MnDOT Flash Flood Vulnerability and Adaptation Assessment Pilot Project

Final Report

Prepared for

The Minnesota Department of Transportation and
the USDOT Federal Highway Administration

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1 Project Introduction

Minnesota's climate is changing. Temperatures are on the rise and extreme precipitation events and associated flooding are becoming more frequent and severe.[1] As the Earth continues to warm, these events are projected to become even more common since a warmer atmosphere is capable of holding more water vapor.

Flooding presents a challenge to fulfilling the Minnesota Department of Transportation's (MnDOT) mission to, "Plan, build, operate, and maintain a safe, accessible, efficient, and reliable multimodal transportation system..."[2] When roads become inundated, the safety of motorists can be threatened, efficiency is reduced by the need to take detours, and system reliability is compromised.

Recognizing this, MnDOT planners and engineers have long considered minimizing the risk of flash flooding in the siting and design of the state's roadway network. However, as has been the standard practice worldwide, they have traditionally assumed that future climate conditions will be similar to those recorded in the past. Climate change challenges this assumption and calls for new approaches to understanding vulnerabilities across the highway system and at specific transportation facilities so that appropriate actions, adaptations, can be taken to minimize expanding risks.

This project, one of 19 Federal Highway Administration (FHWA) climate vulnerability pilot studies nationwide looking at the effects of climate hazards on the transportation system, represents a starting point for developing these new approaches. The focus of this pilot study is on flash flooding risks to the highway system. While flooding is not the only threat to the state's highway system posed by climate change,[3] it is likely to be one of the most significant and has already caused extensive disruptions to the transportation system in many areas.

1.1 Goals

The goals of this study are to:

- Better understand the vulnerability of the state's trunk highway system (interstates, US routes, and state roads) to flash flooding events
- Develop a process to identify cost-effective planning and design solutions for specific projects to increase resiliency
- Support MnDOT's asset management planning efforts
- Provide feedback and lessons learned to FHWA on the assessment process

1.2 Scope

The project was divided into two distinct but closely related tasks in order to achieve the goals outlined above:

- A high-level assessment of the trunk highway system to determine which facilities are most vulnerable to flash flooding events
- Detailed case studies demonstrating how cost-effective planning and design decisions can be made on individual facilities in the context of changing precipitation patterns associated with climate change

[1] Melillo, Terese, and Yohe, 2014
[2] MnDOT, 2014c
[3] Examples of other transportation hazards that could be exacerbated by climate change in Minnesota include landslides, ice storms, and pavement buckling.

The two efforts work together to provide a fuller understanding of the flood vulnerabilities faced by MnDOT. First, the high-level system-wide assessment was undertaken to provide a list of the facilities most vulnerable to flooding. Then, the most vulnerable facilities were given a more detailed facility-level assessment to better understand the risks they face and to inform the development of cost-effective adaptation solutions. If warranted, the adaptation solutions can then be added to capital improvement plans and built. The facility level assessments may also be conducted on any new project already in the capital improvement plan to ensure that the project's life-cycle costs are minimized as the climate changes.

The project focused on two MnDOT Districts that have experienced particularly severe flooding in recent years: District 1 in northeast Minnesota and District 6 in the southeastern portion of the state. Figure 1 provides a reference map showing the location of the study areas. In District 1, Duluth and its environs experienced serious flooding in June 2012 when nearly 10 inches of rain fell on the area over a two-day period resulting in numerous road closures and $75 million in damage to the trunk highway system. District 6 has suffered from repeated rounds of flooding over the past decade with particularly noteworthy events occurring in 2007, 2010, and 2012. The 2012 event dropped nearly nine inches of rain on the town of Cannon Falls setting a new 24-hour rainfall record for the state.

A system-wide flash flood vulnerability assessment was conducted for the entire trunk highway network in both districts. Following this, one highly vulnerable facility in each district was selected to serve as a case study on how cost-effective decision-making can be made in the context of a changing climate.

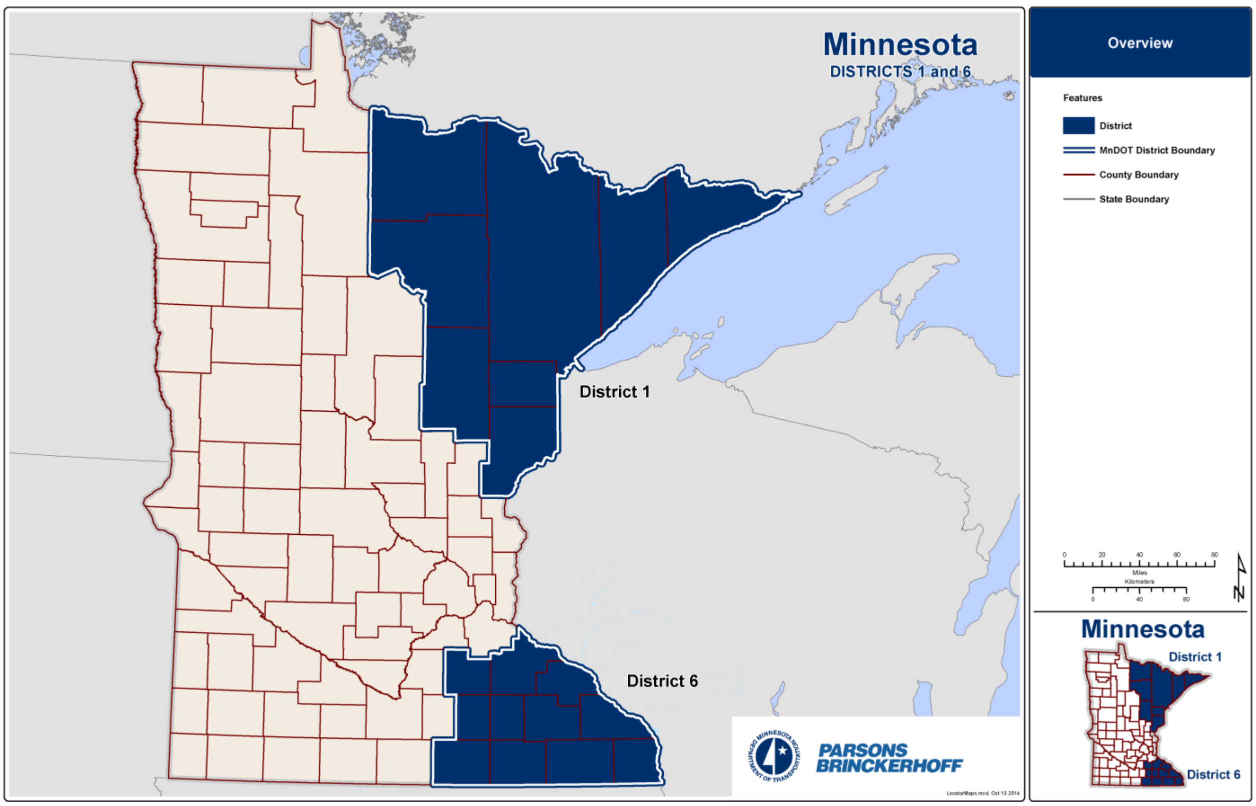


Figure 1: Locations of MnDOT Districts 1 and 6

1.3 Project Team

The project team consisted of the following groups:

- **Project Management Team (PMT)—**The PMT was responsible for the overall management, coordination, and direction of the project. It consisted of key MnDOT planning staff at the agency headquarters in St. Paul and from each of the two districts covered by the study.
- **Core Advisory Panel (CAP)—**The CAP was tasked with providing strategic direction for the project. It consisted of PMT members along with local and county government representatives from jurisdictions within each district.
- **Technical Advisory Committee (TAC)—**The TAC's mandate was to provide critical input on the technical approaches used throughout the study. It consisted of all of the PMT staff along with structural and water resources engineers at the state and district levels.
- **Climate Advisory Committee (CAC)—**The CAC was focused on providing guidance and feedback on the climate projections developed for the project. It was comprised of representatives of local academic institutions and members of other state agencies tasked with understanding how climate changes.
- **Consultant Team—**The consultant team was responsible for developing the technical approach for the project and for conducting the various assessments. Parsons Brinkerhoff was the overall lead consultant on the project with Catalysis Adaptation Partners responsible for the benefit-cost analyses conducted for the case studies of specific facilities.

1.4 Report Organization

The report is organized around the project's major tasks described in the scope above. Chapter 2 discusses the methodology and findings of the system-wide flash flood vulnerability assessment. Next, Chapter 3 presents the approach developed for the facility-level adaptation assessments and walks through two case studies demonstrating its application. Following this, Chapter 4 summarizes the lessons learned on the project and provides recommendations for the FHWA Climate Change and Extreme Weather Vulnerability Assessment Framework. Chapter 5 offers conclusions and next steps towards incorporating climate change into MnDOT activities.

2 System-Wide Vulnerability Assessment

The system-wide vulnerability assessment used the FHWA's Climate Change and Extreme Weather Vulnerability Assessment Framework (the "Framework") as a guide.[4] As illustrated by the diagram in Figure 2, the Framework is comprised of three primary steps:

