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Section 1 - INTRODUCTION

The Pennsylvania Department of Transportation (PennDOT) has initiated a multi-phase effort aimed to better anticipate the consequences and potential impacts of extreme weather events and to identify funding priorities and strategies to improve transportation system resiliency.

Extreme weather events present significant and growing risks to the safety, reliability, effectiveness, and sustainability of transportation infrastructure and operations across the United States. Key components of the national transportation system have become increasingly vulnerable to climate impacts including facilities such as port, airports and rail terminals; and, fixed route infrastructure such as roads, bridges, trails, locks, canals, railways (freight and commuter), subways, and pipelines.

Weather events influence the daily and seasonal operation of transportation systems. Many inland states including Pennsylvania, Vermont, Tennessee, Iowa, and Missouri have experienced severe precipitation events that have recently damaged roads, bridges, and rail systems.

Since 2006, over 140 million dollars of emergency funds have been obligated on the federal aid system in Pennsylvania as illustrated in Figure 1.1. In recent years, tropical storms and hurricanes including Irene, Lee, and Sandy have resulted in flooding that has washed out roadways, damaged bridge abutments, and caused significant traffic and safety impacts.

**Figure 1.1: Emergency Funds Obligated 2006-2014**

In addition, many other intense storm events have resulted in flooding and damages to Pennsylvania’s transportation infrastructure. In April 2014, heavy rain led to flooding throughout the Philadelphia region affecting regional roadways and the SEPTA transit system. Recent storms in October 2016 resulted in over seven inches of rainfall in northern Pennsylvania that damaged several bridges and roadways.
While transportation infrastructure is designed to handle a broad range of impacts based on historic climate, preparing for climate change and extreme weather events is critical to protecting the integrity of the transportation system and financial investments.

The impacts of extreme weather events and a changing climate (such as higher temperatures, sea-level rise, and changes in seasonal precipitation and rain intensity) are affecting the lifecycle of transportation systems and are projected to intensify based on recent climate studies. Inland flooding from unusually heavy downpours can disrupt traffic, damage culverts, and reduce service life. High heat can degrade materials, resulting in shorter replacement cycles and higher maintenance costs. In counties along the Delaware River, sea level rise coupled with storm surge can inundate bridges and roads that would not have inundated in the past, necessitate more emergency evacuations, and require costly, and sometimes recurring repairs to damaged infrastructure.

The *Pennsylvania Climate Impacts Assessment Update*, completed by the Pennsylvania State University in 2015, evaluated available global climate models to identify potential climate scenarios within the state. The study concludes that Pennsylvania’s current warming and wetting trends will continue at an accelerated rate and will include an increase in the number and level of extreme precipitation events.
National studies have identified likely impacts of climate change on the highway system. Table 1.1 summarizes such impacts by climate variable as documented in NCHRP Report 750: Climate Change, Extreme Weather Events, and the Highway System. Understanding historic weather and potential climate impacts on Pennsylvania’s transportation system is an important first step in identifying viable adaptation strategies and prioritizing available funds for infrastructure improvements. Climate adaptation includes actions by individuals or systems to avoid, withstand, or take advantage of current and projected climate changes and impacts. Adaptation decreases a system’s vulnerability, reduces risk and/or increases its resilience to impacts.

**Impetus for Action**

Adaptation planning is in its early stages, with much more research and work to be done. Through FHWA pilot studies, select state and regional transportation agencies have become engaged in adaptation planning and initiated efforts to identify vulnerabilities, ascertain risks, and identify specific strategies. Strategies have included infrastructure design standard changes, retrofit of vulnerable facilities, enhancement of drainage systems, and development of additional information for emergency evacuation planning. It is likely that the understanding of climate risks and risk-based adaptation planning will evolve significantly over time. Several national initiatives and rulemakings have increased the emphasis on transportation resiliency and provide an impetus for PennDOT’s study, including:

**FHWA Actions** – FHWA has taken the following actions and initiatives related to climate adaptation: (1) issued FHWA Order 5520 committing the agency to integrating climate risk considerations into the delivery and stewardship of FHWA programs. Figure 1.4 highlights the agency’s responsibilities under Order 5520; (2) providing funding to support climate adaptation activities including vulnerability assessments and design and construction of projects or features to protect assets from damage associated with climate change; (3) updating the agency’s emergency relief program guidance to reflect climate resilience; (4) supporting efforts to address resiliency within the required risk-based asset management plans; and, (5) the continued development of FHWA tools and guidance for systematic consideration of climate risks at the transportation system and project levels. This has included the sponsorship of pilot vulnerability studies and the development of the 2012 Climate Change and Extreme Weather Vulnerability and Assessment Framework.

**FAST Act** – The Fixing America’s Surface Transportation (FAST) Act is the current transportation funding authorization bill passed by Congress in 2015. It includes the addition of system resiliency as a new planning factor in Section 1201 for Metropolitan Transportation Planning. The FAST Act will require Metropolitan Planning Organizations (MPOs) to address resiliency (e.g. typically through the identification and prioritization of vulnerabilities and strategies). In Pennsylvania, the following MPOs have initiated efforts to address resiliency:

- Delaware Valley Regional Planning Commission (DVRPC),
- Southwestern Pennsylvania Commission (SPC),
- York County Planning Commission (YCPC), and
- SEDA-Council of Governments (SEDA-COG).

The success of these resiliency efforts will require collaboration and coordination between regional and state agencies including PennDOT’s District offices.
### Table 1.1: Impacts of Climate Change on Highway System

<table>
<thead>
<tr>
<th>Climates/Weather Change</th>
<th>Impact to Infrastructure</th>
<th>Impact to Operations/Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Temperature</strong></td>
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</table>
| Change in extreme maximum temperature | • Premature deterioration of infrastructure.  
• Damage to roads from buckling and rutting.  
• Bridges subject to extra stresses through thermal expansion and increased movement. | • Safety concerns for highway workers limiting construction activities.  
• Thermal expansion of bridge joints, adversely affecting bridge operations and increasing maintenance costs.  
• Vehicle overheating and increased risk of tire blowouts.  
• Rising transportation costs (increase need for refrigeration).  
• Materials and load restrictions can limit transportation operations.  
• Closure of roads because of increased wildfires. |
| Change in range of maximum and minimum temperature | • Shorter snow and ice season.  
• Reduced frost heave and road damage.  
• Later freeze and earlier thaw of structures because of shorter freeze-season lengths.  
• Increased freeze–thaw conditions in selected locations creating frost heaves and potholes on road and bridge surfaces.  
• Increased slope instability, landslides, and shoreline erosion from permafrost thawing leads to damaging roads and bridges due to foundation settlement (bridges and large culverts are particularly sensitive to movement caused by thawing permafrost).  
• Hotter summers in Alaska lead to increased glacial melting and longer periods of high stream flows, causing both increased sediment in rivers and scouring of bridge supporting piers and abutments. | • Decrease in frozen precipitation would improve mobility and safety of travel through reduced winter hazards, reduce snow and ice removal costs, decrease need for winter road maintenance, and result in less pollution from road salt, and decrease corrosion of infrastructure and vehicles.  
• Longer road construction season in colder locations.  
• Vehicle load restrictions in place on roads to minimize structural damage due to subsidence and the loss of bearing capacity during spring thaw period (restrictions likely to expand in areas with shorter winters but longer thaw seasons).  
• Roadways built on permafrost likely to be damaged due to lateral spreading and settlement of road embankments.  
• Shorter season for ice roads. |

### Precipitation

| Greater changes in precipitation levels |                          | Regions with more precipitation could see increased weather-related accidents, delays, and traffic disruptions (loss of life and property, increased safety risks, increased risks of hazardous cargo accidents).  
• Roadways and underground tunnels could close due to flooding and mudslides in areas deforested by wildfires.  
• Increased wildfires during droughts could threaten roads directly or cause road closures due to fire threat or reduced visibility.  
• Clay subsurfaces for pavement could expand or contract in prolonged precipitation or drought, causing pavement heave or cracking. |

- If more precipitation falls as rain rather than snow in winter and spring, there will be an increased risk of landslides, slope failures, and floods from the runoff, causing road washouts and closures as well as the need for road repair and reconstruction.  
- Increasing precipitation could lead to soil moisture levels becoming too high (structural integrity of roads, bridges, and tunnels could be compromised leading to accelerated deterioration).  
- Less rain available to dilute surface salt may cause steel reinforcing in concrete structures to corrode.  
- Road embankments could be at risk of subsidence/heave.  
- Subsurface soils may shrink because of drought.
Table 1.1: Impacts of Climate Change on Highway System (continued)

<table>
<thead>
<tr>
<th>Climatic/Weather Change</th>
<th>Impact to Infrastructure</th>
<th>Impact to Operations/Maintenance</th>
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| Increased intense precipitation, other change in storm intensity (except hurricanes) | - Heavy winter rain with accompanying mudslides can damage roads (washouts and undercutting), which could lead to permanent road closures.  
- Heavy precipitation and increased runoff can cause damage to tunnels, culverts, roads in or near flood zones, and coastal highways.  
- Bridges are more prone to extreme wind events and scouring from higher stream runoff.  
- Bridges, signs, overhead cables, and tall structures could be at risk from increased wind speeds. | - The number of road closures due to flooding and washouts will likely rise.  
- Erosion will occur at road construction project sites as heavy rain events take place more frequently.  
- Road construction activities could be disrupted.  
- Increases in weather-related highway accidents, delays, and traffic disruptions are likely.  
- Increases in landslides, closures or major disruptions of roads, emergency evacuations, and travel delays are likely.  
- Increased wind speeds could result in loss of visibility from drifting snow, loss of vehicle stability/maneuverability, lane obstruction (debris), and treatment chemical dispersion.  
- Lightning/electrical disturbance could disrupt transportation electronic infrastructure and signaling, pose risk to personnel, and delay maintenance activity. |

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<thead>
<tr>
<th>Sea Level</th>
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| Sea-level rise          | - Erosion of coastal road bases and undermining of bridge supports due to higher sea levels and storm surges.  
- Temporary and permanent flooding of roads and tunnels due to rising sea levels.  
- Encroachment of saltwater leading to accelerated degradation of tunnels (reduced life expectancy, increased maintenance costs and potential for structural failure during extreme events).  
- Further coastal erosion due to the loss of coastal wetlands and barrier islands removing natural protection from wave action. | - Coastal road flooding and damage resulting from sea-level rise and storm surge.  
- Increased exposure to storm surges.  
- More frequent and severe flooding of underground tunnels and other low-lying infrastructure. |

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<tr>
<th>Hurricanes</th>
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| Increased hurricane intensity | - Increased infrastructure damage and failure (highway and bridge decks being displaced). | - More frequent flooding of coastal roads.  
- More transportation interruptions (storm debris on roads can damage infrastructure and interrupt travel and shipments of goods).  
- More coastal evacuations. |

Source: Table I.1 from NCHRP Report 750: Climate Change, Extreme Weather Events and the Highway System (Transportation Research Board, 2014)
CEQ Final Guidance – In August 2016, the White House Council on Environmental Quality (CEQ) released final guidance on the consideration of climate change in National Environmental Policy Act (NEPA) reviews. The guidance requires agencies to consider the impacts of climate on project alternatives and to consider actions to improve resiliency. Currently, state departments of transportation (DOTs) are working to develop procedures and protocols to address the CEQ guidance. It is expected that information on extreme weather vulnerabilities and future climate change impacts will serve as important resource data for these evaluations.

Executive Order (EO) 13690 – In January 2015, EO 13690 was signed establishing a Federal Flood Risk Management Standard (FFRMS) and a Process for Further Soliciting and Considering Stakeholder Input. The standard requires agencies to consider current and future climate risks for building and rebuilding infrastructure within floodplains. Currently, FHWA floodplain-related actions and design standards are derived from FHWA’s floodplain regulation 23 CFR Part 650, subpart A “Location and Hydraulic Design of Encroachments on Flood Plains.” FHWA is evaluating if changes are required to their existing floodplain regulations. However, until final promulgation of any such FHWA regulatory updates, there is no requirement for FHWA programs or project delivery (including federal-aid) to deviate from the existing floodplain regulation and requirements.

FHWA Rulemaking on Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events (81 FR 73196) – Effective October 2, 2017, state DOTs must perform statewide evaluations to determine if there are reasonable alternatives to roads, highways and bridges that have required repair and reconstruction activities on two or more occasions due to extreme weather or other emergency
events as defined within the rule. The requirements are included in a broader regulation that requires state transportation agencies to develop and implement risk-based asset management plans to improve or preserve the National Highway System. The regulation encourages state DOTs and MPOs to consider the evaluations as they develop transportation plans and programs and during the environmental review process for transportation projects.

