structural numbers by anywhere from 1.5% to 50% and reduced structural capacity by up to 73%. Heavy rainfall and flooding also increase roughness and rutting values.[54]

Key findings from each of these studies is provided in turn below. Additional details on the methods and context can be found in the original papers.

Impacts of extended flooding on roughness, rutting, and cracking[55]

- Extended periods of flooding increase roughness, rutting, and cracking of pavement.
- The subgrade California bearing ratio (CBR) value and structural number can be reduced by up to 67% and 50%, respectively.[56] The subgrade CBR value represents the mechanical strength of the subgrade.

Impact of Hurricane Katrina on roadways in the New Orleans Area

- Flooding from Hurricanes Katrina and Rita reduced the Structural Number by 18% (comparing flooded and non-flooded pavements) and reduced the subgrade modulus by 25% due to saturation.[57]
- For asphalt, Portland Cement Concrete, and composite pavements, generally thinner pavements experience more relative damage for submerged than non-submerged

[48] Gaspard, Kevin, Mark Martinez, Zhongjie Zhang, and Zhong Wu. 2007. Impact of Hurricane Katrina on Roadways in the New Orleans Area. Technical Assistance Report No. 07 2TA. Available at: https://www.ltrc.lsu.edu/pdf/2007/07_2ta.pdf

[49] Zhang, Zhongjie, Zhong Wu, Mark Martinez, and Kevin Gaspard. 2008. Pavement Structures Damage Caused by Hurricane Katrina Flooding. Journal of Geotechnical and Geoenvironmental Engineering, 134(5): 633-643. American Society of Civil Engineers. Available at: https://ascelibrary-org.ezproxy.neu.edu/doi/pdf/10.1061%2F(ASCE)1090-0241(2008)134%3A5(633)

[50] Elshaer, Mohamed and Jo Sias Daniel. 2018. Impact of Pavement Layer Properties on the Structural Performance of Inundated Flexible Pavements. TRB 2018 Annual Meeting

[51] Sultana, Masuda, Gary Chai, Sanaul Chowdhury, and Tim Martin. 2016. Deterioration of Flood Affected Queensland Roads–An Investigative Study. Available at: https://www.sciencedirect.com/science/article/pii/S1996681416300463

[52] Lu, Donghui, Susan Tighe, and Wei-Chau Xie. 2017b. Pavement Fragility Modeling Framework and Build-in Resilience Strategies for Flood Hazard. TRID National Academy of Sciences. Available at: https://trid.trb.org/View/1437729

[53] AASHTO. 1993. AASHTO Guide for Design of Pavement Structures. American Association of State Highway and Transportation Officials (AASHTO). Available at: https://habib00ugm.files.wordpress.com/2010/05/aashto1993.pdf

[54] Sultana et al. 2016.

[55] Lu et al. 2017b.

[56] Lu et al. 2017b.

[57] Elshaer and Daniel. 2018.

pavements.[58] However, other studies found that asphalt-concrete pavement structure was weakened by flooding, both asphalt and subgrade, yet Portland Cement Concrete structures experienced lesser damage.[59]

Impact of flooding on flexible pavements in Utah, Wyoming, and South Dakota[60]

- The ratio between the horizontal strain under saturated conditions to those under optimum conditions show that saturation increases horizontal strain by 6 to 15% for low-volume roads and 3 to 8% for the interstate section. The vertical strain is more critical, with an increase of 15 to 80% under saturated conditions.
- The structural number required under fully saturated conditions to withstand the same level of traffic loads as under optimum moisture conditions increased by 30 to 40% for low volume sections and 20-30% for interstate sections.
- The modified structural capacity was reduced by 10 to 40% for low volume sections and 6 to 22% for interstate sections due to saturation conditions.
- The reduction of the structural capacity was found to be 35 to 73% for low volume sections and 28 to 61% for interstate sections due to saturation conditions.