1. Define the scope
2. Assess vulnerability
3. Integrate into decision-making

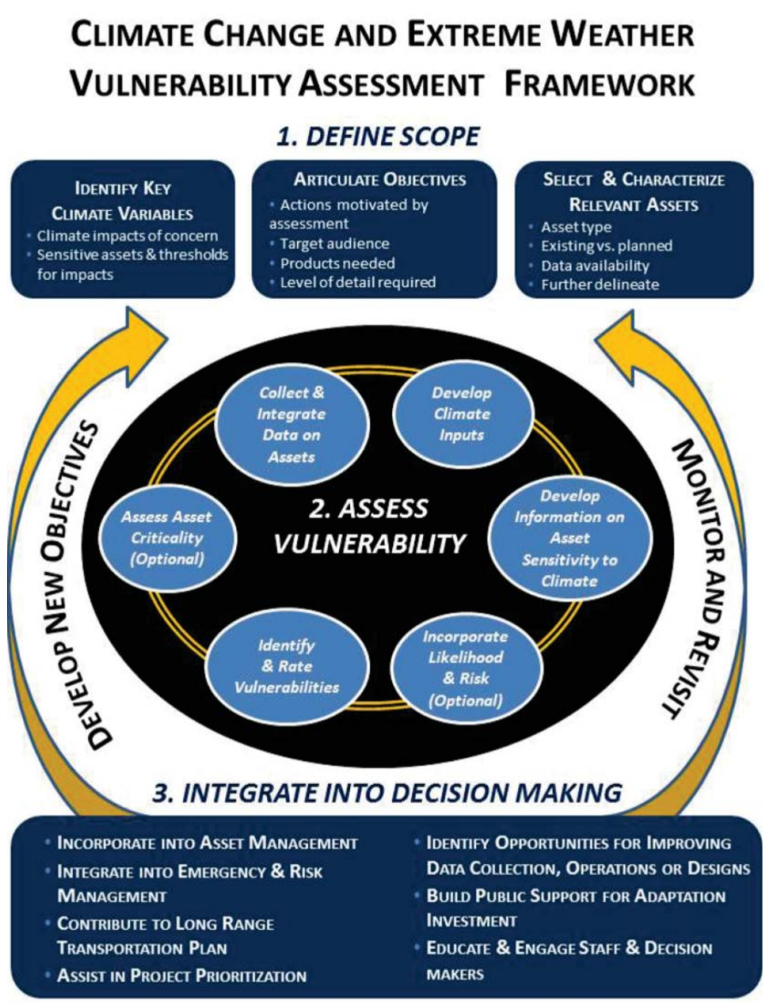
The first step of the vulnerability assessment, scope definition, involved articulating the objective of the study: to identify MnDOT facilities with the greatest vulnerability to flash flooding so that efforts can be made to prioritize adaptation actions that will increase the system's resiliency. It also involved discussions on which assets should be included in the study. It was decided that the assessment should focus on assets in Districts 1 and 6 (the two highway districts that have recently experienced the greatest impacts from flooding) as a pilot study for a process that could then be implemented elsewhere in the state. Section 2.1 below provides more detail on the specific asset types selected for evaluation.

After the scope had been defined, the next step in the Framework was to assess vulnerability. Section 2.2 describes how this was done consistent with the definition of vulnerability provided in the Framework report. Section 2.3 then presents the results of the vulnerability assessment.

The final step in the Framework involves integrating the findings into decision-making. Section 2.4 provides a list of action items MnDOT intends to take towards this end.

2.1 Selection of Assets

The state's trunk highway system was the roadway network selected for analysis in each district. The trunk highway system comprises the entirety of the state owned and maintained road infrastructure and includes all interstates, US routes, and signed state roads. Figure 3 and Figure 4 provide maps showing the trunk highway network within each district.



Source: FHWA, 2012

Figure 2: FHWA Climate Change and Extreme Weather Vulnerability Assessment Framework

[4] FHWA, 2012

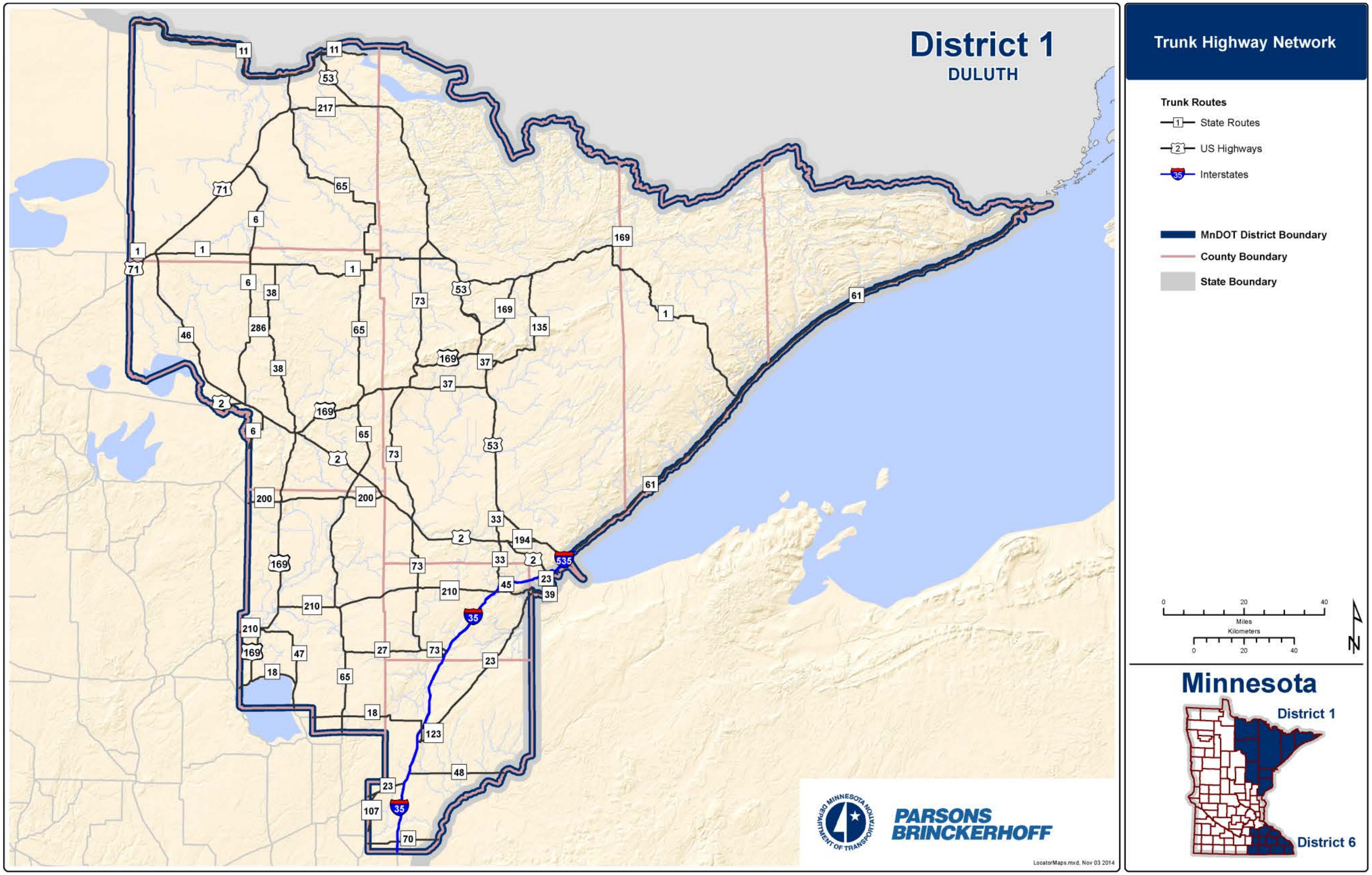


Figure 3: Trunk Highway Network, District 1

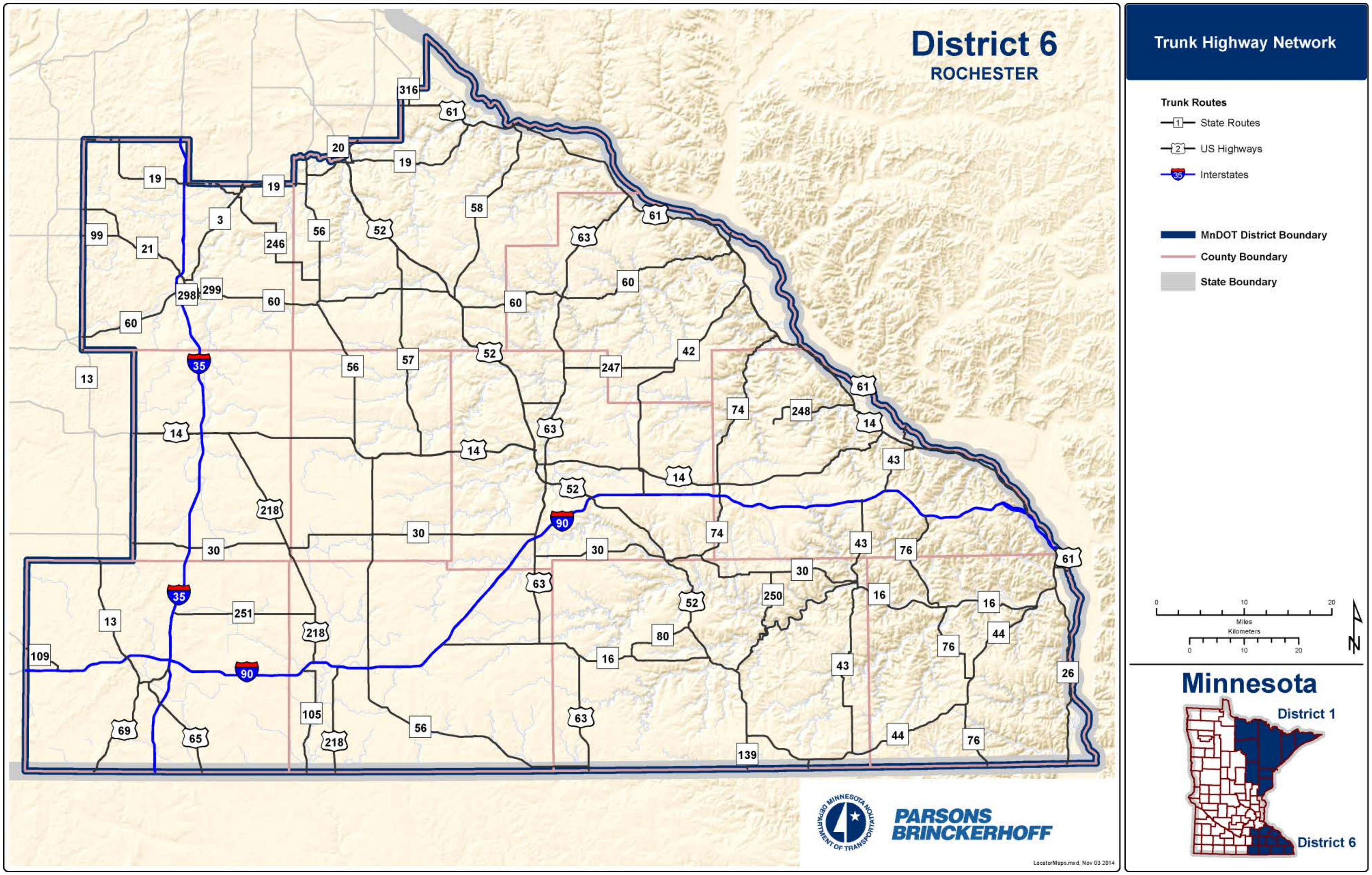


Figure 4: Trunk Highway Network, District 6

The highway system is comprised of a number of different asset types that are susceptible to flooding. The following asset types were included in this assessment: [5]

- **Bridges**
  - 140 in District 1
  - 176 in District 6
- **Large culverts** [6]
  - 160 in District 1
  - 361 in District 6
- **Pipes** [7]
  - 543 in District 1
  - 377 in District 6
- **Roads paralleling streams** [8]
  - 18 segments in District 1 (34.5 total miles in length [9])
  - 44 segments in District 6 (101 total miles in length [9])

Each of these 1,819 assets was given a separate vulnerability score in the assessment. Note that slopes were also identified as being susceptible to heavy precipitation events but the project budget did not allow for their inclusion in this study.