**AASHTO** – The American Association of State Highway and Transportation Officials (AASHTO) is a nonprofit, nonpartisan association representing highway and transportation departments across the United States. Its primary goal is to foster the development, operation, and maintenance of an integrated national transportation system. Through AASHTO’s Center for Environmental Excellence and the Resilient and Sustainable Transportation Systems Technical Assistance Program, AASHTO has developed resources to assist state DOTs in understanding the potential effects of climate change and the range of strategies and options for climate change mitigation and adaptation. These tools and information, as well as those from FHWA, have served as an important resource for PennDOT’s study framework.

**PennDOT’s Phase 1 Study**

To support the recent federal actions discussed above, PennDOT has placed an increased emphasis on ensuring transportation operations are environmentally sustainable and state facilities are sufficiently resilient to withstand the growing frequency of extreme weather events.

A project steering committee was assembled to provide input and direction in defining the objectives, activities and deliverables for this study. This team included the staff and agencies provided in Table 1.2.

This initial study (Phase 1 Extreme Weather Vulnerability Study) focuses on the evaluation of historic vulnerabilities, development of a framework for addressing climate change impacts, and an initial assessment of risks and priorities related to the identified vulnerabilities.

The study’s analyses and mapping products are focused primarily on the flooding impacts on state-owned roadways and bridges. The primary mapping resources produced from the study include the historic and future vulnerabilities and risk assessments as developed in Section 6. These mapping products are intended for future review and assessment by PennDOT and its planning partners.

The following sections of this report and the accompanying appendices provide documentation of the methods, data and procedures used to identify flooding vulnerabilities within the state and of the outreach and coordination efforts completed during this first phase.
<table>
<thead>
<tr>
<th>Name</th>
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<td>Beal, Brenda</td>
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<td>Waple, Andy</td>
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Section 2 – STUDY FRAMEWORK

PennDOT’s Phase 1 Extreme Weather Vulnerability Study framework was developed after reviewing available resources including recently completed state DOT adaptation studies, FHWA/NCHRP research documents, and other national research and tools.

Resources for Study

For many state DOTs, adaptation planning is in its early stages. A significant amount of research and work is still needed to identify cost-effective practices and strategies to improve transportation system resiliency.

To assist states in developing adaptation and resiliency studies, FHWA and other research centers have compiled relevant materials including studies and research focused on climate forecasts and the transportation system. Figure 2.1 summarizes several of the primary resource websites for climate resiliency and adaptation.

**Figure 2.1: Climate Resiliency and Adaptation Resources**

<table>
<thead>
<tr>
<th>Resource Name</th>
<th>Website</th>
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<tbody>
<tr>
<td>AASHTO Resiliency Technical Center</td>
<td><a href="http://climatechange.transportation.org/">http://climatechange.transportation.org/</a></td>
</tr>
<tr>
<td>The Infrastructure and Climate Network</td>
<td><a href="http://theicnet.org/">http://theicnet.org/</a></td>
</tr>
<tr>
<td>Adaptation Clearinghouse (Georgetown Climate Center)</td>
<td><a href="http://www.adaptationclearinghouse.org/sectors/transportation/">http://www.adaptationclearinghouse.org/sectors/transportation/</a></td>
</tr>
</tbody>
</table>

Starting in 2010, FHWA partnered with state DOTs and MPOs to conduct climate change and extreme weather vulnerability assessments of transportation system infrastructure and to analyze options for adapting and improving resiliency. The pilots were jointly sponsored by the Office of Environment, Planning and Realty, and the Office of Infrastructure. Based on the results and lessons learned from these initial pilot studies, FHWA worked to develop and share a framework for transportation vulnerability assessments.
The Federal Highway Administration's (FHWA's) *Climate Change and Extreme Weather Vulnerability Assessment Framework* was developed in December 2012 to support state DOTs, MPOs, and other agencies interested in assessing the transportation system’s vulnerability to climate change and extreme weather events. Its purpose is to identify key considerations, questions, and resources that can be used to design and implement a climate change vulnerability assessment. The resource document provides an overview of key steps in conducting vulnerability assessments and uses in-practice examples to demonstrate a variety of ways to gather and process information.

As illustrated in Figure 2.3, the framework is comprised of three key steps: defining study objectives and scope; assessing vulnerability; and incorporating results into decision making. To complement the vulnerability assessment framework, FHWA has developed other tools to assist in the processing of climate data the identification of risks including:

- **CMIP Climate Data Processing Tool** - Spreadsheet tool that processes raw climate model outputs from the World Climate Research Programme’s Coupled Model Intercomparison Project (CMIP) databases into relevant statistics for transportation planners, including changes in the frequency of very hot days and extreme precipitation events that may affect transportation infrastructure.
- **Vulnerability Assessment Scoring Tool (VAST)** - Spreadsheet tool that guides the user through conducting a quantitative, indicator-based vulnerability screen. Intended for agencies assessing how components of their transportation system may be vulnerable to climate stressors.

FHWA’s framework and tools as well as other recently completed pilot studies were important resources that supported PennDOT’s project steering committee in defining tasks and objectives for the Phase 1 study. The framework and associated tools will also support the development of future PennDOT phases and other vulnerability and adaptation studies conducted by MPOs or other transportation agencies within the state.
Figure 2.3: FHWA Vulnerability Assessment Framework

1. DEFINE SCOPE

- **IDENTIFY KEY CLIMATE VARIABLES**
  - Climate impacts of concern
  - Sensitive assets & thresholds for impacts

- **ARTICULATE OBJECTIVES**
  - Actions motivated by assessment
  - Target audience
  - Products needed
  - Level of detail required

- **SELECT & CHARACTERIZE RELEVANT ASSETS**
  - Asset type
  - Existing vs. planned
  - Data availability
  - Further delineate

2. ASSESS VULNERABILITY

- Collect & Integrate Data on Assets
- Develop Climate Inputs
- Develop Information on Asset Sensitivity to Climate
- Identify & Rate Vulnerabilities
- Incorporate Likelihood & Risk (Optional)
- Assess Asset Criticality (Optional)

3. INTEGRATE INTO DECISION MAKING

- Incorporate into Asset Management
- Integrate into Emergency & Risk Management
- Contribute to Long Range Transportation Plan
- Assist in Project Prioritization
- Identify Opportunities for Improving Data Collection, Operations or Designs
- Build Public Support for Adaptation Investment
- Educate & Engage Staff & Decision Makers

Study Framework and Tasks

This study focuses on the evaluation of historic vulnerabilities, development of a framework for addressing climate change impacts, and an initial assessment of risks and priorities related to the identified vulnerabilities. The study is focused primarily on the flooding impacts on state-owned roadways and bridges. Figure 2.4 provides the project tasks, which serve as key section headings within this study report.

Stakeholder engagement has been conducted to emphasize and share PennDOT’s goals to improve transportation system resiliency, to collect information on known vulnerabilities, and to initiate discussions on adaptation strategies related to transportation planning, design, maintenance and emergency management.
Historic assessments of extreme weather have been conducted utilizing existing information from PennDOT databases and comments received from stakeholders. This task focused on preparing a planning level summary of known transportation system vulnerabilities to extreme weather and to identify enhancements to existing tools and databases to better report and manage weather impacts.

An evaluation of future climate impacts has included several key steps including the assessment of global climate model forecasts and the application of a technical process to estimate potential changes to existing FEMA 1-percent flood zones (100-year flood). These future flood zone scenarios have been used to evaluate changes to stream depths and impacts on transportation infrastructure using Geographic Information System (GIS) and hydrologic methodologies. The analysis has been conducted for three sample counties (Allegheny, Delaware and Lycoming) and could be expanded statewide in future study phases.

The risk assessment process represents an important step to evaluate known (e.g. historic) vulnerabilities for exposure, sensitivity and consequence. The results prioritize vulnerable locations to assist in identifying future study locations, identifying resiliency funding needs, and enhancing planning for maintenance and inspections.

The final task focuses on assembling a toolbox of adaptation strategies from available national and state resources for future assessment. Additional efforts both at a Central Office and District-level will be required to identify what strategies are most viable and cost-effective for specific locations.

Study Data Resources

This study has included the use of multiple data sources and tools to support the identification and assessment of roadway and bridge vulnerabilities to flooding. Table 2.1 provides a summary of these key resources and how each was used within the study. The development of the adaptation strategy toolbox included the review of multiple research documents which are not specifically addressed in this table but are discussed in more detail in Section 7.
### Table 2.1: Key Study Data Resources

<table>
<thead>
<tr>
<th>Data Resource</th>
<th>Source of Information</th>
<th>Study Use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transportation Asset Resources</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road Conditions Reporting System (RCRS)</td>
<td>RCRS database provided by PennDOT containing records from 11/16/2006 to 06/27/2015.</td>
<td>Source of locations for historical flooding</td>
</tr>
<tr>
<td>Stakeholder Comments from Study Website Tool</td>
<td>Stakeholder outreach tool utilized as part of the study to solicit input from regional partners throughout the Commonwealth.</td>
<td></td>
</tr>
<tr>
<td>Bridge Management System (BMS)</td>
<td>PennShare website: <a href="http://data.pennshare.opendata.arcgis.com/datasets?q=bridge">http://data.pennshare.opendata.arcgis.com/datasets?q=bridge</a></td>
<td></td>
</tr>
<tr>
<td>PennDOT RMS Pipe</td>
<td>PennShare website: <a href="http://data.pennshare.opendata.arcgis.com/datasets?q=Roadway">http://data.pennshare.opendata.arcgis.com/datasets?q=Roadway</a></td>
<td></td>
</tr>
<tr>
<td><strong>Digital Elevation Data</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>FEMA Flood Zones and Depth Grids</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEMA 100-year Flood Zone Boundaries</td>
<td>PASDA open data website: <a href="http://maps.psiee.psu.edu/preview/map.ashx?layer=11">http://maps.psiee.psu.edu/preview/map.ashx?layer=11</a></td>
<td>Mapping overlays</td>
</tr>
<tr>
<td>FEMA Digital Flood Insurance Rate Map (DFIRM)</td>
<td>PASDA open data website: <a href="http://www.pasda.psu.edu/uci/SearchResults.aspx?Keyword=DFIRM">http://www.pasda.psu.edu/uci/SearchResults.aspx?Keyword=DFIRM</a></td>
<td>Forecast vulnerability analyses for sample counties</td>
</tr>
<tr>
<td>FEMA Depth Grids</td>
<td>PASDA open data website: <a href="http://www.pasda.psu.edu/uci/SearchResults.aspx?Keyword=depth+grid">http://www.pasda.psu.edu/uci/SearchResults.aspx?Keyword=depth+grid</a></td>
<td></td>
</tr>
<tr>
<td>Pennsylvania Small Watersheds</td>
<td>PASDA open data website: <a href="http://www.pasda.psu.edu/uci/DataSummary.aspx?dataset=3047">http://www.pasda.psu.edu/uci/DataSummary.aspx?dataset=3047</a></td>
<td>Assessment of watersheds with highest mileage of flooding closures</td>
</tr>
<tr>
<td><strong>Historic and Projected Climate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Downscaled CMIPS Climate and Hydrology Projections</td>
<td>Scripps Institution of Oceanography (July 2014 Release): <a href="http://gdo-dcp.ucirnl.org/downscaled_cmip_projections/">http://gdo-dcp.ucirnl.org/downscaled_cmip_projections/</a></td>
<td>Forecast climate impacts for sample county vulnerability analyses</td>
</tr>
<tr>
<td>Historic Rainfall Amounts</td>
<td>NOAA Climate Data Online: <a href="https://www.ncdc.noaa.gov/cdo-web/">https://www.ncdc.noaa.gov/cdo-web/</a></td>
<td>Determine precipitation amounts associated with each closure event</td>
</tr>
</tbody>
</table>

* Pennsylvania Spatial Data Access
Section 3 – STAKEHOLDER ENGAGEMENT

Stakeholder engagement was an important component of PennDOT’s Phase 1 study. Specific outreach efforts included a March 3, 2016 webinar with over 120 participants from around the state. The webinar participants included staff from PennDOT’s Central Office and eleven District offices, MPO/RPOs, the Pennsylvania Turnpike Commission, FEMA, Army Corp of Engineers, as well as other agencies and educational institutions. The webinar introduced the project study and emphasized PennDOT’s focus on developing a more resilient transportation system.