Impact of flooding on pavements in Queensland, Australia[61]

- This investigation found that structural strength of pavements deteriorated rapidly after a flood in South-East Queensland, Australia
- The pavements' modified structural number decreased from 1.5 to 50% after the flood.[62]
- A small increase (0.4%) in pavement failures was observed following the flood.
- The study's analysis of the flood affected sections of the Queensland roads showed that the roughness and rutting values had significantly increased following the heavy rainfall and flooding event from 2010 to 2014.[63]

Pavement Damage Ratios and Fragility Functions

Three studies conducted by Lu et al. in Ontario, Canada assessed the impact of flooding on pavement damage ratios and fragility. They found that short duration exposure to extreme precipitation had little impact, while longer duration precipitation events had a greater impact on

[58] Gaspard et al. 2007.
[59] Zhang et al. 2008.
[60] Elshaer and Daniel. 2018.
[61] Sultana et al. 2016.
[62] Sultana et al. 2016.
[63] Sultana et al. 2016.

the pavement damage ratios.[64] In addition, fragility calculations showed that the probability of pavement damage increases with increases in extreme precipitation levels.[65]

Lu et al. employed the Mechanistic-Empirical Pavement Design Guide (MEPDG) to simulate the effect of 36 extreme hydrologic events on typical pavements in Ontario, Canada.[66] Results show that the MEPDG is not sensitive to short duration exposure of extreme precipitation, and only extreme events contribute to notable international roughness index changes.

The study presents results for 22-day and 61-day duration extreme events. In a 22-day duration event, pavement damage ratio ranges from 0.39% to 1.17%. For all levels of precipitation, the damage ratio for 1-and 2-cycle events is the same (0.46%), whereas that for 3-cycle events is 0.91%. In a 61-day duration event, the pavement damage ratio ranges from 0.78% to 1.96%.[67]

There is a difference in the fragility of arterial pavements and collector pavements because, as precipitation depth increases, collector pavements experience a larger jump in damage compared to arterial pavements.[68] The results are shown in Table 22.

Table 22. Loss of pavement life caused by extreme precipitation events[69]

Pavement Types and Event Cycles	**Loss of Pavement Life (Years)**					
	50-year Return Period		**100-year Return Period**		**200-year Return Period**	
	22-day	***61-day***	***22-day***	***61-day***	***22-day***	***61-day***
Arterial						
1	0.08	0.25	0.08	0.33	0.17	0.33
2	0.17	0.50	0.17	0.58	0.25	0.58
3	0.25	0.75	0.33	0.75	0.33	0.83
Collector						
1	0.08	0.42	0.08	0.33	0.17	0.33
2	0.17	0.50	0.25	0.58	0.25	0.67
3	0.33	0.75	0.33	0.75	0.33	0.83

[64] Lu et al. 2017b.
[65] Lu, Donghui, Susan Tighe, and Wei-Chau Xie. 2017c. Pavement Risk Assessment for Future Extreme Precipitation Events under Climate Change. TRB 2018 Annual Meeting.
[66] Lu et al. 2017b.
[67] Lu et al. 2017b.
[68] Lu et al. 2017c.
[69] Lu et al. 2017b.

Lu et al. also used the MEPDG and a probabilistic pavement fragility modeling method to generate fragility functions that integrate flood hazards.[70] The results indicate that pavement life is shortened due to extreme events, including flooding.[71] Fragility functions and curves show the probability of exceeding certain levels of pavement damage given flood hazards.[72]

Lu et al. assesses pavement risk to flood hazards, quantified based on the numerical integration of probability of hazard, pavement fragility, and cost:[73]

$$\text{Risk} = \sum_{All} P\{\text{EP}\} \times P\{\text{Damage} \mid \text{EP}\} \times P\{\text{Cost} \mid (\text{Damage} \mid \text{EP})\},$$

where P{EP} is extreme precipitation hazards, P{Damage|EP} is the pavement fragility representing the probability of exceeding certain damage when the level of extreme precipitation hazards occur, and P{Cost|(Damage|EP)} is the cost of each possible damage given each extreme precipitation hazard.