2.2 Methodology

A methodology was developed that balances the need for a detailed assessment of facility performance rooted in engineering principles with the requirement that the assessment be applied en masse to thousands of assets. The approach taken, illustrated in Figure 5, involves developing a series of vulnerability metrics for each asset, combining them mathematically into a single vulnerability score, and ranking and classifying those scores to identify the most vulnerable facilities. The final results show the vulnerability of each asset relative to other assets in the same district. The following sub-sections describe the details of the approach.

2.2.1 Vulnerability Definition

The system-wide vulnerability scoring was conducted in accordance with the definition of vulnerability offered in the Framework document. [10] FHWA defines vulnerability as being comprised of three components:

- **Exposure:** The degree to which an asset may be affected by a climate stressor.
- **Sensitivity:** How well an asset impacted by a climate stressor is able to cope with the impacts.

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[5] There are additional assets of each type that could not be included in the analysis due to missing or inaccurate asset data, their location over or along a river bordering Wisconsin or Canada (some key input data was not available for these neighboring jurisdictions), the observation that they did not cross a stream delineated in the Minnesota Department of Natural Resources 1:24,000 stream network geographic information system (GIS) shapefile (a shapefile needed for some of the calculations), or for which the US Geological Survey's StreamStats program could not generate flow data (another necessary input to the analysis). The vast majority of assets within each district, however, did have data available and were included in the analysis. Also, note that in District 6, bridges over the Mississippi River and roads paralleling it were not included in the analysis because the focus of the analysis is on smaller scale flash flooding events as opposed to large scale riverine flooding which has a different dynamic. Assets affected by the Mississippi River were included in District 1 because the river is much smaller in this area.

[6] Large culverts are defined by MnDOT as culverts with 10 ft. or greater individual span length

[7] Pipes are defined by MnDOT as culverts with less than 10 ft. of individual span length. Pipes were selected in coordination with MnDOT's bridge office. Only centerline pipes conveying a stream across the roadway were analyzed. General drainage and stormwater pipes, whether crossing the centerline or to the side of the road, were not included in this assessment.

[8] Roads paralleling streams were included as an asset type to account for flood vulnerabilities to roads that follow along stream valleys but don't necessarily cross the stream as do bridges, culverts, and pipes. It was comprised of road segments that, for a mile or more of length, fell (1) within 200 ft. of the current Federal Emergency Management Agency (FEMA) 100-year floodplain or (2), where FEMA flood studies had not been conducted, a buffer-based value defined as 200 ft. times the stream's Strahler stream order. The 200 ft. buffer of the FEMA floodplain was used to account for potential future expansion of the floodplain that may occur with climate change.

[9] Mileage for each carriageway on divided highways counted separately

[10] FHWA, 2012

- **Adaptive Capacity:** How resilient the transportation system as a whole is if the asset were to be taken out of service.

A series of metrics were created to capture each of the three components of vulnerability and are described in detail below.

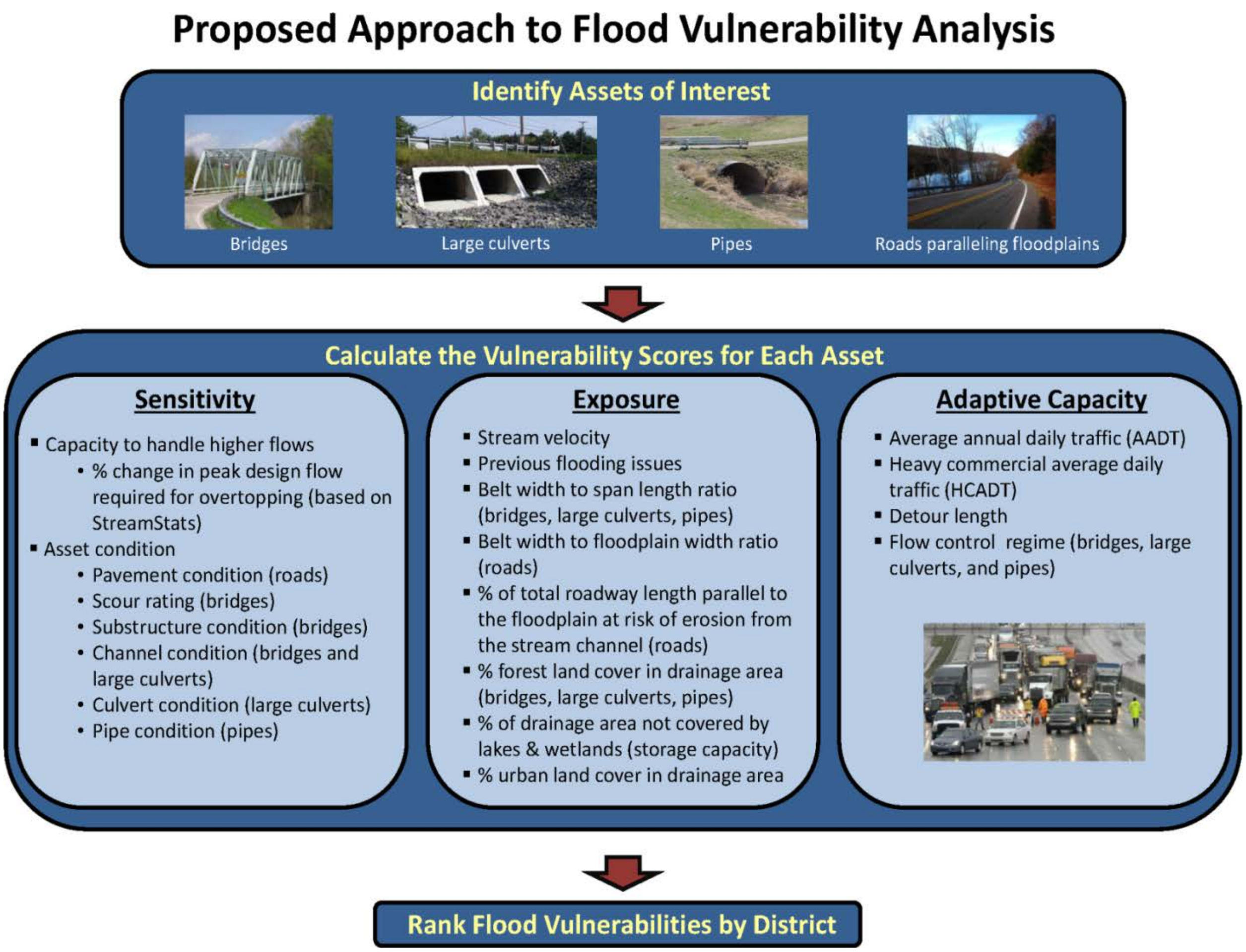


Figure 5: System-Wide Vulnerability Assessment Approach

2.2.2 Metrics

Dozens of metrics were developed in order to quantify each facility's vulnerability. Each asset type has a unique set of metrics tailored to the factors important to understanding its vulnerability. For example, scour ratings are important to understanding the sensitivity of bridges to flooding but are not relevant to pipes. Table 1 provides a listing of the metrics used for each asset type in the study, a description of each metric, why they were included in the study and how they were generated. For consistent scoring purposes, the metrics were set up so that higher values are indicative of greater vulnerability.

Note that there is no metric explicitly capturing exposure to future precipitation changes or flooding. A metric capturing differences in projected future 24-hour precipitation depths within each asset's drainage area was considered, however, the CAC felt that any variations in climate model projections across an area as small as a district would not be reliable. Thus, the assessment took a sensitivity based approach to capturing vulnerability asking, "Given what we know about each asset and its environmental setting, what percentage change in the design storm would be required to overtop the roadway?" All other metrics being equal, assets that required less of a change in design flow to overtop were considered more vulnerable to potential increases in precipitation.

Table 1: Description and Summary of Metrics Used to Quantify Flood Vulnerability

Metric	Description	Rationale for Inclusion	Data Source	Asset Type Applied To			
				Bridges	Large Culverts	Pipes	Roads Paralleling Streams
Exposure							
Stream velocity	The velocity of the stream at peak design flow (50-year storm) or at overtopping flow (if it's return period is less than 50-years)	Higher velocity flows are capable of producing greater damage to infrastructure	Hydraulic analysis	X	X	X	X
Previous flooding issues	Indicator of whether previous flooding was reported at the facility in the last 20 years	Existing flooding hotspots are known vulnerabilities and a priority for adaptive actions	Work sessions with district staff	X	X	X	X
Belt width[1] to span length ratio	The ratio of the maximum stream meander belt width near the structure to the structure's total span length	Higher ratios are indicative of spans that could be at greater risk of erosion as the stream shifts course over time	GIS analysis & MnDOT databases	X	X	X	
Belt width to floodplain width ratio	The ratio of the maximum stream meander belt width near the segment to the floodplain width at the segment	Higher ratios are indicative of roads that could be at greater risk of erosion as the stream shifts course over time	GIS & hydraulic analyses				X
Percent of total segment length at risk of erosion from the stream channel	The percentage of the roadway segment within 200 ft. of the stream channel	Roads closer to the stream channel are more exposed to erosion during flood events	GIS analysis				X
Percent forest land cover in the drainage area	The percentage of forest land cover within the drainage area of each facility.	More woodlands in the drainage area increases the possibility of woody debris getting lodged underneath the facility and causing damage	GIS analysis	X	X	X	
Percent of drainage area not covered by lakes and wetlands	The percentage of each facility's drainage area that is not covered by lakes and wetlands	Fewer lakes and wetlands means less water storage and more runoff and flooding	GIS analysis	X	X	X	X
Percent urban land cover in the drainage area	The percentage of each facility's drainage area that is covered by urbanized land cover	More impervious urban land cover leads to more runoff and flooding	GIS analysis	X	X	X	X

Table 1: Description and Summary of Metrics Used to Quantify Flood Vulnerability (continued)