Between May and June of 2016, separate outreach meetings were held at each PennDOT District office. These outreach meetings typically included District staff, the local MPO/RPO, PEMA and/or the County Office of Emergency Management (OEM). The meetings were about two hours in length and included presentations and discussions on the following topics:

- Transportation assets impacted by historical weather events including available data sources;
- Web engagement tools to allow for input of specific vulnerable locations;
- Methods and procedures for assessing risk and criticality;
- Types of adaptation strategies already implemented or needed in the future including barriers or implementation issues for those strategies

Minutes and attendees for each of the District meetings are provided in Appendix A.

Figure 3.1: PennDOT’s 11 Districts

During the project study period, separate agency outreach meetings were also conducted to coordinate and share information. These included meetings within Central Office (GIS, Asset Management, etc.), the Bureau of Maintenance and Operations (BOMO), the Pennsylvania Department of Community and Economic Development (DCED), and the Pennsylvania Homeland Security.

Web-Based Survey Tool

To assist in the collection and identification of transportation assets vulnerable to extreme weather, a web-based survey and data collection tool was established for the study period. PennDOT District and MPO staff were the primary respondents to the survey.
The survey included the collection of specific vulnerable locations using an interactive map. These locations represented transportation assets that have been impacted by flooding, snow, high winds and landslides.

The tool also serves as a potential framework for future data collection efforts, which could include an effort to better understand and report extreme weather impacts on local-owned roadways and bridges. Appendix B provides a complete summary of the survey platform including the survey question forms.

**Themes on Weather Impacts**

The District outreach highlighted weather events that were of most concern to design and maintenance personnel within PennDOT. Figure 3.3 summarizes some of the key themes identified regarding weather impacts on the transportation system. Snow and ice continue to be of most concern, but processes and procedures are in place to deal with these events. Flooding was also identified as a key weather issue for the Department. Currently, the Districts are primarily reactive to flooding events and most of the participants stressed that more data, procedures and strategies (for planning, maintenance and design) are needed to better address flooding. Heat (e.g. high temperatures) has had some impacts on the transportation system but was not identified as a major issue for many of the Districts. Most District participants stressed that secondary impacts of weather events, including downed trees and utility lines, are important issues requiring more processes and coordination to limit the duration of roadway closures.

**Identified Vulnerable Locations**

Through the District meetings and supporting web-based mapping tools, over 450 vulnerable locations were identified within the state. Figure 3.4 provides a summary of the identified locations, which included impacts from various weather events. Land and rock slides were identified as important vulnerabilities that were often grouped in with the flooding category. For example, Greene County was highlighted with notes indicating that landslides are prevalent throughout the entire county. The locations provided by stakeholders were used to evaluate PennDOT’s road closure database and were included in the risk assessment process as discussed in the following sections.
Figure 3.3: Primary Themes on Weather Impacts From District Outreach

**Flooding**
- Flooding has caused roadway damage and traffic impacts throughout the state
- Districts are primarily reactive to repeated flash flooding
- Most significant issues have resulted from tropical storms or deficiencies in local drainage systems

**Snow/Ice**
- Major area of focus but hard to predict
- Processes and procedures in place
- Snow drifting issue in some areas

**Heat**
- Pavement joint buckling
- Practices in place to address
- Not a major issue for most Districts

**Tornado/Earthquake**
- Has impacted roads and bridges
- More protocols needed

**Other Impacts**
- Secondary impacts from weather have often caused most impacts on traffic and road closures
- Trees down from wind and storms
- Utilities
- Coal and acid mine drainage have degraded metal pipes under many roads
- Land/rock slides a major issue in mountainous areas of state
- Retaining wall failures

**Adaptation Strategies**

The outreach meetings also provided valuable insights on potential strategies that could improve resiliency, maintain safety, and support emergency response planning to extreme weather events. The specific strategies have been summarized in **Section 7** of this report. Nearly all Districts stressed the need for better reporting and mapping of historic weather impacts including flooding. Maintenance personnel typically are aware of such locations; however, more efforts are needed to share this information within PennDOT and across other agencies. Efforts to map and prioritize vulnerable locations can provide benefits to planning, design and emergency management personnel.
Figure 3.4: Vulnerable Locations Identified Through Stakeholder Meetings

Section 4 – HISTORICAL FLOODING ASSESSMENT

This section provides an assessment of historical flooding vulnerabilities in Pennsylvania and is complemented by the GIS shapefiles and online mapping products provided in Appendix C. The assessment makes use of two primary data sources: PennDOT’s Road Conditions Reporting System (RCRS) and the stakeholder comments discussed in the previous section. The objectives of the historical flooding assessment include:

- Identify and map historic vulnerabilities to support future resiliency planning and other maintenance and emergency management activities;
- Provide example map formats and content that PennDOT may include on their internal GIS-IQ and Maintenance-IQ file sharing systems; and,
- Evaluate the coverage and content of flooding locations within the RCRS system.

PennDOT RCRS

PennDOT’s RCRS system was developed in 2006 and offers consistent and accurate road condition information for planning and reporting purposes. RCRS enables PennDOT to report road closures, lane restrictions, highway conditions, construction activities, and bridge failures and closures to outside agencies and the general public in a uniform method.

Figure 4.1: PennDOT RCRS User’s Manual
The RCRS has primarily been used to provide real-time information as follows:

- **Feeds** – Information is provided to 19 entities (including 511, the Automated Permit Routing and Analysis System [APRAS], and the Advanced Traffic Management System [ATMS]). The feeds are not currently integrated with the 911 system.
- **Incident Command Process (ICP)** – All fields entered in RCRS are emailed out to PennDOT registered staff as events occur.
- **Reports** – Reports and summaries can be generated, primarily for real time data. Most of the reports are not currently distributed or shared.

Traffic Management Center (TMC), Incident Command Center (ICC) and other District Maintenance staff are primarily responsible for entering information to the RCRS.

RCRS allows those entering information to specify the cause of the roadway closure. The RCRS “Cause” field provides a specific list of options that follow Traffic Management Data Dictionary (TMDD) standards. **Figure 4.2** illustrates the available “Cause” field drop down options. RCRS includes options for flooding and winter weather events, as well as secondary weather impacts including downed trees and utilities. For the historical flooding analyses in this study, RCRS data records were extracted with the following causes:

- **BRIDGE FLOOD PRECAUTION** – Represents an event due to a short-term closure of a bridge or culvert resulting from overtopping water, pressure flow, flooded approaches, or severe debris blockage of the bridge opening during a high water or flood event.
- **BRIDGE FLOOD WASHOUT/DAMAGE** – Represents a prolonged closure of a bridge or culvert resulting from complete or partial washout or other flood-related damage.
- **FLOODING** – Represents flooding events including whether the roadway is under water, damaged, or washed out.

These records were the basis for the mapping and summary tables representing historic conditions over the last decade.

**Figure 4.2: RCRS Cause Field Definitions**

![Image of Event Administration form](image-url)
Historic Flooding Assessment

Although PennDOT does not currently produce formal reports and mapping of historic flooding vulnerabilities, several of the Department’s resources have information that can support a historical flooding assessment. As highlighted in Section 1, PennDOT continues to track federal obligation funds for emergency disasters. This includes over $100 million of funding distributed for the federal aid highway system to address flooding since 2006 primarily related to multiple hurricane events. In that timeframe, PennDOT has also allocated over $90 million of state disaster recovery funds for the non-federal aid system as distributed from PEMA. More efforts are needed to track other funding sources that have been used to address extreme weather impacts on the transportation system. This can include summarizing costs for specific Work Breakdown Structure (WBS) coding related to disaster events and other emergency funding.

The RCRS is another PennDOT resource that can assist in identifying historic flooding impacts and specific vulnerabilities. For this study, RCRS historical database records between 11/16/2006 and 06/27/2015 were combined with the stakeholder comments on flooding locations summarized and mapped as part of this study. This combined data source is used to identify the locations of flooding vulnerabilities within the state. The RCRS data records were extracted for any designated causes related to flooding. Several of the stakeholder comments that addressed an extensive length of roadway were modified to limit the vulnerabilities to reported RCRS closure locations or areas within FEMA 1-percent flood zones. The RCRS and stakeholder comment data were linked to PennDOT’s state route and segment system to obtain key attributes including roadway length and functional class.

Based on this linked data system, Table 4.1 provides a summary of the state roadway mileage vulnerable to flooding by PennDOT District. District 3 and 8 are highlighted as having the highest mileage of roadway flooding vulnerabilities within the state. The tabular results also illustrate that most vulnerabilities occur on roadways classified as minor arterial or lower.

As discussed later in this section, there are a number of limitations in using RCRS data to identify flooding vulnerabilities including:

- data is only available since 2006;
- all flooding events may not be entered into the system;
- roadway closures may not always indicate the exact locations of flooding; and
- other data input errors may exist.

As a comparison to the RCRS flooding locations, a separate analysis was done to identify any state roadway segment (PennDOT’s RMS) that falls within a FEMA’s 1% (100-year) flood zone boundary, which are available for every county within the state. This boundary represents the extent of flooding for a flood that has a 1% chance of being equaled or exceeded in any single year. Table 4.2 summarizes the state and District roadway mileage that falls within flood zone boundaries. These estimates also have limitations in determining roadways or bridges that have flooded as it does not consider infrastructure
elevation and stream depths. The resulting total state roadway mileage is similar to the coverage of the RCRS flooding record mileage.

Assessing historic flooding by watershed also provides information on future study needs. Other agencies, such as the Vermont Agency of Transportation, have undertaken broader range efforts to study and apply innovative multi-agency strategies aimed to reduce flooding impacts across watersheds. Figure 4.3 illustrates watersheds, at the USGS Hydrologic Unit Code (HUC) 8 level, that have the most state roadway mileage vulnerable to flooding using the vulnerable locations determined through RCRS and stakeholder comments. Figure 4.4 illustrates watersheds that have the most state roadway mileage that fall within the FEMA 1% flood zone boundary. These maps provide insights into the prioritization of future watershed focus studies within the state.

Table 4.1: PennDOT State Roadway Mileage Vulnerable to Flooding

<table>
<thead>
<tr>
<th>Functional Class</th>
<th>Definition</th>
<th>Total Miles</th>
<th>Roadway Miles by PennDOT District</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Interstate</td>
<td>8</td>
<td>0 0 0 0 1 7 0 0 0 0</td>
</tr>
<tr>
<td>2</td>
<td>Principal Arterial - Freeways/Expressways</td>
<td>16</td>
<td>0 1 0 0 2 1 0 0 0 5</td>
</tr>
<tr>
<td>3</td>
<td>Principal Arterial - Other</td>
<td>351</td>
<td>46 19 33 15 33 101 35 12 13 36 9</td>
</tr>
<tr>
<td>4</td>
<td>Minor Arterial</td>
<td>617</td>
<td>62 43 80 87 71 98 61 19 40 30 27</td>
</tr>
<tr>
<td>5</td>
<td>Major Collector</td>
<td>850</td>
<td>53 105 123 90 79 71 156 45 34 20 73</td>
</tr>
<tr>
<td>6</td>
<td>Minor Collector</td>
<td>621</td>
<td>62 90 126 47 32 16 116 41 46 16 30</td>
</tr>
<tr>
<td>7</td>
<td>Local</td>
<td>683</td>
<td>30 30 105 84 51 26 108 96 25 25 21</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>3096</strong></td>
<td><strong>252 289 467 323 269 320 477 219 168 140 170</strong></td>
</tr>
</tbody>
</table>

* Local roadways are those included in the PennDOT RMS and designated with a local functional class code

Table 4.2: State Roadway Mileage within FEMA 1% Flood Zone Boundary

<table>
<thead>
<tr>
<th>Roadways Included</th>
<th>Total Miles</th>
<th>Roadway Miles by PennDOT District</th>
</tr>
</thead>
<tbody>
<tr>
<td>All State Roadways within 1% Flood Zone Boundary</td>
<td>3450</td>
<td>196 368 533 327 295 459 379 272 174 214 234</td>
</tr>
</tbody>
</table>

* NHS = National Highway System; ** ADT = Average Daily Traffic
Figure 4.3: PennDOT State Roadway Mileage Vulnerable to Flooding by Watershed

http://s3.amazonaws.com/tmp-map/climate/watershed-ranks.html

Figure 4.4: State Roadway Mileage within FEMA 1% Flood Zone Boundary by Watershed
Mapping of Vulnerable Locations

Identifying specific vulnerabilities is an important component of FHWA’s Vulnerability Assessment Framework. This study has prepared mapping products that can support resiliency planning efforts for PennDOT and its planning partners. Based on these examples, PennDOT may develop similar mapping services that provide direct linkages to the RCRS, RMS and BMS systems. A summary of the maps developed for this study are provided below. Note, the links to the maps work best using a Google Chrome browser.