The study provides damage ratio results from the pavement performance simulations for both collector and arterial pavements. Extreme precipitation depth is used to reflect flood potential and to estimate damage. The results are shown in Table 23.

Table 23. Damage ratio results from pavement performance simulations[74]

Precipitation Scenarios (mm)	Arterial Pavement Damage	Collector Pavement Damage
20	0.8%	0.47%
40	0.8%	0.93%
60	1.2%	1.4%
80	1.6%	1.86%
100	2.0%	1.86%
120	2.0%	1.86%
150	2.4%	2.79%

Critical Time to Saturate Pavement

The amount of damage sustained by pavement depends in part on the amount of water that permeates through the pavement during inundation. For different types of pavements, the

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[70] Lu, Donghui, Susan Tighe, and Wei-Chau Xie. 2017a. Impacts of Flooding on Asphalt Pavements Under Climate Change. Transportation Association of Canada. Available at: https://trid.trb.org/View/1511407

[71] Lu et al. 2017a.

[72] Lu et al. 2017[a].

[73] Lu et al. 2017c.

[74] Lu et al. 2017c.

amount of time to saturate the pavement varies. The thicker the pavement, the less susceptible to damage due to saturation.

Mallick et al. presents a system dynamic approach to evaluate the susceptibility of Hot Mix Asphalt (HMA) to flooding.[75] Mallick et al. includes a model to predict pavement response to different types of vehicles, soils, thicknesses and drainage conditions. Simulations with the model showed significant impacts when subgrade layer moduli were below 50 MPa and layer thickness was less than 200 mm for the HMA and less than 600 mm for the base.[76] Mallick et al. also includes a framework for evaluating the condition of the road after flooding has been developed. Mallick et al. found that the thickness of the asphalt layer is the most critical factor. For a HMA pavement with a thickness greater than 100mm, the asphalt was never compromised, even when the base is saturated.[77] Table 24 shows some examples of critical times for selected pavements.[78]

Table 24. Summary of effects on pavement[79]

Pavement Type	Critical Time for Safety Factor (SF)[80] (SF<1), hours
Low subgrade resilient modulus (10 MPa)	20
Low HMA layer thickness (30 mm)	>3 weeks
Low Base layer thickness (200 mm)	50
Low HMA layer modulus (1,000 MPa)	30
High vehicle load (100 kN per axle)	20

Additional Resources

The following resources provide additional information on the topics discussed above:

- Nivedya et al. discuss how the degree of saturation of pavement base layers is the major cause of distress in asphalt pavements. The study evaluates the impact of various

[75] Mallick, Rajib, Mingjiang Tao, and Jo Sias Daniel. 2015. A Systems Approach for the Evaluation of Susceptibility of Hot Mix Asphalt Pavements to Flooding. Transportation Research Board.

[76] Mallick et al. 2015.

[77] Mallick, Rajib, Tao Mingjiang, Jo Sias Daniel, Jennifer Jacobs, and A. Veeraragavan. 2016. A Combined Model Framework for Asphalt Pavement Condition Determination After Flooding. Transportation Research Board. Available at: https://trrjournalonline.trb.org/doi/abs/10.3141/2639-09

[78] Mallick et al. 2016.

[79] Mallick et al. 2016.