Metric	Description	Rationale for Inclusion	Data Source	Asset Type Applied To			
				Bridges	Large Culverts	Pipes	Roads Paralleling Streams
Sensitivity							
Percent change in peak design flow required for overtopping	The percentage change in the design flow (50-year storm) required to overtop the facility	The smaller the change necessary to overtop the facility, the more sensitive the facility is to increases in flood elevations due to climate change	Hydraulic analysis	X	X	X	X
Pavement condition	The ride quality index value at the sump (lowest point) of the roadway segment	Pavement that is in poor condition is more prone to being uplifted and washed away during flood events	MnDOT databases				X
Scour rating	MnDOT scour rating value	Bridges that have current scour issues are more prone to damage during flood events	MnDOT databases	X			
Substructure condition rating	National Bridge Inventory substructure condition rating	Bridges with substructures that are in poor condition are more prone to damage during flood events	MnDOT databases	X			
Channel condition rating	National Bridge Inventory channel condition rating	Facilities with poor channel conditions in the vicinity of the structure are more prone to damage during flood events	MnDOT databases	X	X		
Culvert condition rating	National Bridge Inventory culvert condition rating	Culverts that are in poor condition are more prone to damage during flood events	MnDOT databases		X		
Pipe condition rating	MnDOT pipe condition rating	Pipes that are in poor condition are more prone to damage during flood events	MnDOT databases			X	

Table 1: Description and Summary of Metrics Used to Quantify Flood Vulnerability (continued)

Metric	Description	Rationale for Inclusion	Data Source	Asset Type Applied To			
				Bridges	Large Culverts	Pipes	Roads Paralleling Streams
Adaptive Capacity							
Average annual daily traffic	The average annual daily traffic using the facility as of the latest available date	Provides an indication of the number of motorists affected if a flood event were to occur	MnDOT databases	X	X	X	X
Heavy commercial average daily traffic	The average daily truck traffic using the facility as of the latest available date	Provides an indication of the disruption to freight flows if a flood event were to occur	MnDOT databases	X	X	X	X
Detour length	The additional travel distance required to bypass the affected facility using approved detour routes[2]	Provides an indication of system redundancy in the event of a road closure caused by flooding	GIS analysis	X	X	X	X
Flow control regime	An indicator of whether the facility is inlet or outlet controlled	Outlet controlled facilities will be more difficult to adapt than inlet controlled facilities	Hydraulic analysis	X	X	X	

[1] Belt width refers to the lateral width of stream meanders

[2] For the purposes of the analysis, approved detour routes consisted of other trunk roads and paved county and state aid roadways

Development of the metrics was a large undertaking. While some of the metrics were available directly from MnDOT databases, other metrics required intensive GIS processing to generate. Some of the most important metrics to the analysis (e.g. the percentage change in design flow required for overtopping) were developed with the aid of a hydraulics tool developed as part of this project. The tool draws upon MnDOT databases, LIDAR derived elevation information, current peak flow values obtained from the U.S. Geological Survey's StreamStats program, and standard hydraulics formulas in order to estimate the percent change in flow required to overtop the facility, stream velocities at peak flows, and other important measures. Appendix A provides more detail on the hydraulics tool and its limitations.

2.2.3 Scoring

Once all the metrics had been calculated, the next step was to combine the information into a single over-arching vulnerability score for each asset. Table 2 provides an example of how the calculations are made for a hypothetical large culvert and is a useful reference throughout this section. As part of this process, each of the metrics was re-scaled to a common 0 to 100 point scale with 0 assigned to the facility with the lowest (least vulnerable) score for a given metric in that district and 100 assigned to the facility with the highest (most vulnerable) score for that metric in that district. This scaling was done for each of the metrics independently. Categorical metrics were manually assigned scaled values based on input provided by the project's TAC. Appendix B summarizes the scaled values assigned to each category for categorical metrics.

After scaling was complete, the project team worked with the TAC to weight each metric so that those metrics perceived as being more important to characterizing vulnerability could be factored more heavily into the final scores. Table 3 shows the weights that were employed for each measure. The weights were defined as percentages such that the weights for all of the metrics under a given asset class must add up to 100 within each component of vulnerability (exposure, sensitivity, adaptive capacity). For example, all of the weights for the exposure metrics for bridges must add to 100, all of the weights for the sensitivity metrics for bridges must add to 100, all of the weights for the exposure metrics for pipes must add to 100, etc.

The weights were then multiplied by the value of each metric and combined into a series of interim scores summarizing each asset's exposure, sensitivity, and adaptive capacity (shown in the light orange shaded cells in Table 2). Another round of weighting was then undertaken amongst these three interim scores to allow some components of vulnerability to more heavily influence the final asset score than others. After discussions with the TAC, however, it was decided that each vulnerability component should factor equally into the final score for bridges, large culverts, and pipes. Thus, each of the three vulnerability components received an equal weight (33.3 percent) for these assets. For roads paralleling streams, it was decided that exposure should be given the highest weight (43.3 percent) followed by adaptive capacity (33.3 percent) and sensitivity (23.3 percent).

Although it was beyond the available budget on this project, the project team felt that running a second analysis that considered only exposure and sensitivity and gave zero weight to the adaptive capacity metrics would also be useful. It is believed that this analysis would better isolate those assets that are most under-designed (regardless of their role within the network), an important consideration in capital programming.

Table 2: Example Vulnerability Scoring Process for a Large Culvert

Variable	Value for the Example Asset	Range of Values Across All Assets		Scaled Value for the Example Asset (0-100)	Variable Weight	Score
		Low	High			
Sensitivity						
% change in design flow required for overtopping	-18.00%	-78.00%	2375.00%	98	60%	58.5
Channel condition rating	6	–	–	50	15%	7.5
Culvert condition rating	5	–	–	50	25%	12.5
				Sum of Sensitivity Variable Scores:		*78.5*
				Sensitivity Weight:		*33%*
				Final Sensitivity Score:		**25.9**
Exposure						
Stream velocity	7.01	0.74	37.53	17	20%	3.4
Previous flooding issues	1	0	1	100	35%	35.0
Belt width to span length ratio	3.68	0.32	209.24	2	10%	0.2
% forest land cover in drainage area	1.85%	0.00%	91.23%	2	10%	0.2
% of drainage area not lakes and wetlands	99.91%	97.71%	100.00%	96	10%	9.6
% drainage area urban land cover	4.00%	0.00%	53.52%	7	15%	1.1
				Sum of Exposure Variable Scores:		*49.5*
				Exposure Weight:		*33%*
				Final Exposure Score:		**16.3**
Adaptive Capacity						
Average Annual Daily Traffic (AADT)	5,700	90	49,200	11	35%	4.0
Heavy Commercial Average Daily Traffic (HCADT)	610	5	5,900	10	25%	2.6
Detour Length	0.6	-0.37	20	4	35%	1.3
Flow control regime	0	0	1	0	5%	0.0
				Sum of Adap. Cap. Variable Scores:		*7.8*
				Adaptive Capacity Weight:		*33%*
				Final Adaptive Capacity Score:		**2.6**
				OVERALL VULNERABILITY SCORE:		**45**

Table 3: Weights Assigned by Metric

Metric	Percentage Weights by Asset Class: Bridges	Large Culverts	Pipes	Roads Paralleling Streams
Exposure				
Stream velocity	20%	20%	20%	10%
Previous flooding issues	35%	35%	35%	30%
Belt width[1] to span length ratio	10%	10%	10%	–
Belt width to floodplain width ratio	–	–	–	10%
Percent of total segment length at risk of erosion from the stream channel	–	–	–	25%
Percent forest land cover in the drainage area[2]	10%	10%	10%	–
Percent of drainage area not covered by lakes and wetlands	10%	10%	10%	10%
Percent urban land cover in the drainage area	15%	15%	15%	15%
TOTAL	100%	100%	100%	100%
Sensitivity				
Percent change in peak design flow required for overtopping	60%	60%	60%	70%
Pavement condition	–	–	–	30%
Scour rating	25%	–	–	–
Substructure condition rating	5%	–	–	–
Channel condition rating	10%	15%	–	–
Culvert condition rating	–	25%	–	–
Pipe condition rating	–	–	40%	–
TOTAL	100%	100%	100%	100%
Adaptive Capacity				
Average annual daily traffic	35%	35%	35%	35%
Heavy commercial average daily traffic	25%	25%	25%	30%
Detour length	35%	35%	35%	35%
Flow control regime	5%	5%	5%	–
TOTAL	100%	100%	100%	100%

Notes: For each asset class, within each of the three components of vulnerability (exposure, sensitivity, and adaptive capacity), the weights must add to 100%. Dashes (–) indicate metrics that were not applicable to a given asset class.
Belt width refers to the lateral width of stream meanders
[2] This metric was used as a proxy for the potential for woody debris to cause blockages at bridges, large culverts, and pipes. It is recognized, however, that forest land cover also has the potential to mitigate runoff. In future analyses, a more refined metric could be developed that considers the amount of forest cover only in the area immediately upstream of the facility or only along the upstream floodplains.

The final output of the scoring process was an overall vulnerability score for each facility (shown in the dark orange shaded cell in Table 2). These scores are rankable such that one could list, for example, the most to least vulnerable bridges in each district. However, given some of the generalizations that were necessary to develop the metrics, there was a concern that the differences between individual scores may not be meaningful and within the margins of error involved in the analysis. Therefore, it was felt that the most appropriate means of presenting the results would be to group assets with similar scores into classes, or tiers, of vulnerability. Five tiers of vulnerability were developed:

- **Tier 1:** Highest vulnerability
- **Tier 2:** High vulnerability
- **Tier 3:** Moderate vulnerability
- **Tier 4:** Low vulnerability
- **Tier 5:** Lowest vulnerability

The classification of the data was done using the Jenks natural breaks methods which searches for statistical clusters in the data distribution and puts class boundaries around those clusters. The classification was performed using the values for all asset types within a district so that the most vulnerable facilities within a district, regardless of type, showed up as being the most vulnerable. This approach allows for the possibility (unlikely as it is) that all the Tier 1 assets in a district may, for example, be pipes and not other assets types.

When interpreting the results, it is important to be aware that highly vulnerable (Tier 1 and Tier 2) assets are not in imminent danger of flooding. Nor are lower vulnerability (Tier 4 and Tier 5) assets immune to flooding. Instead, the values should be interpreted as indicators of the *relative* vulnerability of assets compared with others in the same district (not between the two districts). The decision was made to set the analysis up in this manner for the following reasons:

- Many important aspects of long range and capital planning for which the findings are likely to be applied occur at the district level. It is helpful to have a summary of the greatest vulnerabilities by district to help with these activities.
- In the future, additional districts around the state are likely to have similar vulnerability assessments undertaken. If the analysis was set up to compare results between districts, not only would new results be generated for the most recently studied districts but the results for Districts 1 and 6 would change as well since the scores would need to be re-calculated relative to a whole new range of numbers from the newly studied district.