- **RCRS Data Filtered by Closure Date** - [rcrs-count-by-day.html](mailto:rcrs-count-by-day.html) - Requires Google Chrome Browser

  This map provides a view of the RCRS records over selected date ranges. There are two ways to use this map. The first option is to simply change the map view using the zoom button control in the upper left corner of the map. Below the map window is a graph of closure date frequencies that will dynamically change based upon the area being viewed. The second method is to select a date range on the graph. Only RCRS data points within this date range will be shown. The date range can be expanded or narrowed by selecting the brackets enclosing the range. Between the combination of the map and the graph, one can visualize the impacts of specific storm systems on the transportation network, such as Hurricane Irene (August 2011) and Hurricane Sandy (October 2012).

- **RCRS Data Grouped by Closure Event Comments** - [rcrs-map.html](mailto:rcrs-map.html)

  This map evaluates the descriptive comments included within the RCRS flooding closures database. The data in the comments field is unstructured but may lend additional insights into the impacts of flooding across the transportation network. The comments field was systematically searched for keywords that would provide logical groupings such as ice-snow, high wind, downed utilities, erosion and landslides. Also included as an independent map overlay is a layer containing the RCRS closure segments clipped to FEMA’s 1-percent flood zone boundary. This layer provides further insights into the actual flooding locations.

- **Vulnerable Locations Identified Through Stakeholder Meetings** - [wiki-mapping-category.html](mailto:wiki-mapping-category.html)

  This map displays vulnerable locations as identified by participants in the stakeholder outreach process. Participants were able to use a web-based mapping tool to identify and classify locations that are known to be impacted by rain, snow & heavy winds.

- **RCRS Closure Data Clustered by Frequency** - [rcrs-closure-cluster.html](mailto:rcrs-closure-cluster.html)

  An RCRS cluster frequency map was created by taking the midpoint of the road centerline and then aggregating the resulting points by proximity and map zoom level. When zooming in or out, the cluster count is automatically adjusted by the proximity of RCRS events to one another.

- **RCRS and 1 and 4-Day Observed Precipitation** - [rcrs-closure-observed-1day.html](mailto:rcrs-closure-observed-1day.html); [rcrs-closure-observed-4day.html](mailto:rcrs-closure-observed-4day.html)

  The RCRS records have been linked to historical precipitation values associated with each RCRS closure date. The 1-Day Observed Precipitation map was created using the NOAA Climate Data Online tool which provides daily weather data for stations around the world. The maximum daily precipitation values were assigned to each of Pennsylvania’s defined watersheds (HUC 8). Then, using the RCRS closure location and date, precipitation values were assigned to each record. For the 4-Day Observed Precipitation Map (as
shown in Figure 4.5), the process was duplicated using precipitation values for the day of the closure and the previous three days.

**Figure 4.5: Illustration of Linkage of RCRS Flooding Closures to NOAA 4-Day Precipitation**

Appendix C provides the source ARCGIS geodatabase and shapefiles used to create the above maps. The data and mapping provided above were key resources used for the risk assessment analyses and mapping as documented in Section 6.

**Evaluation of RCRS**

The mapping examples provided above illustrate ways to summarize and visualize the historic flooding closures in the RCRS system. Integrating these types of reports and maps into PennDOT’s GIS-IQ and Maintenance-IQ file sharing systems can provide PennDOT and its planning partners historic data for resiliency planning, bridge inspection prioritization, maintenance activities, etc.

Although the RCRS system is a valuable data source for understanding historic flooding vulnerabilities, further evaluations are required to assess deficiencies including those provided below:

- **Missing Locations** – Figure 4.6 highlights a comparison of stakeholder comments and RCRS closure records related to flooding. The map conveys the value of the RCRS system as the stakeholder comments are a much smaller sample than what RCRS contains. However, there are a number of flooding vulnerabilities provided by stakeholders that are not in RCRS. Further evaluations may be needed to address why such locations are missing. In addition, RCRS only contains closures on the state roadway system, thus any local roadway closures will not be represented.

- **Incorrect Locations** – The RCRS does have some limitations in identifying locations of flooding. A roadway closure location may not always indicate the exact location of flooding. There are instances where roads have been closed due to downstream flooding issues.

- **Flooding Details and Causes** – RCRS lacks specific information to indicate the cause of flooding (e.g., river inundation, stormwater issue, culvert blockage, etc.). Evaluations of the RCRS structure could be
conducted to identify additional data detail to support resiliency purposes. However, any modifications to RCRS must be balanced with the burden put on those staff who enter data as they may have multiple responsibilities.

- **Data Quality** – Continued evaluation of the RCRS data systems may identify incorrect closure causes and route/segment assignment. Structural changes may support the improvement of data clarity and the ease of entry, which could reduce errors. Several participants of this project’s outreach efforts have stressed the important of RCRS training related to resiliency needs. The vulnerability and risk maps provided in **Section 6** allow for reviewers to provide feedback on each location.

**Figure 4.6: Map Comparing Stakeholder Comments vs. RCRS Closure Segments**

[rcrs-vs-stakeholder.html](rcrs-vs-stakeholder.html)

*(Stakeholder Comments Obtained Through Online Survey Site)*
Section 5 – CLIMATE CHANGE IMPACTS ON FLOODING

This study has incorporated a planning level analysis to evaluate flooding inundation of PennDOT’s state-owned roadways and bridges based on existing FEMA 1-percent chance flood zone maps and climate model projections for Pennsylvania. The analysis is intended to provide general insights on potential transportation vulnerabilities within the state as a result of climate change and increased extreme weather events. The analysis may be supplemented in the future by more detailed hydraulic modeling at specific site locations. Such modeling may focus on stormwater management, drainage and the details of culvert design and capacity at individual sites.

The study analysis has been conducted for three sample counties (Lycoming, Allegheny and Delaware) with a focus on procedures and tools that can be cost-effectively applied in other counties. The results from the analysis are to be evaluated against local stakeholder knowledge and other historic flooding information including PennDOT’s RCRS. Assessing the reasonableness and planning value of the study analysis will determine whether additional county analyses are conducted.

Climate Change in Pennsylvania

The Pennsylvania Climate Change Act (PCCA), Act 70 of 2008, directed Pennsylvania’s Department of Environmental Protection (DEP) to conduct a study of the potential impacts of global climate change on Pennsylvania over the next century. The original study and subsequent updates in 2013 and 2015 were conducted for DEP by a team of scientists at the Pennsylvania State University. The purpose of the updates was to capture advances in the scientific understanding of climate change and make use of new data sets relevant to Pennsylvania.

The study included an assessment of historical changes in Pennsylvania’s climate, which was used to assess performance of available global climate models. Key conclusions on historical trends include:

- While there has been a 10 percent increase in average annual precipitation across Pennsylvania during the past century, there has been a noteworthy increase in the number of extreme precipitation events in more recent times.
- According to the National Climate Assessment issued in May, 2014, in the period 1958-2012, there was a 71 percent increase in the frequency of the heaviest 1-percent precipitation events in the Northeast United States, including Pennsylvania.
- Out of the 127 stream flow stations analyzed in Pennsylvania, 32 percent have seen the 50-year (1965-2014) largest event in the most recent decade.

The DEP study used the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) to evaluate available climate change scenarios. This included review of the available General Circulation Model (GCM) outputs and associated downscaling simulations. Based on this assessment, the study concludes:

- Global Climate Models have improved in replicating historic trends in Pennsylvania.
- Pennsylvania’s current warming and wetting trends will continue at an accelerated rate.
- Extreme precipitation events will very likely become more intense and more frequent. Models predict an 8-12 percent increase in the annual mean precipitation with seasonal variances as illustrated in Figure 5.1.
Forecasting Methodology

A planning-level analysis methodology has been developed to evaluate flooding inundation of state-owned roadways and bridges within Allegheny, Lycoming and Delaware counties. The methodology is similar to efforts conducted in several other states. Regression equations have been used to estimate future flood discharges based on specific variables that may change in the future including impervious area (due to development) and precipitation (due to climate change). Other hydraulic “power” equations are used to translate discharge increases to stream depth increases for specific locations within each county. The focus of the effort is not to predict future discharges but to scale the discharges and corresponding depths used in developing the FEMA Flood Insurance Rate Maps (FIRM) based on the projected impacts of climate change.

Forecast precipitation changes were based on projected values of daily precipitation from Global Climate Models (GCMs) through 2099. The projections for the Representative Concentration Pathway (RCP) 8.5 scenario were used in the analysis and are consistent with the projections used for the Pennsylvania Climate Impacts Assessments Update (Pennsylvania State University, 2015).

Appendix D provides a summary of the methodology including details on the data and approaches for assessing inland flooding, sea-level rise and the identification of vulnerable (e.g. inundation due to flooding) transportation infrastructure. A section on limitations is also provided and should be reviewed before applying the results of this study for any planning purposes.

Analysis Scenarios

The flooding vulnerabilities were determined for three different scenarios as shown in Table 5.1. Based on each of these flood zone scenarios, stream and river depths were estimated and compared to the elevation of the transportation infrastructure to determine locations of flooding inundation. The highlighted “Forecast Scenario 2” is the primary scenario used in subsequent risk assessment steps (Section 6).

Under all scenarios, FEMA’s “Zone AE” areas are included in the analysis, which are defined as areas inundated by the 1-percent annual flood, for which base flood elevations (BFEs) are available.
The existing scenario analysis also includes FEMA’s designated “Zone A” areas. These are areas inundated by the 1-percent annual flood for which no BFEs have been determined. These generally include smaller streams and/or more rural areas. For the future analysis scenarios “Zone A” areas are not included due to lack of available model information.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing 1-percent Flood Zone</td>
<td>Utilizing existing FEMA 1-percent (e.g. 100-year) flood insurance rate maps</td>
</tr>
<tr>
<td>Forecast Scenario 1 Flood Zone</td>
<td>FEMA 1-percent flood zone increased based on projected climate change impacts on precipitation through 2050</td>
</tr>
<tr>
<td>Forecast Scenario 2 Flood Zone</td>
<td>FEMA 1-percent flood zone increased based on projected climate change impacts on precipitation through 2100</td>
</tr>
</tbody>
</table>

Note, the 100-year flood zones have been used as a basis for projecting climate changes within this study. FEMA does produce 500-year flood zone information but it is not as widely mapped as the 100-year flood zones (i.e. 100-year flood zones are readily available for more streams in Pennsylvania). The 100-year flood is the basis for flood insurance rates and are used for the design of major projects such as major roads, levees, flood detention structures, etc.

**Mapping Products**

The forecast vulnerability analyses have been summarized into several mapping products as described below:

- **Map Books**
  
  Appendix E provides a summary of the technical results for each of the three counties. The Map Books are provided in PDF format and illustrate all vulnerable state roadway and bridge locations. Vulnerable locations are defined as those that are inundated by some level of water during the extreme flooding event. The illustrations provide the estimated water depths at each location. The results are provided for the three scenarios shown in Table 5.1.

  Figure 5.2 provides a sample Map Book page for Lycoming County. For Delaware County, two Map Book versions are provided to represent alternative sea-level rise assumptions (NOAA and IPCC) as described in the Appendix D methodology report.

- **Summary GIS Maps of Vulnerable Roads / Bridges**

  Separate GIS mapping files were also developed to summarize and evaluate vulnerable locations from the Map Books. These maps highlight vulnerable roads and bridges for two water depth ranges (overtopping infrastructure): greater than 1 ft and 0-1 ft. The summary GIS maps can be accessed through the hyperlinks shown in Figure 5.3 and using the files provided in Appendix C.
Within the mapping set for Delaware County, the future scenario results are only provided for the NOAA sea level rise estimates as that resource provided the most conservative values. The maps also contain several additional layers that can be selected:

- **DFIRM** – Existing FEMA 1-percent flood boundaries for Zone AE areas
- **Depth Grid** – Color illustration of estimated 1-percent flood stream depths
- **2100 1% Flood Vulnerability** – Forecast flood boundaries which can be compared to the DFIRM
- **Map Scan** – Linkages to the Map Book scan sheets.