[80] The authors (Mallick et al.) calculate Safety Factor as 750/Predicted Surface Deflection (in micrometers). A SF<1 indicates an unsafe pavement, while SF>1 is considered safe.

drainage conditions on the structural performance of pavements with recycled layers when subjected to rainfall and flooding.[81]

- Rasdof and Almalki assess the deterioration rates of unpaved shoulder and outline assets in North Carolina based on field condition evaluations. The research was motivated to gain a better understanding of roadway asset deterioration for North Carolina DOT to prioritize maintenance needs.[82]
- Sultana details the development of mechanistic-empirical, deterministic-based pavement deterioration models to predict rutting and roughness of pavements impacted by flooding. These models have been used to predict rapid deterioration processes after flood events.[83]
- Sultana et al. present an extensive literature review on assessment and modeling deterioration of flood-affected pavements, including information on the development of new deterioration models.[84]

[81] Nivedya, M.K., Rajib Mallick, Cesar Tirado, Setare Ghahri Saremi, and Soheil Nazarian. 2018. An Evaluation of Moisture-Induced Structural Damage of Pavements with Cold Recycled Layers. Transportation Research Board. Available at: https://trid.trb.org/View/1496668

[82] Rasdorf, William and Ali Almalki. 2017. Highway Asset Deterioration Rates. TRB 2018 Annual Meeting.

[83] Sultana, M. 2016. Assessment and Modelling Deterioration of Flood Affected Asphalt Pavements. National Academy of Sciences. Available at: https://trid.trb.org/View/1471071

[84] Sultana, Masuda, Gary Chai, Sanaul Chowdhury, Tim Martin, Yuri Anissimov, and Anisur Rahman. 2018. Rutting and Roughness of Flood-Affected Pavements: Literature Review and Deterioration Models. American Society of Civil Engineers. Available at: https://trid.trb.org/View/1508453

APPENDIX C: DRAFT PROJECT LEVEL CLIMATE RISK SCREEN

This appendix outlines a working draft of an internal process to consider risks related to future environmental conditions—including sea level change, storm surge, and flooding from extreme rainfall—in project planning. Users would refer to the results of the vulnerability assessment conducted during this process to answer questions 1-3, and then supplement with additional asset-specific context and other details as needed. Completion of this document still requires input from the Office of Structures, the Office of Planning and Preliminary Engineering, District Maintenance, the Office of Maintenance, and the Office of Highway Development.

(If the answer to a question is yes, proceed to the next question)

1. Is the asset **exposed**[85] to any of the hazards?
   (see MDOT SHA Bridge Vulnerability Assessment_Results spreadsheet – answer Yes if Exposure Score > 2))
   Sea level change? Yes/No
   Storm surge? Yes/No
   Heavy precipitation? Yes/No

If yes…

2. Is the asset **sensitive**[86] to any of the hazards?
   (see MDOT SHA Bridge Vulnerability Assessment_Results spreadsheet – answer Yes if Sensitivity Score > 2))
   Sea level change? Yes/No
   Storm surge? Yes/No
   Heavy precipitation? Yes/No

If yes…

3. Document available data from the MDOT SHA Climate Risk Screen (copy/paste from results spreadsheet) – and **confirm any data in yellow cells**)

Identifying Information	**Structure Number**	
	Latitude	
	Longitude	
	Facility Carried	
	Feature Crossed	
	Location	
	Mile Point	
	Structure Approach HVI	

[85] Exposure refers to whether an asset is located in an area that would experience the hazard
[86] Sensitivity refers to how the asset fares when exposed to a climate variable (e.g., is it likely to experience damage or disruption)?