If vulnerability assessments are completed for all the districts throughout the state in the future, a separate statewide vulnerability scoring exercise could be conducted to identify which portions of the state have the overall highest vulnerabilities. These findings could then be used, for example, to allocate more flood adaptation funding to the districts having the highest overall vulnerability levels.

2.3 Findings

The asset vulnerability scores discussed above were summarized in tabular format and mapped for each of the two districts studied. A brief discussion of the broad patterns that emerged in each district is provided in the subsections below.

2.3.1 District 1

Figure 6 provides a graph showing the breakdown of asset types within each vulnerability tier in District 1. Bridges and pipes were the asset types that had the greatest proportions of highly vulnerable Tier 1 and Tier 2 assets although the proportions of most vulnerable assets were fairly comparable across all asset types in the district. Figure 7 shows the same information presented in terms of the number of assets by tier.

Figure 8 provides a map illustrating the spatial distribution of flash flood vulnerabilities across all asset types in District 1. Overall, vulnerabilities tend to be highest for facilities along MN 61 which follows the shoreline of Lake Superior from Duluth to the Canadian border. This roadway has limited redundancy and crosses many high velocity streams that flow from the Superior Uplands into the lake. That said high vulnerability facilities are located throughout the district.

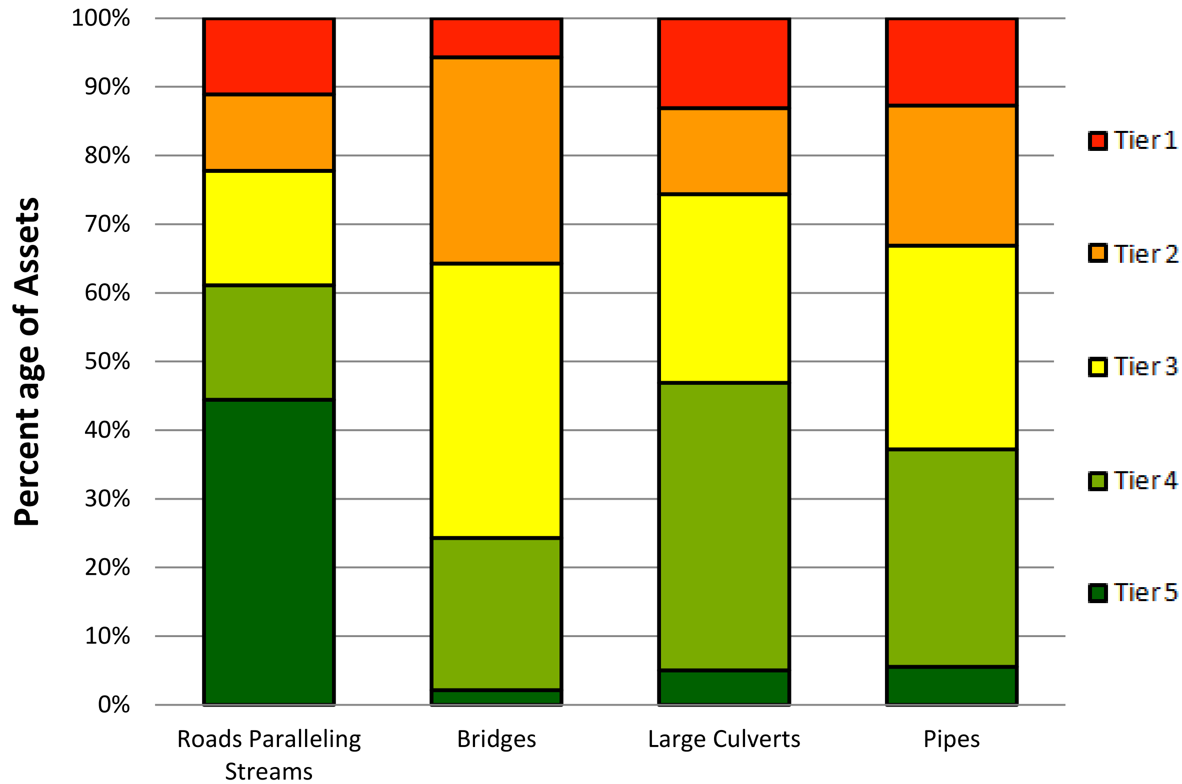


Figure 6: Vulnerability by Asset Type, District 1

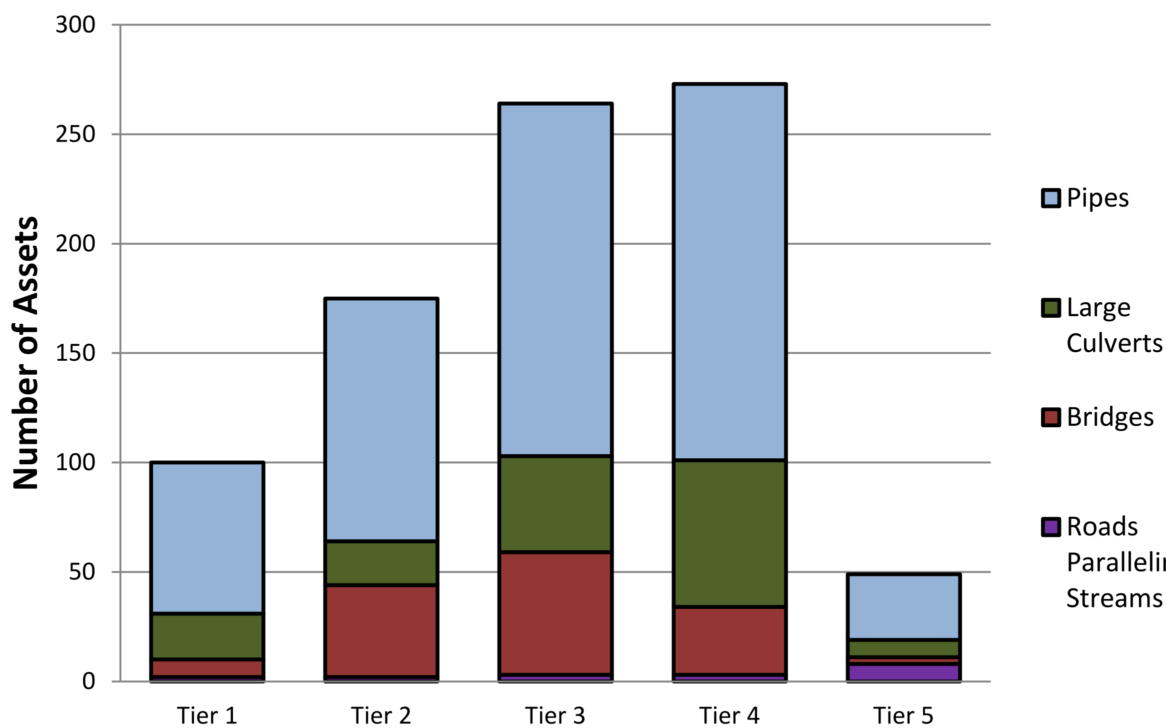


Figure 7: Vulnerability by Tier, District 1

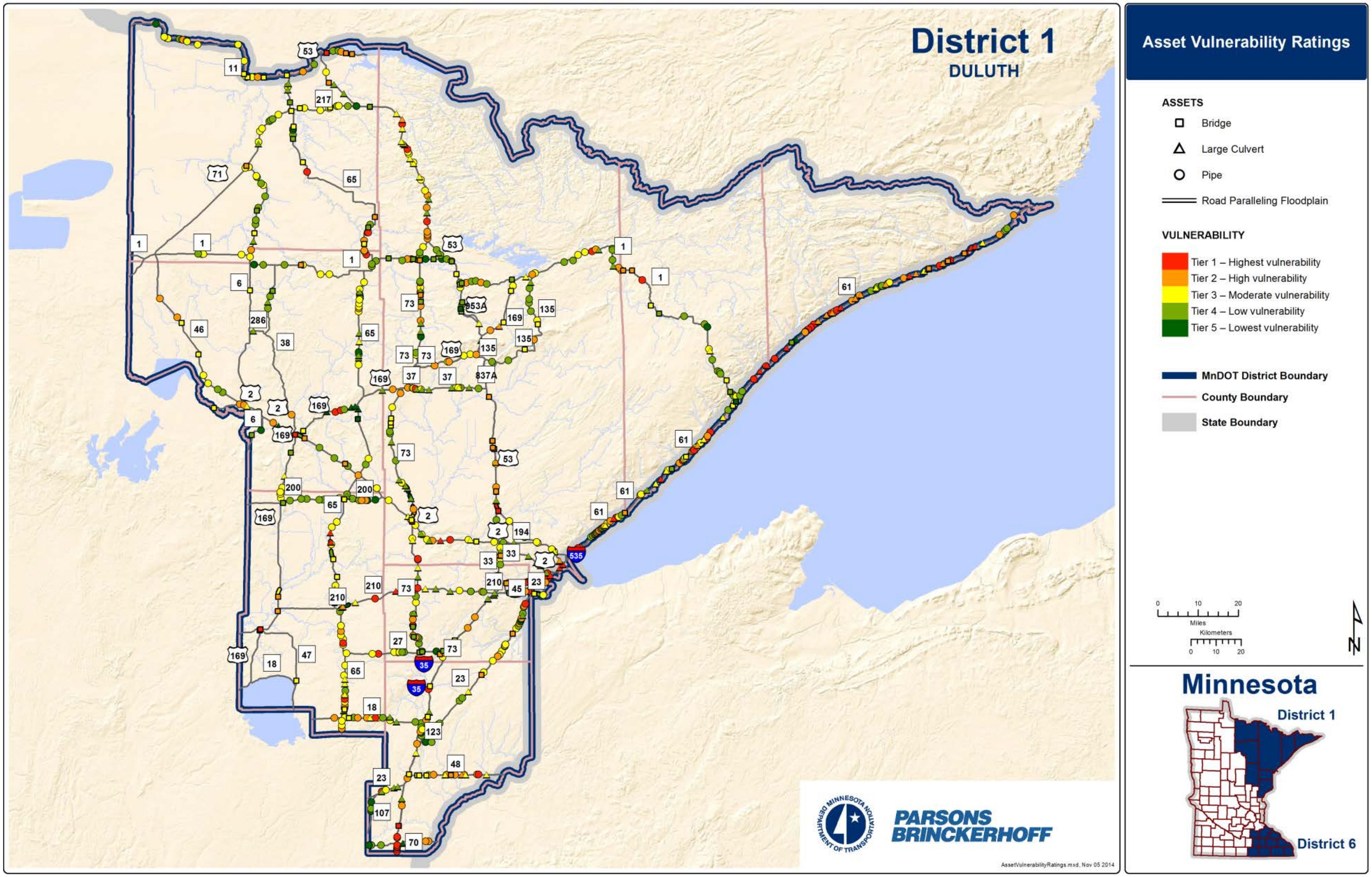


Figure 8: Asset Vulnerability Ratings, District 1

2.3.2 District 6

Figure 9 provides a graph showing the breakdown of asset types within each vulnerability tier in District 6. High vulnerability (Tier 1 and Tier 2) assets make up a greater proportion of all assets than in District 1. There is also greater variation amongst asset types with roads paralleling streams and bridges being found to be much more vulnerable than the district's large culverts and pipes. Figure 10 shows the same information presented in terms of the number of assets by tier.