## Evaluation of Results

The forecast mapping analyses conducted for this study will be evaluated by PennDOT, SPC, SEDA-COG and DVRPC. These MPO/RPOs are in the process of evaluating vulnerabilities in their respective regions and can provide local insights regarding the value and validity of the results as well as potential improvements to the analysis process.

**Figure 5.4** provides a comparison of the forecast and historic vulnerable locations. Even though there are overlapping locations, there are locations that are historically vulnerable that are not captured through the future analyses. Further efforts are needed to assess why the forecast analyses do not show inundation (e.g. the RCRS or stakeholder comment is incorrect, the future data assumptions are not valid, etc.). Again it is important to carefully interpret RCRS information as it represents a roadway closure due to flooding and does not necessarily mean the entire section is inundated. In contrast, the forecast analysis identifies specific locations of inundation.

There are also a large number of locations that are inundated in the future analyses but are not classified as such historically. These locations may be considered vulnerable areas for future planning review and assessment.

**Figure 5.4: Comparisons of Historic and Future Vulnerable Locations**

[Link](http://s3.amazonaws.com/tmp-map/climate/future-vs-historic.html)
Section 6 – RISK ASSESSMENT FRAMEWORK

An initial risk assessment framework has been developed for this study to evaluate historic and future flooding vulnerabilities within Pennsylvania. The primary goals of developing a risk assessment process include:

- understanding potential consequences and costs of extreme weather impacts on specific locations;
- helping PennDOT determine priority locations for more detailed further study; and,
- providing information to support planning and programming of projects (including the potential integration into DOT/MPO/RPO project prioritization processes).

The risk assessment process may also provide other information in support of District maintenance planning, emergency management activities and the evaluation of project design alternatives.

FHWA has developed a Vulnerability Assessment Scoring Tool (VAST) to help State DOTs, MPOs, and other organizations implement a vulnerability screening process. The tool’s approach involves collecting information about indicators of each vulnerability component and operationalizing that information into relative vulnerability scores.

![Figure 6.1: Example of Risk Assessment Scoring](image)

Although the VAST tool was not directly used for this study, concepts and information from the tool have been integrated into GIS and spreadsheet processes to facilitate the risk calculations, test alternative risk formula weighting and provide methods to visualize results. In addition, the VAST tool has been directly used by SPC for a pilot vulnerability study in the Pittsburgh region.

Risk Framework and Data

A quantitative process has been developed to assess flooding vulnerability risks. The process integrates information on exposure, sensitivity and consequence. The formulas and input data are to be evaluated by PennDOT and its planning partners to assess the reasonableness of the results and potential enhancements including the integration of qualitative input from local staff. The framework utilizes the PennDOT data as shown in Table 6.1. The data includes information from PennDOT’s RMS, BMS, and RMS Pipe databases.

The primary source for historic flooding exposure information includes the RCRS road closure locations and stakeholder comments as described in Section 4. Future exposure locations are determined from the 2100 forecast flooding analysis scenario described in Section 5 (only for Allegheny, Delaware and Lycoming counties). The identified vulnerable locations were linked to the RMS using the county, state route (SR) and segment variables within the database. As a result, all vulnerable roadway and bridge locations are represented by specific segments within the RMS.
Additional exposure variables are also included in the risk assessment scoring system. To emphasize actual flooding locations, FEMA 1-percent flood zone boundaries are used within the scoring process (e.g. additional scoring value for RMS segments that fall within the flood zone). A final exposure variable has been included to address frequency. Originally this variable was to be based on the number of closure dates within the RCRS. However, repeated records and different closure lengths made the application of this information cumbersome. As a result, the results of the NOAA precipitation data linkage to RCRS, as discussed in Section 4, is used to address how often the specific location may flood. If the location flooded historically with low rainfall amounts then a higher score is applied within the formula. For the forecast scenario such data is not available. As a result, the risk analyses for the forecast vulnerabilities utilize information on the calculated depth of water. Higher scores are provided for higher projected water depths overtopping the transportation infrastructure.

Sensitivity variables are included to address asset characteristics that make the asset more vulnerable to flooding. For this initial process, variables related to bridge scour rating, pavement condition and pipe or culvert deficiencies were incorporated into the formula. Segments of road which have deficient roads, bridges or pipes receive additional scoring values for risk.

Consequence variables address the potential impact of the roadway closure on traffic operations. Variables are included for traffic and truck volumes, roadway functional class, and whether the segment is designated as one of PennDOT’s official state detour routes.

Figure 6.2 provides the formula used to estimate a cumulative risk score for each vulnerable roadway segment. It was developed using the variables discussed above with a weighting scheme determined through an iterative process that provided emphasis to roadway traffic volumes. The application of the risk formula was conducted using the EXCEL worksheets provided in Appendix F. The sheets allows for alternative weighting schemes to be tested.

### Risk Assessment Mapping

The risk assessment mapping represents the primary mapping products of this study. Figure 6.3 and Figure 6.4 summarize risk assessment scoring for the existing and future conditions respectively. The scoring values are based on those presented in the spreadsheets in Appendix F.

In both maps, colors correspond to the percentile ranges of roadway segments with the highest cumulative risk scores (e.g. 5% = top 5 percent of segments ordered from highest to lowest risk score). Additional layers are provided as overlays including:

- **Flood Zone** – FEMA’s 1-percent flood zone boundary
- **Engineering Dist** – PennDOT’s District boundaries
- **Flood Signs** – Locations of PennDOT flood warning signs (e.g. “ROAD MAY FLOOD”) as provided from PennDOT’s sign inventory database
- **Levee / Floodwall / Levee Protected Area and Stafford Act Properties** – As assembled from the U.S. Army Corps of Engineers National Levee database

In both maps, users may select any vulnerable segments and view specific data fields that include the state route number, segment number, total score and percentile rank. The future roadways are based on a different data layer system that does not directly correlate to the segment lengths within the RMS. In addition, a feedback field is provided that allows users to provide an evaluation of specific vulnerable segments.
### Table 6.1: Risk Assessment Variables and Scoring Values

<table>
<thead>
<tr>
<th>Variable</th>
<th>Source</th>
<th>Scoring Methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity to Flooding</td>
<td>NOAA Climate Data Online</td>
<td>• ≤ 1.5 inch = 10&lt;br&gt;• ≤3 inches = 7.5&lt;br&gt;• ≤5 inches (or for comment locations) = 5&lt;br&gt;• ≤7 inches = 2.5&lt;br&gt;• &gt; 7 inches = 1</td>
</tr>
<tr>
<td>Average Depth</td>
<td>Pilot Study Analyses for Allegheny, Delaware and Lycoming Counties</td>
<td>• &lt; 3 inches = 1&lt;br&gt;• &lt; 5 inches = 2.5&lt;br&gt;• &lt; 9 inches = 5&lt;br&gt;• &lt; 12 inches = 7.5&lt;br&gt;• &gt; 12 inches= 10</td>
</tr>
<tr>
<td>Floodplain</td>
<td>PASDA Floodplain</td>
<td>• Yes = 10&lt;br&gt;• No = 0</td>
</tr>
<tr>
<td>Overall Pavement Index</td>
<td>RMSSEG</td>
<td>• Excellent = 2.5&lt;br&gt;• Good, Other = 5.0&lt;br&gt;• Fair = 7.5&lt;br&gt;• Poor = 10.0</td>
</tr>
<tr>
<td>Scour Critical Bridges</td>
<td>BMS 2</td>
<td>• Yes = 10 ; • No = 0</td>
</tr>
<tr>
<td>Deficient Pipes</td>
<td>RMSPIPE</td>
<td>• Yes = 10 ; • No = 0</td>
</tr>
<tr>
<td>Two-Way Volume</td>
<td>RMSTRAFFIC</td>
<td>• &lt; 5,000 = 1&lt;br&gt;• &lt; 10,000 = 2&lt;br&gt;• &lt; 15,000 = 3&lt;br&gt;• &lt; 20,000 = 4&lt;br&gt;• &lt; 25,000 = 5&lt;br&gt;• &lt; 5,000 = 6&lt;br&gt;• &lt; 35,000 = 7&lt;br&gt;• &lt; 40,000 = 8&lt;br&gt;• &lt; 45,000 = 9&lt;br&gt;• &gt; 45,000 = 10</td>
</tr>
<tr>
<td>Two-Way Truck Volume</td>
<td>RMSTRAFFIC</td>
<td>• &lt; 500 = 1&lt;br&gt;• &lt; 1,000 = 2&lt;br&gt;• &lt; 2,000 = 3&lt;br&gt;• &lt; 3,000 = 4&lt;br&gt;• &lt; 4,000 = 5&lt;br&gt;• &lt; 5,000 = 6&lt;br&gt;• &lt; 6,000 = 7&lt;br&gt;• &lt; 7,000 = 8&lt;br&gt;• &lt; 8,000 = 9&lt;br&gt;• &gt; 8,000 = 10</td>
</tr>
<tr>
<td>Functional Class</td>
<td>RMSADMIN</td>
<td>• Local = 1&lt;br&gt;• Collector or Minor Arterial = 2.5&lt;br&gt;• Other = 5&lt;br&gt;• Principal Arterial = 7.5&lt;br&gt;• Interstate = 10</td>
</tr>
<tr>
<td>Included as PennDOT Official Detour Route</td>
<td>Shapefiles provided by PennDOT GIS Department</td>
<td>• Yes = 10 ; • No = 0</td>
</tr>
</tbody>
</table>

**Figure 6.2: Risk Assessment Cumulative Scoring Formula**

*(Maximum Score = 100)*

**Risk Cumulative Score =**

\[
3 \times (\text{Precipitation Score or Average Depth} \times 0.5 + \text{Floodplain Score} \times 0.5) + \\
3 \times (\text{OPI Score} \times 0.4 + \text{Scour Score} \times 0.4 + \text{Pipe Score} \times 0.2) + \\
4 \times (\text{Volume Score} \times 0.4 + \text{Functional Class Score} \times 0.3 + \text{Detour Score} \times 0.1 + \text{Truck Volume Score} \times 0.2)
\]
Figure 6.3: Historic Risk Assessment Online Map

Alternative map version that allows users to select defined percentile ranges of risk assessment

- Users can select the view as statewide or one of PennDOT’s eleven Districts. The risk assessment percentiles are specific to the area chosen.
- A Data Source field is provided which indicates if the historic record is from the RCRS system or a provided stakeholder comment.
- If an individual segment is selected, the user may provide comments on the vulnerable location by selecting the “Feedback Form” option. A form is provided that requests:
  - Email Address of Commenter
  - Assessment of Location
  - Assessment of Risk Scoring
  - Information on the Primary Cause of Flooding in the Area
  - Additional Comments
Figure 6.4: Future Risk Assessment Online Map

- By selecting the High Risk Road checkbox, users can view the future analysis risk assessment. Vulnerable roads include any roadway with inundation.
- The Vulnerability Zone A layer (no base flood elevations available) provides any inundated roadway segments based on limited information from FEMA’s flood zone data. The Zone A values have not been prioritized using the risk assessment procedures.
- The Map Book layer is provided that will allow users to select and view the detailed analysis result sheets for each vulnerable area. Map book sheets are not available for Zone A areas.
- Specific roadway extents have been linked to the RMS. The RoadID field includes a coding scheme to represent the county (first 2 digits), state route number (next 4 digits), and segment number (last 4 digits).
- To view how future vulnerable locations compare to historic locations, see Figure 5.4 map link: http://s3.amazonaws.com/tmp-map/climate/future-vs-historic.html
- If an individual segment is selected, the user may provide comments on the vulnerable location by selecting the “Feedback Form” option. A form is provided that requests:
  - Email Address of Commenter
  - Assessment of Location
  - Assessment of Risk Scoring
  - Information on the Primary Cause of Flooding in the Area
  - Additional Comments
Section 7 – STRATEGIES FOR IMPROVING RESILIENCY

Improving the resiliency of Pennsylvania’s transportation system ultimately requires the application and integration of cost-effective adaptation strategies. For this study, example strategies are highlighted from stakeholder outreach comments, current practices within Pennsylvania, and a national literature review. These strategies and the associated toolbox are intended as a starting point for future discussions and activities in determining what strategies may be most viable for PennDOT and its planning partners.

Stakeholder Input on Strategies

The District outreach meetings (as discussed in Section 3 and Appendix A) provided valuable insights on potential strategies that could improve resiliency, maintain safety, and support emergency response to extreme weather events. Figure 7.1 provides a summary of the identified strategies, which include ideas and implementation steps addressing coordination, planning, data mapping, infrastructure design, and other maintenance activities. Some of the strategy concepts are integrated into Section 9, which identifies key steps to further enhance the Department’s ability to identify and implement adaptation strategies.