Sea Level Change Results	**Sea Level Change Exposure Score**	
	Sea Level Change Exposure Interpretation	
	Sea Level Change Sensitivity Score	
	Sea Level Change Sensitivity Interpretation	
	Sea Level Change Adaptive Capacity Score	
	Sea Level Change Adaptive Capacity Interpretation	
	Sea Level Change Vulnerability Score	
Storm Surge Results	**Storm Surge Exposure Score**	
	Storm Surge Exposure Interpretation	
	Storm Surge Sensitivity Score	
	Storm Surge Sensitivity Interpretation	
	Storm Surge Adaptive Capacity Score	
	Storm Surge Adaptive Capacity Interpretation	
	Storm Surge Vulnerability Score	
Precipitation Change Results	**Precipitation Change Exposure Score**	
	Precipitation Change Exposure Interpretation	
	Precipitation Change Sensitivity Score	
	Precipitation Change Sensitivity Interpretation	
	Precipitation Change Adaptive Capacity Score	
	Precipitation Change Adaptive Capacity Interpretation	
	Precipitation Change Vulnerability Score	
Exposure Indicators and Scores	**Sea Level Change Inundation Depth (ft)**	
	Sea Level Change Inundation Depth Score	
	Proximity to Coastline (ft)	
	Proximity to Coastline Score	
	Storm Surge Inundation Depth (ft)	
	Storm Surge Inundation Depth Score	
	FEMA Flood Zone	
	FEMA Flood Zone Score	
	Change in 24-hr, 50-yr Precipitation (%)	
	Change in 24-hr, 50-yr Precipitation Score	
Sensitivity Indicators and Scores	**Past Flooding from High Tides?**	
	Frequency of Past Flooding from High Tides	
	Past Closures from Tidal Flooding	
	Past Damages from Tidal Flooding	
	Tidal Flooding (SLC) Past Experience Score	
	Past Flooding from Storm Surge?	
	Frequency of Past Flooding from Storm Surge	
	Past Closures from Storm Surge Flooding	
	Past Damages from Storm Surge Flooding	

	Storm Surge Past Experience Score	
	Past Flooding from Heavy Rain Events?	
	Frequency of Past Flooding from Heavy Rain Events	
	Past Closures from Heavy Rain Event Flooding	
	Past Damages from Heavy Rain Event Flooding	
	Heavy Rain (Precip Change) Past Experience Score	
	Past Experience Maintenance Survey Notes	
	Underclearance	
	Underclearance Score (SLC and Surge)	
	Underclearance Score (Precip)	
	Scour Criticality Rating	
	Scour Criticality Rating Score	
	Substructure Condition	
	Substructure Condition Score	
	Superstructure Condition	
	Superstructure Condition Score	
	Deck Condition	
	Deck Condition Score	
	Year Built	
	Year Reconstructed	
	Bridge Age	
	Bridge Age Score	
Adaptive Capacity Indicators and Scores	**Average Daily Traffic**	
	Average Daily Traffic Score	
	Functional Classification	
	Functional Classification Score	
	Evacuation Route	
	Evacuation Route Score	
	Detour Length (miles)	
	Detour Length Score	

4. Consider additional context for the structure:

- Has the asset experienced any recent flooding?
- What was the root cause of the flooding (e.g., Riverine Flooding, Roadway drainage, Tidal Flooding)?
- What is the underclearance/low chord elevation of the structure?

  Review low chord elevation from bridge design documents to confirm the underclearance compared to the table above.
- What is the latest scour rating for the asset?

- Has the asset experience past closures from scour and/or roadway embankment erosion?
- Is the asset located downstream from any dams?
- If so, who owns the dam(s) and what is the condition and height of the dam? What is the distance to the dam? Is the dam(s) slated to be removed in the future?
- Were there any dams located upstream from the asset in the past? If so, when were they removed? What was the distance to the dam?
- Does the structure have a history of woody debris issues?
- Does the stream have a history of lateral migration? Please include relevant photographs, if available.
- Is any other important context about the structure missing from this document? If so, please record notes below.
    - Recent or nearby flooding events:
    - Channel instability:
    - Characteristics of the surrounding landscape (e.g., is the surrounding landscape likely to be inundated by sea level rise?):
    - Information about the connecting roadways (e.g., is the road an evacuation route?):

5. Final recommendation: Based on the available information should expected climate risks and the context above be considered, alongside other factors, in structure design?

    Yes No

    Justification:

6. If yes, consider following the FHWA Adaptation Decision-making Assessment Process (ADAP), starting with Step 5. https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/adap/index.cfm