Figure 11 maps the spatial distribution of flash flood vulnerabilities across District 6. As one can see, the vulnerabilities tend to be greatest in the hillier eastern portion of the district. There is also a cluster of higher vulnerability assets along I-35 in the northwestern portion of the district (possibly caused at least partially by the high traffic volumes in this area).

2.4 Action Items

MnDOT is considering the following action items given the experience with the system-wide pilot study in Districts 1 and 6:

- **Long range transportation planning actions**
  - Test sensitivity of flood vulnerability assessment scoring to different weighting criteria and exclusion of the adaptive capacity component. Exclusion of the adaptive capacity component would be useful for understanding the physical and environmental components of vulnerability in isolation from the asset's role within the network. This may address the tendency for assets on interstates to score higher simply because of the high traffic volumes on these facilities and not because they're under-designed.
  - Query facilities that are currently under-capacity (not capable of passing the 50-year design storm), have high social costs of failure (high traffic volumes or long detour routes), and are not planned for replacement. Consider conducting facility-level adaptation assessments for these assets
  - Conduct follow-up assessments on specific assets to identify whether assessment methods are scoring appropriately for observed conditions and, if not, adjust the input metrics, scaling, and weighting appropriately.
  - Complete flood vulnerability assessments in other districts
  - Use the study results to illustrate the threat posed by flooding/climate change in the next long-range transportation plan
- **Operations and maintenance actions**
  - Develop emergency action plans for Tier 1 and selective Tier 2 assets
  - Explore partnerships with floodplain managers to develop real-time monitoring and warning systems for Tier 1 and 2 assets
- **Capital planning actions**
  - Incorporate vulnerability assessment scores into the project prioritization system at the state and district levels
  - Consider the vulnerability scores when prioritizing culvert replacements, particularly on the National Highway System
  - Incorporate considerations of risk into ongoing culvert and bridge improvement programs