Identifying and mapping vulnerabilities to flooding, land/rock slides, and other extreme weather impacts was a key planning-level strategy identified by many of the participants. This report and the associated appendices and mapping products begin to address this need and will serve as a basis for more detailed local studies.

Pennsylvania Resiliency Examples

Several PennDOT Districts and MPOs have already started to study and implement strategies to improve system resiliency. Figure 7.2 provides a sample of known resiliency efforts throughout the state. Developing protocols to assemble and share these and other best practices will allow other regions to identify successful and cost-effective ways to address resiliency.

In addition to the above examples, Pennsylvania’s universities provide another important resource for the identification and assessment of vulnerabilities and strategies. Penn State University’s Center for Climate Risk Management (CLIMA) is working to integrate research on climate change, mitigation, adaptation, and decision making across multiple disciplines. CLIMA provided insights on the climate projections used for this study. In addition, Carnegie Mellon University and Lehigh University are conducting resiliency efforts and could support future PennDOT assessments. Carnegie Mellon has established the Center for Engineering and Resiliency for Climate Adaptation (CERCA). Their current research efforts including assessing transportation design criteria.

Other Strategy Resources

Adaptation strategies can also be identified by examining best practices in other states or regions that have already experienced severe weather events. For example, the state DOTs along the Gulf Coast region have started to identify strategies to address sea-level rise, while states like Vermont are looking to apply innovative stream management and land use strategies. Many of these and other strategies are being compiled into national research studies and resource documents. The website resources provided previously in Figure 2.1 will be continually updated to provide best practices as they are implemented around the country.
Figure 7.1: Strategies Identified Through District Outreach

PLANNING, COORDINATION AND TRAINING

• Integrate resiliency and vulnerability information into PennDOT and MPO project prioritization process
• Improve coordination between state, local and property owners to address stormwater systems on non-PennDOT roadways
• Improve coordination between agencies (PEMA, PSP, ACOE, District, County EMA, Municipalities, DEP, Utilities)
• Develop metrics to evaluate and monitor extreme weather impacts and establish working groups to evaluate resiliency progress

DATA ANALYSES AND INFORMATION SHARING

• Summarize RCRS data for planning and emergency response preparation (enhance RCRS detail for weather impacts)
• Improve integration of resiliency planning efforts (PennDOT, MPO/RPO, Hazard Mitigation plans)
• Improve efforts to track and understand past maintenance dollar spending over time related to extreme weather
• Build on PennDOT’s study to identify and evaluate extreme weather vulnerabilities within local regions

MAINTENANCE AND INSPECTIONS

• Improve maintenance procedures and armoring of stream banks to prepare for potential increased flooding events in the future
• Continue to expand and improve methods and procedures for pre and post flood inspections of roadways, bridges, and streams
• Plan for increasing redundancy at roadway locations that may be impacted by storms (ensure secondary roads are maintained and available for use)
• Conduct stormwater management studies using a watershed approach including municipalities, PennDOT and DEP

DESIGN

• Identify updates to PennDOT design manuals based on national research and other university studies
• Program projects to improve stormwater capacity, reduce impermeability and ensure adequate maintenance of infrastructure
• Work with municipalities to identify the impacts of development on stormwater management
• Identify facilities requiring design upgrade in advance of funding requests

EQUIPMENT, MATERIALS AND TECHNOLOGY

• Identify and integrate technology like web cameras to better monitor storm impacts and flood stages
• Continue efforts to ensure equipment needs are coordinated across PennDOT Districts and develop plans in case more equipment needed
• Evaluate District equipment purchases to address weather events including drill rigs, portable bridges, swing gates, and pumps
• Integration of automated warning systems to establish road closures and alternative routes
• PennDOT included on study’s "Infrastructure Working Group". Identified general adaptation strategies for each category of transportation vulnerabilities.

SEPTA Vulnerability and Risk Assessment
• Identified vulnerabilities and adaptation strategies across all weather event types through research and discussions with SEPTA staff.

Growing Stronger Toward a Climate-Ready Philadelphia
• Multi-year planning process convened by the Mayor’s Office of Sustainability (MOS) with the participation of a broad set of City departments and agencies.

DVRPC Planning Efforts
• DVRPC led a regional discussion on integrating hazard mitigation and comprehensive planning. Working with county, municipalities, PEMA, FEMA to create a set of tools to assist in evaluating vulnerabilities.

LeTort Spring Run Watershed Planning
• Collaboration study with PennDOT, DEP and municipalities (via MOUs and resolutions) to manage stormwater across the watershed. Identified priority locations where stormwater could be better managed.

Saw Mill Run Project (City of Pittsburgh)
• Focus study to identify strategies to address flooding along roadway. Strategies were investigated that addressed in-stream management, floodplain management, watershed management and flood damage reduction.

York MPO and SEDA-COG Efforts Related to Planning
• York MPO has initiated a county flooding study to identify vulnerabilities. SEDA-COG identifying structures at risk to flooding (bridges, rail lines).

PennDOT District 2 Slide Rating System
• Several Districts have procedures to identify and prioritize slide locations.

PennDOT Technology Applications
• Pumping stations along I-95 are currently being redesigned. PennDOT is evaluating the BridgeWatch system that links NEXRAD radar rainfall to infrastructure locations.
For this study a literature review has been conducted across a variety of publications and resource websites. Strategy types have been assembled from these available resources and compiled into a strategy toolbox (i.e. a listing of strategies by category). Some of the key resources reviewed include:

■ **FHWA 2013-2015 Climate Resilience Pilot Program**


  This report synthesizes strategies for climate change resiliency from 19 FHWA-sponsored pilot studies conducted by state DOTs and MPOs from around the nation between 2013 and 2015. Each of the pilot projects took unique approaches to conducting vulnerability assessments and evaluating adaptation options. The methods and findings reflect local specific transportation priorities and climate conditions.

■ **Climate Change, Extreme Weather Events, and the Highway System**


  TRB’s National Cooperative Highway Research Program (NCHRP) Report 750 provides guidance on adaptation strategies to the likely impacts of climate change in the planning, design, construction, operation, and maintenance of infrastructure assets in the United States. In addition to the practitioner’s guide and research report, the project also developed a software tool that runs in common web browsers and provides specific, region-based information on incorporating climate change adaptation into the planning and design of bridges, culverts, stormwater infrastructure, slopes, walls, and pavements. It also provides spreadsheets that illustrate examples of the benefit-cost analysis of adaptation strategies.

■ **Climate change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance**


  This USDOT sponsored guidebook provides information and resources to help transportation management, operations and maintenance staff incorporate climate change into their planning and ongoing activities. It provides state DOTs and other transportation agencies actions that can help reduce climate risks.

■ **Transportation System Resilience, Extreme Weather and Climate Change**


  This report summarizes the Volpe, The National Transportation System Center’s thought leadership speaker series on Transportation System Resilience, Extreme Weather and Climate Change. From October 2013-April 2014, Volpe, part of the U.S. Department of Transportation, convened notable and influential voices in transportation system resiliency and climate change to present the current state of climate science and to discuss challenges, opportunities and fresh approaches related to the most pressing multi-modal, multi-sector issues.
■ Response to Extreme Weather Impacts on Transportation Systems


TRB’s National Cooperative Highway Research Program (NCHRP) Synthesis 454: Response to Extreme Weather Impacts on Transportation Systems examines eight recent cases of extreme weather in the United States from the perspectives of transportation operations, maintenance, design, construction, planning, communications, interagency coordination, and data and knowledge management.

■ Adapting Transportation to the Impacts of Climate Change

http://onlinepubs.trb.org/onlinepubs/circulars/ec152.pdf

This E-Circular on adaptation, developed under the auspices of the TRB Special Task Force on Climate Change and Energy, is a companion to the TR News Special Edition issue of May–June 2010 on climate change mitigation. This document focuses on transportation adaptation practices that can be implemented to yield benefits now and in the longer term. It highlights the importance of climate change adaptation for the transportation industry.

■ Transportation Adaptation to Global Climate Change


The National Transportation Policy Project (NTPP) and the National Commission on Energy Policy (NCEP) commissioned this white paper to identify the policy options available to support proactive measures for addressing climate change adaptation in transportation. This white paper is intended to inform Congress and other policy-makers about policy options at the federal level that will ensure a robust transportation system in the face of a changing climate.

■ Caltrans Activities to Address Climate Change: Reducing Greenhouse Gas Emissions and Adapting to Impacts

http://www.dot.ca.gov/hq/tpp/offices/orip/climate_change/documents/Caltrans_ClimateChangeRprt-Final_April_2013.pdf#zoom=75

This report provides a comprehensive overview of activities undertaken by the California Department of Transportation (Caltrans) to reduce greenhouse gas (GHG) emissions and adapt the state’s transportation system to prepare for the impacts of climate change. It also identifies opportunities for additional reductions in GHG emissions and climate adaptation activities that Caltrans may wish to consider in the future.

■ Design Standards for US Transportation Infrastructure


This paper examines the changes to engineering design practice that might occur given climate-induced changes in environmental factors. A project design is separated into the individual components that might be affected by changing environmental conditions: subsurface conditions, materials specifications, cross sections and standard dimensions, drainage and erosion, structures and location engineering.
FEHRL US Scanning Tour 2012

The Forum of European Highway Research Laboratories (FEHRL) coordinated a Climate Change Resilient Transport Scanning Tour, held 24-31 March, 2012 across the USA, visiting Federal, State and city Transportation Departments. This report collates the key findings of the tour. It sets the scene for climate change projections in terms of temperature, precipitation, sea level rise and storms. The sections have been formatted according to the following key themes: vulnerability studies, adaptation measures, policy research efforts, and opportunities for collaboration.

Climate Change Impacts and Adaptation for International Transport Networks

This report was prepared by the United Nations Economic Commission for Europe (UNECE). The study reviewed the emerging implications that climate change has on transportation and conducted a survey questionnaire to identify potential adaptation strategies. Adaptation strategies are provided for different mechanisms of transport, and for different locations around the globe.

Strategy Toolbox

Based on a review of the resources provided above, a toolbox of over 200 strategies was assembled in an EXCEL database as provided in Appendix G. The database organizes the strategies by the categories shown in Figure 7.3. Within the database, information is provided on specific strategy examples (for each category), the type of weather event(s) most directly pertinent to each strategy, and a strategy type. Strategy types are initially organized into these categories:

- Administrative/Regulatory/Planning
- Design
- Maintenance and Operations
- Technology Applications

In some cases it may be difficult to classify certain strategies as they may encompass more than one of the categories above.

This toolbox may be expanded as PennDOT reviews and assesses adaptation strategies in more detail. National guidebooks (including those referenced previously) and evolving university research will provide more details on viable and effective strategies. For example, the USDOT guidebook, Climate Change Adaptation Guide for Transportation Systems Management, Operations, and Maintenance, is an excellent source for adaptation strategies related to transportation operations and maintenance. The tables and appendices in that resource provide decision matrices that provide the basis for developing adaptation strategies.

Evaluation of Strategies

Evaluation criteria and processes will be needed to further define and assess viable strategies for PennDOT and other supporting agencies. The evaluation process will require criteria that will most likely include technical and political feasibility, cost and benefits; effectiveness and success in other areas, and flexibility. The identification of performance measures will also be important for measuring strategy effectiveness and identifying areas of need.
A literature review was also conducted to evaluate the cost-effectiveness of potential adaptation strategies; however information is limited. The evaluations include the following:

- Some studies that used benefit/cost analyses to evaluate various types of extreme weather responses found that the greatest costs savings were in “non-structural” and “avoidance” solutions, such as land-use planning to limit or eliminate construction of any kind in high hazard areas. However, it was also determined that this depends on the situation and that in high growth urban areas, especially coastal ones, a “hybrid” approach may be needed (i.e. one that combines non-structural strategies with
structural ones including levees, dams, newly-designed or retrofitted structures, etc.). Included among these non-structural solutions is abandonment of at least some existing infrastructure.

One common resilience measure identified in the research was incorporating “redundancy” into infrastructure systems so that extreme events can be weathered. This measure, however, also increases costs, as does retrofitting existing infrastructure to meet increased standards. Redundancy of a bridge substructure is defined as the capability of the substructure system to continue to carry loads (vertical and lateral) after the failure of any of its components. In a nonredundant system, the failure of any critical member (a weakest link) will result in the collapse of the system. In a redundant structural system, two or more components must fail before the structural system collapses. The degree of redundancy for a given substructure system may vary over a wide range.