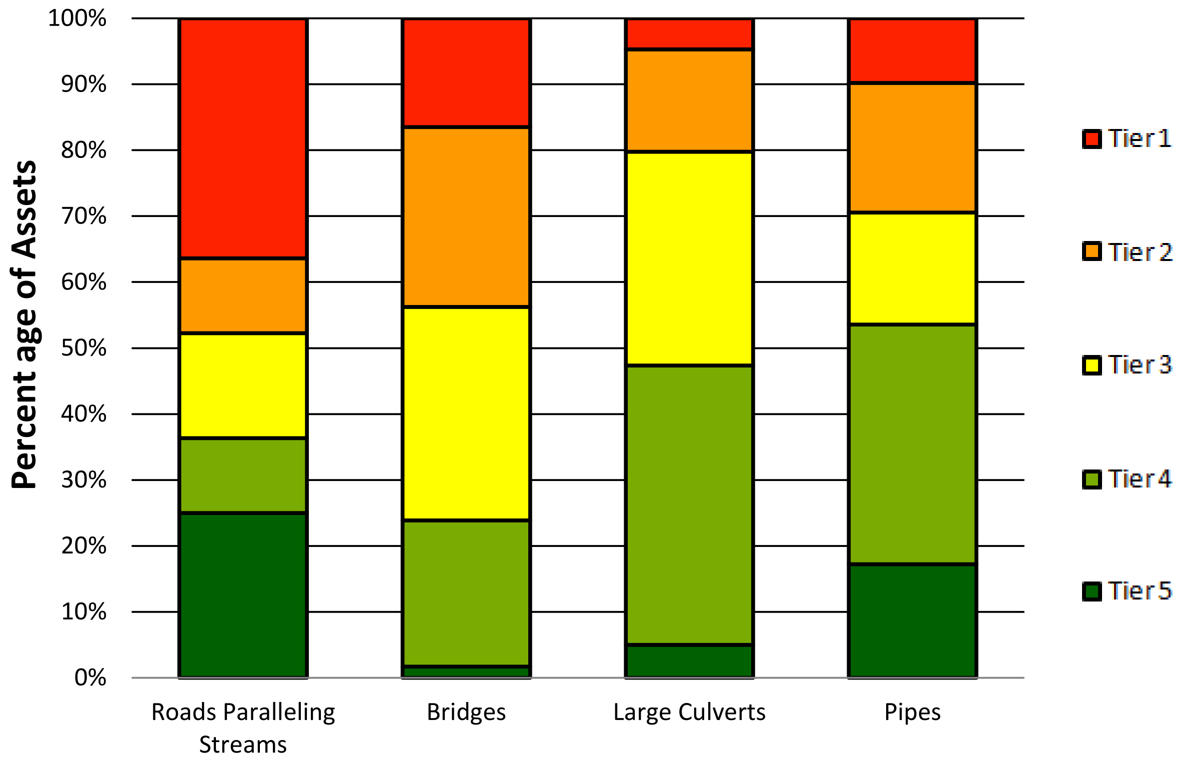


Figure 9: Vulnerability by Asset Type, District 6

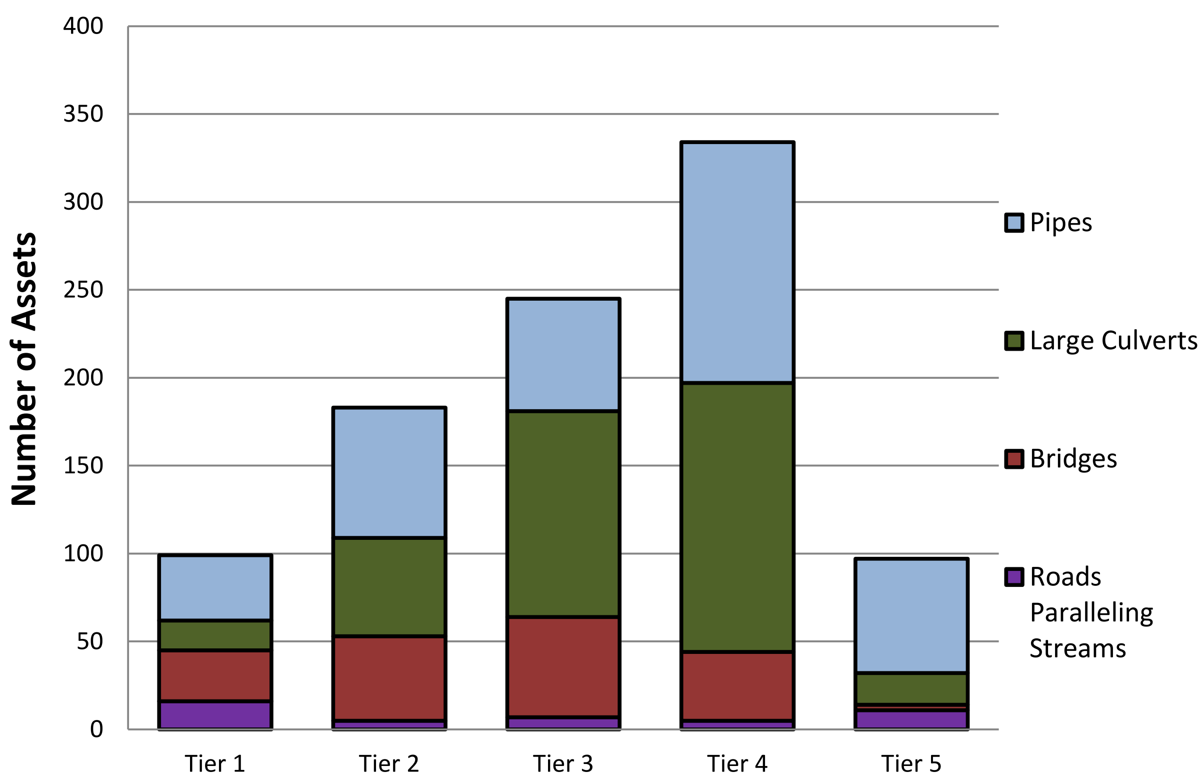


Figure 10: Vulnerability by Tier, District 6

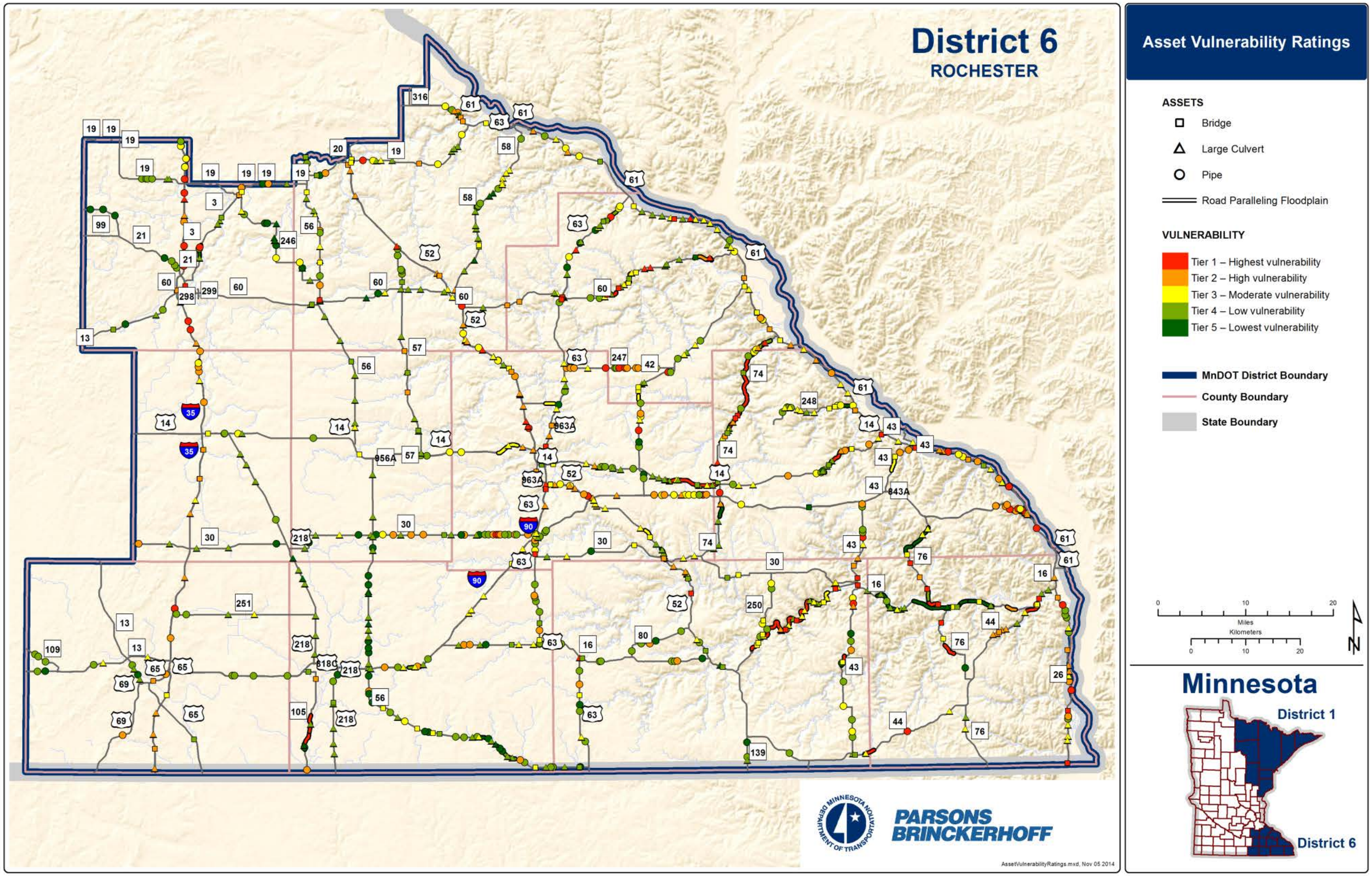


Figure 11: Asset Vulnerability Ratings, District 6

- **Asset management actions**
  - Gather data on waterway opening dimensions and other relevant variables that would be useful to future flood vulnerability assessments
  - Incorporate vulnerability assessment scores into asset management databases and the asset management plan
  - Update MnDOT's risk registers to reflect the vulnerability assessment

3 Facility Adaptation Assessments

Once potentially vulnerable facilities have been identified, the next step is to perform more detailed facility level assessments to better understand how those vulnerabilities will evolve as climate changes, develop adaptation options (if necessary), and test their cost-effectiveness. This study describes a process for undertaking facility level adaptation assessments and illustrates the application of that process through two case studies.

3.1 Selection of Assets

The selection of the two case study facilities was guided by the following criteria:

- The chosen facilities should have been found to be vulnerable to flooding in the system-wide vulnerability analysis and/or have been affected by flooding recently
- The cases should be illustrative of issues likely to be commonly encountered across the state
- Detailed hydrologic, hydraulic, and asset data must be available
- District 1 and District 6 should each have their own case study

With these criteria in mind, the project team worked with district staff to develop a short list of potential case study facilities. Case study selection meetings were then held in each district and the following facilities were chosen for evaluation:

- **District 1:** A large culvert (MnDOT number 5648) carrying MN 61 over Silver Creek located in the state's Arrowhead Region northeast of Two Harbors
- **District 6:** A large culvert (MnDOT number 5722) carrying US 63 over Spring Valley Creek in the town of Spring Valley, just south of Rochester

Both facilities fell into Tier 1 (highest vulnerability) in the system-wide vulnerability assessment. The chosen cases also offered dichotomies between a rural setting (the Silver Creek site) and a more urban one (the Spring Valley site) and whether the facility was one in which improvements are already programmed (the Silver Creek site) versus one in which no improvements are currently planned (the Spring Valley site).

3.2 Methodology

Engineering design practices for bridges, culverts, pipes and roads paralleling streams have traditionally been based on applying probabilistic values (e.g. return period storms) derived from statistical analysis of historic precipitation events. Climate change raises important questions about the validity of these traditional practices since rising temperatures will likely affect precipitation patterns, extreme storm recurrence intervals, and other conditions. There are significant questions on the timing of potential change, the rate of change, and the amount of change expected. In short there is a fair amount of uncertainty that needs to be considered as engineers design transportation facilities and consider what may be different into the future.

To address the need to consider possible climate changes and the uncertainties associated with them, the U.S. Department of Transportation (USDOT) developed a *General Process for Transportation Facility Adaptation Assessments* (the *Process*). The *Process* was developed for use on the USDOT's Gulf Coast Study, Phase 2 and distributed to adaptation pilot project grant recipients (including MnDOT) for use on the pilot projects. The description of the *Process* that follows in the remainder of this subsection has been excerpted from the Gulf Coast 2 Study's Task 3.2 Report[11] with the permission of USDOT. Some modifications to the text have been made to shorten the length of the description to better fit this document and provide examples relevant to MnDOT.

[11] USDOT, 2014

The *Process* provides an 11-step framework to consider climate change and identify the best methods for decision-making at the project level. The steps are generally as follows:

1. Describe the Site Context
2. Describe the Existing/Proposed Facility
3. Identify Climate Stressors that May Impact Infrastructure Components
4. Decide on Climate Scenarios and Determine the Magnitude of Changes
5. Assess Performance of the Existing/Proposed Facility
6. Identify Adaptation Option(s)
7. Assess Performance of the Adaptation Option(s)
8. Conduct an Economic Analysis
9. Evaluate Additional Decision-Making Considerations
10. Select a Course of Action
11. Plan and Conduct Ongoing Activities

Each of these steps is described in more detail below.

It should be noted that the *Process* is not intended to change specific current approaches to design. What the *Process* potentially does change, however, are, (1) the climate-related inputs used in the design methodology, (2) the number and type of design options one develops, and (3) how the final option is chosen to provide a cost-effective and resilient improvement to the transportation network.

3.2.1 Step 1—Describe the Site Context

The first step involves developing and defining a thorough understanding of the site context. The site's context is key to determining the appropriateness of various adaptation options considered in subsequent steps. Some of the important issues to be identified in this step include:

- Characteristics of the surrounding land uses, population, economic activities and significant environmental or community resources
- Existing performance of the facility including information such as volumes/ridership, fleet mix, and role in network continuity
- Characteristics of the surrounding topography and hydrography
- The function that the facility will serve within the broader transportation network, both in the near term and in the future (e.g., evacuation route or critical network link)

3.2.2 Step 2—Describe the Existing/Proposed Facility

This step involves developing detailed knowledge on the existing or proposed facility to be studied. This knowledge is critical to developing appropriate and effective adaptation options in subsequent steps. Key information that should be gathered includes: location, functional purpose, design type, dimensions, elevations, proposed/remaining design life, age/condition, and design criteria.

3.2.3 Step 3—Identify Climate Stressors That May Impact Infrastructure Components

This step involves documenting the climate-related variables typically considered in the planning and design of the type of facility being investigated. The design standards associated with these variables, if applicable, should also be noted (e.g., a policy that all bridges and their approaches must be designed to pass the 50-year storm without overtopping). For many facilities, there could be multiple climate stressors relevant to designers that should be considered.

3.2.4 Step 4—Decide on Climate Scenarios and Determine the Magnitude of Changes

After the climate-related variables that affect the facility have been identified in Step 3, the next step is to use climate model projections (or proxies if unavailable) to determine whether and how much each of the variables of concern may change in the future. The information gathered for each variable should, if possible, relate to the design standards identified in Step 3. Recognizing the uncertainty inherent in climate projections, a scenario-based approach is recommended, involving generating a variety of climate scenarios to capture the range of possible future values of each climate variable.

After gathering the climate projections and considering the full range of potential climate changes, it might be determined that none of the climate variables are expected to change significantly or in a way that would potentially threaten the facility. If this is the case, then the assessment is complete and no further climate adaptation analysis is required at this time.

3.2.5 Step 5—Assess Performance of the Existing/Proposed Facility

The purpose of this step is to ascertain whether the facility is currently operating effectively and whether it would be expected to continue to do so under each of the possible future climate scenarios selected in Step 4. The standards by which performance is assessed can vary depending on the asset being studied. Whenever possible, however, performance should be assessed against the design standards tied to the climate variables of interest that were noted in Step 3. For example, if a bridge and its approaches were required not to overtop during the 50-year storm, one would test each scenario's 50-year storm to determine if it overtops the facility.

At the conclusion of Step 5, it is possible that the facility is found to perform adequately under the full range of potential climate changes that it could experience throughout its intended design life: if this is the case, no further analysis is necessary at this time and the assessment is complete.

3.2.6 Step 6—Identify Adaptation Option(s)

Adaptation options should be identified for each scenario that does not meet design expectations as determined in Step 5. The adaptation options could be planning or design-oriented; in many cases, the best adaptation may be to avoid a hazardous area altogether rather than to design an engineered solution.

In general, at least one adaptation option should be identified for each climate scenario selected. These options then become the basis for analyzing performance and decision-making. Adaptation options could consist of either one action (raising a bridge) or a package of actions that address a climate stressor or set of climate stressors (e.g. raising a bridge and armoring the approach embankments). Each option should be developed so that applicable design standards are met under the given scenario realizing that, as is the case with such standards generally, some exceptions may be necessary based on unique site constraints.

Note that there are likely to be multiple possible ways to achieve design standards under any given scenario (e.g., to accommodate higher flows through a culvert, one could add additional culvert cells or convert the culvert to a bridge): it is up to the project team to decide on how many options to develop and test. Whatever approach is chosen, a high-level cost estimate to construct and maintain each adaptation option should be developed. This will be used in the economic analysis in Step 8.