Resources:
http://science.sciencemag.org/content/344/6183/473.full
https://www.climate.gov/news-features/climate-case-studies/planning-future-floodplain

Appropriate investments addressing a combination of early warning systems, critical infrastructure and environmental buffers is likely the best approach since neither major infrastructure investment in flood control measures, nor a flood early warning system can avert disaster completely alone. Together, however, they can greatly reduce loss of life and infrastructure.

Resources:
https://www.nap.edu/read/18309/chapter/8#105

Although not without its own challenges, enforcement of storm-water management and/or green infrastructure is widely considered an effective means of reducing the risks of flood damage. Green stormwater infrastructure (GSI) in particular has the financial advantage of being implementable in phases and at varying scales, and in addition to practical usefulness it can add to the aesthetic appeal of developments. Among the challenges are the costs. Fully achieving a large-scale GSI-based program is not typically something that municipalities can implement alone in a cost-effective way. Partnerships between agencies, funders, private developers and industries are critical to leverage resources and bring costs down.

Resources:

There is a need to advance the effectiveness of the post-extreme event bridge assessment by a review and evaluation of the available data acquisition and transmittal systems and procedures. The visual field inspections have been most informative. In recent years such assessments have been enhanced in the following important ways: (1) digitized data acquisition, storage and transmission have made the information more manageable and easier to use for decision support; (2) structures are increasingly monitored by sensitive instruments; (3) infrastructure management has evolved from the project to a network level.

Resources:
Section 8 – INTEGRATION TO DECISION MAKING

As emphasized within FHWA’s Vulnerability Assessment Framework, integrating results of the vulnerability assessment into decision making is important to ensure that study results are used in practice. It is anticipated that multiple PennDOT divisions, as well as other state and regional agencies, may benefit from the information assembled for this project. Figure 8.1 lists potential applications that are described in more detail below. Through these efforts further evaluations of available data, tools, processes and strategies can be made to improve and refine the study products.

Figure 8.1: Integration of PennDOT Study Results

PennDOT and MPO Planning

As discussed in Section 1, the FAST Act authorization bill has added resiliency as a metropolitan planning factor. As a result, PennDOT as well as MPO/RPOs throughout the state will be looking for ways to consider resiliency within their planning processes. This may include educating and engaging staff and decision makers; identifying opportunities for improving data collection, operations or design; and integrating resiliency needs within the Long Range Transportation Planning an Linking Planning and NEPA processes. Ultimately, this may lead to the inclusion of vulnerability concepts within the project prioritization process.

Several MPO/RPOs within Pennsylvania have initiated resiliency planning efforts. The SPC and York MPOs are focusing on the identification of transportation vulnerabilities related to flooding. DVPRC has recently worked to develop a program to assist municipalities to prepare for extreme weather events by providing...
methods to identify vulnerabilities; and, SEDA-COG has conducted efforts to inventory and prioritize local-owned bridge structures vulnerable to weather impacts.

The data and mapping provided for this study can support the evaluation and prioritization activities being conducted by PennDOT’s planning partners. As such, implementation steps to share information and receive comments are integral to further evolve PennDOT’s adaptation planning. Possible MPO and District work groups may be useful to ensure consistent methods for identifying vulnerabilities on the state transportation system and to prioritize projects and other adaptation strategies.

**PennDOT Asset Management**

The asset management process is a natural fit for incorporating climate change and extreme weather vulnerability information. AASHTO’s *Integrating Extreme Weather into Transportation Asset Management Plans* (September 21, 2015) provides a process for DOTs to incorporate these considerations into the Transportation Asset Management Plans (TAMP). Table 8.1 provides a table from the AASHTO report that maps climate change and extreme weather factors to the TAMP.

The PennDOT vulnerability study can provide supporting information for several of the tabular items (as highlighted in the table). This includes identifying locations on the state-owned system where assets might be highly vulnerable to flooding and identifying which of those assets might be of most risk. The actions relating to risk management are the most critical for effectively considering climate and extreme weather factor in asset management decision making.

**PennDOT Maintenance & Design**

PennDOT’s outreach meetings conducted for this study included District maintenance and design staff from across the state. The District staff have knowledge of key vulnerabilities, risks, and strategies within their region. However, the following benefits of an extreme weather vulnerability study were identified:

- Mapping and documentation of known vulnerabilities can assist in planning for extreme weather events and serve as an important record for new staff;
- Prioritizing and/or assessing risks can assist in planning for maintenance activities including inspections and roadway closures;
- Forecasting extreme event flooding scenarios can be considered during project design phases to ensure sufficient design of infrastructure in balance with potential costs; and
- Identifying potential adaptation strategy ideas can initiate further review and evaluation by each District.

Some Districts have developed vulnerability and risk assessment procedures to assess slides. District 2 has developed a prioritization tool for known vulnerable locations to assess criteria related to the consequence of roadway closure. However, such concepts and procedures are not currently applied to flooding.
Table 8.1: Mapping of Climate Change / Extreme Weather Factors and a TAMP


(Highlights indicate potential supporting information from PennDOT Phase 1 study)

<table>
<thead>
<tr>
<th>Section</th>
<th>Climate Change/Extreme Weather Material</th>
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| Asset inventory and conditions         | • Summarize the climate- and weather-related conditions that affected the system historically.  
                                         | • Identify changing climatic conditions that are likely to occur in the future. |
| Asset management objectives and measures| • Define the objectives of the asset management program that relate to system resiliency, redundancy, evacuation and recovery.  
                                         | • Identify the types of assets or network segments that will receive attention with respect to climate- and weather-related disruptions.  
                                         | • Define levels of service and measures relating to climate- and weather-related system operations and conditions.  
                                         | • Define short term and long term condition targets for resiliency, redundancy, evacuation and recovery. |
| Performance gap assessment              | • Define short-term and long-term asset management planning horizons as they relate to climate/extreme weather factors.  
                                         | • Illustrate the performance gap between existing performance levels and future performance levels with respect to system disruption. |
| Lifecycle cost considerations           | • In the context of lifecycle costs, discuss the tradeoffs associated with minimizing asset vulnerabilities as part of the normal capital program versus waiting until an extreme weather event occurs. |
| Risk management analysis                | • Within the context for risk management, identify climate/extreme weather event risks to the system.  
                                         | • Identify state assets that are at most risk.  
                                         | • Include a risk register that provides the following for each programmatic risk – likelihood of occurrence, consequences of occurrence, and mitigation activities. |
| Financial plan                          | • Incorporate into the TAMP financial plan a strategy for funding needed improvements to reduce system risks, whether as part of normal capital investment or as a stand-alone funding initiative. |
| Investment strategies                   | • Describe typical approaches to minimizing climate- and weather-related risks. |
| Investment asset management process enhancements | • Identify priorities for asset management improvement as it relates to climate- and weather-related considerations.  
                                         | • Incorporate lessons learned from system disruptions that occur over time. |
Hazard Mitigation Planning

Hazard mitigation describes the action taken to reduce or eliminate risk to life and property by lessening the impact of disasters. Hazard mitigation planning is the process by which risk and vulnerability are identified in order to develop and direct long-term strategies for protecting people and property. Mitigation action is then recommended and taken in advance of a disaster with the intent of breaking the disaster cycle of damage, reconstruction and repeated damage.

The Federal Emergency Management Agency (FEMA) lists the following objectives associated with hazard mitigation plan development:

- Increase education and awareness around threats, hazards, and vulnerabilities;
- Build partnerships for risk reduction involving government, organizations, businesses, and the public;
- Identify long-term, broadly-supported strategies for risk reduction;
- Align risk reduction with other state, tribal, or community objectives;
- Identify implementation approaches that focus resources on the greatest risks and vulnerabilities; and
- Communicate priorities to potential sources of funding.

The Pennsylvania Emergency Management Agency (PEMA) has been legislatively charged with coordinating Commonwealth government to prepare the State Hazard Mitigation Plan. PEMA also reviews and approves all local Hazard Mitigation Plans (HMPs). In Pennsylvania, local hazard mitigation planning is typically done at the County level although some single municipality HMPs do exist. The Pennsylvania State HMP includes risk and vulnerability assessment for all 67 counties. County HMPs include local risk and vulnerability assessment for all participating jurisdictions. Every five years the State HMP is updated and information from county HMPs is incorporated as needed.

As part of state and local hazard mitigation planning, hazards are identified and ranked, vulnerability is assessed, and a mitigation strategy is prepared based on existing capabilities and the findings of the vulnerability study. Disasters associated with extreme weather including flooding, extreme temperature, and transportation related hazards are included in the Pennsylvania State HMP and frequently identified in Pennsylvania county HMPs.

Hazard mitigation planning and the development of a hazard mitigation strategy, starts with assessing risk and quantifying, when possible, vulnerability. The findings of the PennDOT Extreme Weather

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**Pennsylvania Department of Transportation**
Vulnerability Study can be used to inform the Risk Assessment requirements of local and state HMP’s for transportation infrastructure.

Identifying vulnerabilities as part of the risk assessment allows local and state government officials to target and prioritize mitigation action and develop a mitigation strategy as required. Action can then be taken to mitigate vulnerable transportation infrastructure including roads and bridges. Mitigation could include elevation, relocation, stormwater retrofitting, and even signage. Mitigation in the form of planning and changes to requirements and specifications can also be applied in order to address risk associated with future conditions. The future conditions modeling completed for flooding can be utilized by the Commonwealth and local governments to quantify future occurrence for flooding and assessing potential losses for structures including homes, businesses, and critical facilities.

Continued coordination and data sharing with the hazard mitigation process may also result in the identification of data and strategies that can improve transportation system resiliency. Other multi-agency efforts like Silver Jackets can also provide valuable information. The Pennsylvania Silver Jackets is an interagency team dedicated to working collaboratively with the commonwealth and stakeholders in developing and implementing solutions to flood hazards. They combine agency resources, which include funding, programs, and technical expertise.

**NEPA Resiliency**

PennDOT’s Bureau of Project Delivery is currently working to address the recent CEQ requirements as published in *Final Guidance for Federal Departments and Agencies on Consideration of Greenhouse Gas Emissions and the Effects of Climate Change in National Environmental Policy Act Reviews*. These new guidelines establish the framework to address climate change impacts on project alternatives within the NEPA documentation.

Publication 321 is PennDOT’s *Project-Level Air Quality Handbook*. It is intended to assist the Department, its consultants, and other potential users in the completion of project-level mobile source air quality analyses to satisfy current state and federal requirements. The Handbook will undergo updates to address the CEQ guidance and provide the resources and methods to address climate change within the NEPA document for Environmental Assessments (EAs) and Environmental Impact Statements (EIS).

As discussed in Section 5, Pennsylvania’s climate forecasts anticipate increases in annual precipitation and the number and intensity of extreme weather events within the state. As a result, flooding is expected to be one of the primary climate impacts that are expected to be addressed within the NEPA process.

This study provides important mapping and resources that can be used and referenced when addressing the CEQ requirements. This includes: identification of the impacts of extreme weather, known historic vulnerabilities and associated risks, and forecast flooding inundation under climate change scenarios. Although forecast flooding analyses have been completed for only three sample counties, they may be expanded in the future to cover the entire state. With the potential use of this study results for NEPA efforts, this will further emphasize the need to share and provide access to the study data and mapping.
DEP & DCNR Climate Planning

Although not a requirement of Act 70 the DEP and the Climate Change Advisory Committee (CCAC) recognize the need to address adaptation planning. During the February 27, 2009 meeting of the CCAC, a motion was made and passed with unanimous support that the action plans should include a recommendation to the Governor and the Pennsylvania General Assembly to address adaptation. In 2010, the Pennsylvania Climate Adaptation Planning Report was prepared to identify practical implementation strategies to address climate change impacts on the state’s human environment, including the built environment, and natural resources. This report was the first statewide effort addressing the need for climate change adaptation planning in Pennsylvania. The report is intended as a working document and a starting point for assessing development of the next climate action plan that is currently under development. Four working groups were established to cover the broad array of impacted sectors. The infrastructure group included the transportation sectors as well as the energy, water, buildings, communications, and land use sectors.

DEP is aware of PennDOT’s current efforts and will be looking for PennDOT’s assistance on the Climate Action Plan update in 2017. They are anticipating that some of the concepts and data within PennDOT’s Phase 1 study may support the development of that plan and lead to additional adaptation measures and coordination between the two departments.

Other opportunities to integrate PennDOT’s efforts into state agency climate planning may arise in the future. The Department of Conservation and Natural Resources (DCNR) is embarking on a year-long effort to assess DCNR’s vulnerability and craft an agency adaptation plan. Although DCNR will not be specifically addressing the state transportation system, there may be opportunities to share information on specialized topics including:

- Sinkholes;
- Landslides;
- Stream bank armoring; and
- Land cover impacts on flooding.
Section 9 – IMPLEMENTATION STEPS

This study provides PennDOT an initial assessment of data and processes that can be used to identify flooding vulnerabilities on state-owned roads and bridges. Efforts have been conducted to gain a better understanding of historic flooding vulnerabilities over the last decade. The study has also included outreach to staff within PennDOT and other state and regional agencies, testing of methodologies to evaluate the impacts of changing climate, estimates of risk utilizing readily-available information from PennDOT data management systems, and the identification of potential strategies to improve system resiliency.

The completed study tasks have addressed several components of FHWA’s Vulnerability Assessment Framework as discussed in Section 2. Further work efforts are still needed to formalize data reporting, understand statewide impacts of future climate changes, and to conduct a more detailed assessment of viable adaptation strategies and procedures within the Department.

Through the outreach process and the project steering committee, an initial set of recommendations has been prepared to assist PennDOT in applying the results of this study and further enhancing the Department’s efforts to identify and implement adaptation strategies. These recommendations (or “implementation steps”) are highlighted below. Further action on any of these steps will most likely require a more detailed assessment of the scope of each action, identification of lead parties and supporting staff, and further assessments of data, research and procedures at the local and national levels.

Managing Historic Vulnerabilities

Monitoring historic impacts of extreme weather is an important component of the Department’s adaptation and resiliency planning. Understanding historic impacts assists in identifying vulnerabilities to future extreme weather events. The following steps can support efforts to better identify, monitor and prioritize vulnerabilities:

- **Share RCRS vulnerability mapping for review and evaluation.** The historic maps provided through this study are intended to illustrate key flooding vulnerabilities and priorities based on PennDOT’s RCRS data system as well as other stakeholder comments. Further evaluation efforts are needed to better assess whether these maps accurately reflect known vulnerabilities and are useful for PennDOT or other agency planning, design, maintenance, or emergency response activities. Agency reviews can focus on identifying any shortcomings of the RCRS data (e.g. missing locations or other inaccuracies) and the types of maps most useful for resiliency planning. Some maps produced for this study, including those linking the RCRS vulnerable segments to storm event rainfall, may provide supporting information that may benefit other PennDOT tools. For example, the study assessments may assist in identifying thresholds within the BridgeWatch system that initiate closure or inspection actions.

- **Evaluate historic risk assessment process.** The risk assessment process represents a draft quantitative methodology to rank and prioritize historic flooding vulnerabilities throughout the state. The maps produced from these analyses represent one of the key products from the study. The current methodology utilizes existing data available within PennDOT’s data systems including the RMS and BMS. District staff should evaluate the draft results to identify any concerns or issues with the prioritization process and results. These insights may assist in developing potential revisions to
attribute weighting, the identification of new attributes for risk evaluation, and methods for integrating qualitative input from maintenance and other planning staff.

- **Develop PennDOT vulnerability mapping and data report products for Department and Planning Partner use.** Based on the above evaluation steps, PennDOT may choose and produce the mapping products that provide the most benefit to the Department, planning partners and other supporting agencies. As discussed in Section 4, it has been recommended that the RCRS system not be modified directly to support extreme weather assessments and reporting. As a result, PennDOT will need to consider separate reporting and data sharing methods including use of the GIS-IQ and Maintenance-IQ systems. Mapping developed on these systems can allow for direct linkages to other supporting databases. For example, the risk assessment mapping can be linked to the RMS and BMS systems providing a direct feed of important risk formula attributes like scour rating, traffic volumes, and culvert conditions. As data is updated in those systems, the risk assessment map would update automatically providing the latest information.

- **Identify methods to better monitor costs associated with extreme weather.** PennDOT has reported and tracked costs related to several of the major hurricanes over the last decade. As identified during the project outreach, developing formal processes and reports of costs related to extreme weather events may assist in tracking progress and identifying adaptation needs. Such reports could be linked to the existing Endeca and PennShare systems.

- **Identify and develop other data and mapping reports that assist in identifying needs or monitoring resiliency progress.** The RCRS system does not currently address the cause of flooding closures. Understanding whether flooding is related to the stormwater system or river inundation are important considerations for the types of adaptation strategies. Future data and survey efforts may focus on obtaining such information for all RCRS flooding closure locations. Other ideas identified through the project outreach include the development of survey tools to collect information on local flooding issues and other extreme weather events. Many District staff noted the integration between local and state drainage and stormwater systems. Knowing key flooding or other vulnerabilities on the local systems may help PennDOT in developing strategies that do not create or cause local problems to worsen. In addition, more substantial data collection efforts may be needed to identify other extreme weather impacts including those from land and rock slides. The survey tool and interactive web map developed for this project serve as a potential framework for other data collection efforts.

- **Develop methods to share best practices.** Many of PennDOT’s Districts are already identifying and implementing strategies to improve system resiliency. Some of these practices are summarized in Section 7. Sharing unique practices in one area of the state may benefit other areas. As a result, some stakeholders have indicated the importance in coordinating and communicating success stories and project ideas. PennDOT may consider methods to share practices related to adaptation strategies highlighting new design and maintenance approaches, strategies to address watershed planning, and other ways to improve coordination with other state agencies and project partners.
Assessing the impacts of climate change is an area of emphasis for FHWA and state DOTs across the country. While this study has focused heavily on understanding and reporting historic vulnerabilities, Section 5 has identified methods and data that may be used to evaluate the impacts of changing climate. Although climate science has progressed greatly in recent years, there are still many uncertainties regarding climate change impacts on extreme weather and forecast conditions at smaller aggregation levels (e.g. the state). This study’s approach was applied for three sample counties to identify potential scenarios of stream and river inundation. These results have been used to assess vulnerable transportation assets that can be compared and contrasted with historical results. The following steps aim to evaluate the current study results and identify future PennDOT activities to expand climate analyses in support of the vulnerability risk assessment process:

- **Share forecast scenario vulnerability analyses for further assessment and review.** For this study, sample county analyses have been conducted for Allegheny, Delaware and Lycoming counties. MPOs can provide valuable assistance in conducting reviews of the analysis results. SPC, DVRPC and SEDA-COG have each initiated efforts related to resiliency and adaptation and can provide insights into the validity and usefulness of these products.

- **Possible application of forecasting methodology to other areas.** Pending the above review of sample county results, PennDOT may consider applying a similar methodology statewide in partner with other MPOs and counties. These results allow for the identification of potential vulnerabilities that may not be currently in the RCRS system. The results of these assessments can potentially be integrated with the risk assessment process to provide another key prioritization attribute that addresses forecast conditions.

- **Continue to track DEP/PSU climate assessments and adaptation efforts.** As PennDOT continues to address resiliency issues, the agency should coordinate with other statewide efforts. Penn State University periodically updates the *Pennsylvania Climate Impacts Assessment* report based on the latest global climate model and downscaling procedures. The results from these assessments provided insights into the climate variables used for forecasting the changes to stream depths within this study. DEP has initiated efforts to address climate resiliency and adaptation. It is expected that PennDOT will coordinate with DEP on efforts and strategies identified for the transportation sector.

- **Evaluate new data sources and agency activities related to flood zones.** To ensure that PennDOT does not duplicate analytical efforts in forecasting flood zone and stream depth changes, PennDOT should continue to track efforts being undertaken by USGS, PEMA, and FEMA. Each of these agencies may address the role of climate change on existing flood zones over the next several years. Opportunities may existing in sharing information to reduce duplicate computations.

Assessing Adaptation Strategies

This study does not formally recommend specific adaptation strategies for PennDOT. Section 7 of the study provides a toolbox of strategies that was developed from stakeholder outreach comments, example practices within Pennsylvania, and other strategies identified from a national literature review.

The strategy toolbox is provided to guide future discussions and activities in determining what strategies may be most viable for PennDOT and its planning partners. Strategy assessment remains an important future activity for PennDOT and may be accomplished through the following steps:

- **Establish strategy working groups to evaluate strategies in more detail.** The identification and evaluation of adaptation strategies will require expertise across a multitude of disciplines including
highway design, maintenance, hydrology, planning, and traffic engineering. Establishing multi-agency working groups can bring experts in each discipline together to identify effective adaptation strategies. Evaluations of strategies can include addressing technical and political feasibility, cost and benefits, effectiveness in other areas, and flexibility. MPOs and counties may provide additional insights in identifying strategies. For example, strategies to increase stormwater capacity should be integrated with county/local Municipal Separate Storm Sewer System (MS4) Programs for planning and permitting of stormwater/sewer systems.

- **Conduct more detailed focus studies to evaluate vulnerabilities and strategies for specific locations.** The selection of specific strategies for a project study area will typically require a more detailed assessment and evaluation. Some past example projects include Saw Mill Run (Pittsburgh) and the LeTort Spring Run Watershed Planning (Carlisle) as described in Section 7. Each of these projects identified specific strategies to address flooding and storm water vulnerabilities. Conducting detailed assessment studies may not be cost-effective at all locations. This PennDOT Phase 1 study may provide insights into locations where future studies may be warranted (i.e. the location ranks high in the risk assessment scoring). The LeTort Spring Run project also highlights the evolving practice of watershed planning. Such studies focus on the entire watershed addressing the linkages between local and state storm water and drainage systems. These studies have also worked to develop a more collaborative process to help manage stormwater. Section 4 has highlighted Pennsylvania watersheds with the most miles of historic flooding closures and may provide insights into which watersheds should be of highest priority for study.

### Integrating Resiliency Concepts

Improving transportation system resiliency will require a coordinated effort among multiple disciplines and divisions (e.g. Bureaus, Districts) within the Department. Integrating resiliency concepts will be an important initial step and include the sharing of the study data, mapping and strategies. Specific integration steps can include:

- **Support integration of study results to address other Department requirements and initiatives.** As discussed in Section 8, there are several PennDOT and Planning Partner initiatives currently underway that may need to address climate and extreme weather. Through webinars, a possible future resiliency summit, meetings and other data sharing implementation steps discussed above, PennDOT can ensure that available study data is used to its highest potential. Opportunities for integrating information on flooding vulnerabilities and risks may include:
  - enhancement of DOT and MPO project prioritization processes to address FAST Act resiliency requirements,
  - Bureau of Project Delivery’s update of Publication 321 to address the CEQ Guidance affecting NEPA’s considerations of climate change,
  - enhancements to the Linking Planning and NEPA (LPN) process and forms to address resiliency,
  - development of supplemental data maps to support the PennDOT Connects System that focuses on local government outreach with specific components for stormwater management and green infrastructure, and
  - identifying methods to integrate infrastructure resiliency through the Department’s Highway Occupancy Permit (HOP) application process.

- **Support Districts and MPOs in conducting resiliency planning.** Integrating resiliency into District and MPO planning and maintenance activities will be a key area of emphasis. District staff provide the expertise and local knowledge to evaluate vulnerability risks, evaluate and select adaptation measures,
and monitor the performance of specific projects over time. Identifying ways that each District can develop and address resiliency planning, considering available resources, will assist in ensuring that cost-effective strategies are implemented. PennDOT can work with their federal partners and other supporting organizations like AASHTO to identify tools and processes to assist in addressing resiliency. For example, AASHTO & FHWA have developed a Road Weather Management Capability Maturity Self-Evaluation Tool (Figure 9.1) to assist in addressing weather issues related to maintenance and operations.

**Figure 9.1: AASHTO Road Weather Management Tool**


- **Provide local technical assistance to support resiliency planning.** Addressing resiliency at the local level will require increased coordination with state and local agencies. Local and state stormwater systems are often impacted by each other and should be considered in whole for watershed planning purposes. PennDOT may consider ways to support local agencies either through educational, technical or financial means.

- **Determine other improvements in capabilities and funding necessary for successful implementation.** The integration of resiliency within PennDOT will most likely include changes to existing business processes, systems and technology, performance management, culture, organization and workforce, and collaboration. Identifying means to fund resiliency projects will also be a significant challenge. Both FEMA and FTA have provided funding grants to support infrastructure improvements related to disaster events. Further work is needed to identify other funding opportunities to address the highest risk vulnerabilities within the state.