3.2.7 Step 7—Assess Performance of the Adaptation Option(s)

This step involves assessing the performance of each adaptation option under each potential climate change scenario selected in Step 4. This analysis is similar to Step 5 except that it is performed on the adaptation options as opposed to the existing facility or, in the case of new facilities, the standard design without adaptations. The key determination is whether each adapted facility satisfies its mandated performance standard (e.g., a 50-year design storm for a culvert) under each scenario.

3.2.8 Step 8—Conduct an Economic Analysis

An economic analysis is of great value to informing decision-making on project level adaptation assessments. The analysis enables one to determine how the benefits of undertaking a given adaptation option, defined as the costs avoided[12] with adaptation, compare to its incremental costs under each of the possible future scenarios developed in Step 4. The basic technique involves estimating the expected impact costs from climate or weather events over the life of the facility and discounting them to determine the present value of these expected costs. This is done for the base case of the existing facility or standard new design and repeated for each adaptation option under each climate change scenario selected in Step 4. The (lower) costs with the adaptation options in place can then be compared to the base case costs to determine the cost savings expected as a result of adaptation. The net present value and/or the benefit-cost ratio of each adaptation option can then be computed and compared amongst the adaptation options. The results can be presented in tables showing each adaptation option's cost-effectiveness under each scenario.

Decision-makers can then look for (1) adaptation options that have benefit-cost ratios greater than one and (2) the adaptation option that performs best across the full range of scenarios tested (the robust option). It should be noted that the economic analysis does not in and of itself always provide an answer as to whether an adaptation option makes financial sense. There is no guarantee that an adaptation option that performs cost-effectively under each scenario will exist: an option may be cost-effective under one scenario but not another. Likewise, there may be no single adaptation option that is the most robust economic performer across all scenarios. In every case, but in these cases especially, trade-offs will have to be made and the community's and/or facility owner's risk tolerance evaluated to help choose the "best" option from a financial standpoint. Ultimately, because of the uncertainty involved in knowing what climate scenario will actually occur, determining the "best" option financially is often subjective and based on the decision-maker's appetite for risk.

3.2.9 Step 9—Evaluate Additional Decision-Making Considerations

As in other areas of transportation decision-making, the cost-effectiveness of adaptation options is not the only factor important to making wise investment decisions. Other factors that can be difficult to monetize (for benefit/cost analysis) should also be considered before a final decision is reached. These may include: broader project sustainability, project feasibility and practicality, ongoing maintenance needs, capital funds availability, and stakeholders' tolerance for risk of service interruption and associated costs of all types.

3.2.10 Step 10—Select a Course of Action

Once as much information as possible has been gathered on both economic and non-economic factors, decision-makers should weigh the information presented and decide on a course of action. Those involved should keep in mind that adaptation does not always make sense from a financial feasibility or community acceptance standpoint and a decision to take no action may be justified in some cases.

3.2.11 Step 11—Plan and Conduct Ongoing Activities

Once a decision has been made on a course of action, a management plan for the facility should be developed. At a minimum, the management plan should contain an element of monitoring to determine if the facility is performing as expected over time. If an adaptation option was used, estimates of the costs saved from

[12] Costs avoided might include the costs of damage to the facility, clean-up costs, costs to the traveling public due to detours and delays, death and injury costs, costs to businesses and others dependent on the transportation facility, potential costs to surrounding land uses from impacts generated by the facility (e.g., an undersized culvert resulting in upstream flooding that affects neighboring properties), and, potentially, environmental impacts generated by the facility (e.g., a coastal causeway that prevents marsh migration inland as sea levels rise).

implementing the adaptation could be developed so that the benefits of the adaptation are documented and compared to its costs. This information could prove beneficial in future years as the community continues to make decisions on which adaptations, if any, make sense in various situations.

3.3 Case Studies

This subsection presents the analysis and findings from the two case studies. The Silver Creek site is presented first followed by the Spring Valley Creek site. The case study descriptions are organized around the steps in the *Process* illustrating how it can be applied in practice.

3.3.1 MN 61 Culvert (#5648) over Silver Creek

This case study provides an example of a facility level assessment for a previously planned replacement project. The subject facility, Culvert 5648, has been designated for replacement in 2018 in the Draft 2015-2018 State Transportation Improvement Program (STIP).[13]

Application of the General Adaptation Process for Engineering

Step 1—Describe the Site Context

Culvert 5648 carries MN 61 over Silver Creek and is located northeast of Two Harbors and immediately adjacent to Lake Superior. MN 61 is an important state highway and link in the National Highway System that runs from Duluth to the Canadian border and connects the city of Thunder Bay, Ontario to the Midwestern United States. The road is also a critical link to tourist destinations along Lake Superior and in the Superior Uplands and Boundary Waters regions. Average annual daily traffic (AADT) at the facility is currently 5,900 vehicles per day and heavy commercial average daily traffic (HCADT) is currently 500 trucks per day. Figure 12 shows the location of the culvert.

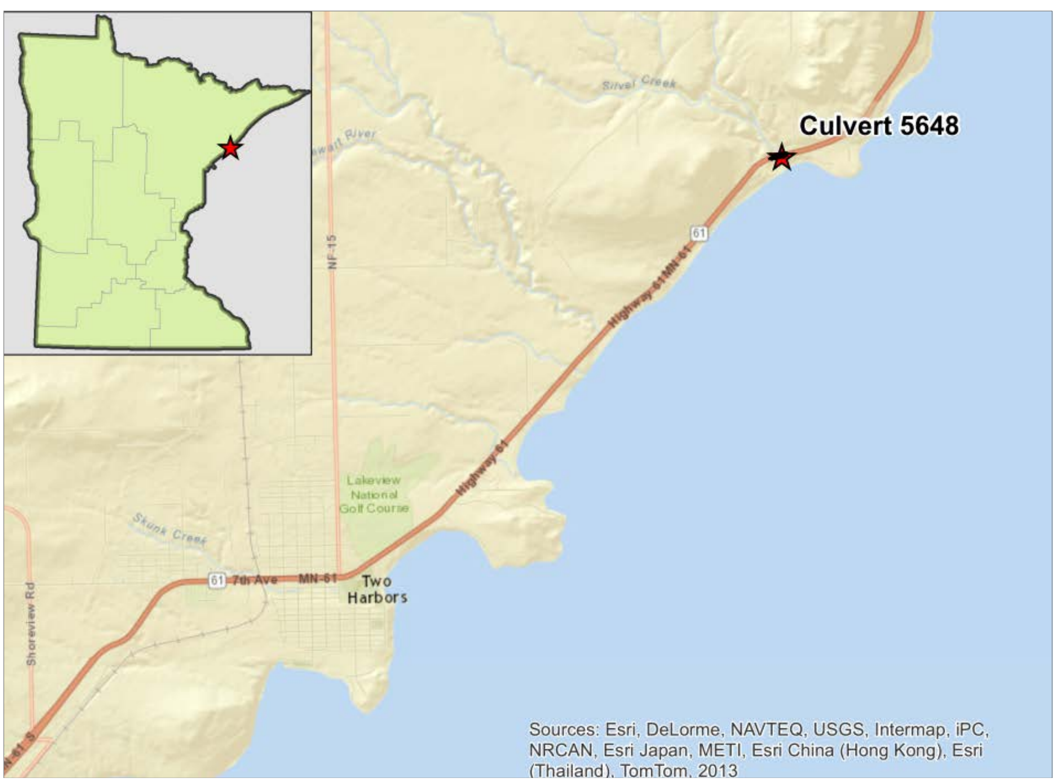


Figure 12. Location of Culvert 5648

[13] MnDOT, 2014b

Hydrologic Setting

Silver Creek is a stream coming off the Superior Uplands that discharges into Lake Superior near Culvert 5648. Figure 13 shows the drainage area for water flowing to the culvert. The total drainage area to the culvert is 19.65 square miles. The segment upstream of the culvert is a natural channel with steep slopes.

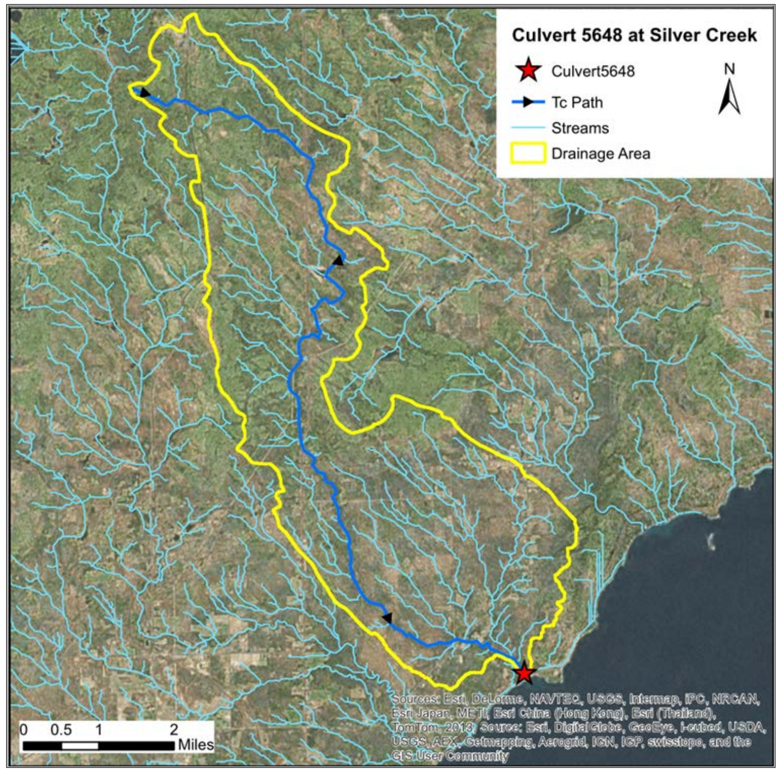


Figure 13: Drainage Area to Culvert 5648 Showing Time of Concentration (Tc) Path

Note: The Tc path line shown denotes the path used to compute the time of concentration for this facility. Time of concentration is the time needed for water to flow from the most hydrologically remote point of the drainage area to the discharge point of the drainage area.

Step 2—Describe the Existing Facility

Culvert 5648 has two cells —each having a 10 foot span (width) by 10 foot rise (height). The longitudinal length of the culvert is approximately 90 feet. Built in 1936, the culvert is at the end of its useful life. A 2013 inspection report[14] describes the presence of cracks and spalling with exposed rebar on the culvert barrel. In addition, the culvert headwall[15] is heavily cracked and the southeast wing wall[16] is detached and lying in the channel bed. The slope of the cells was estimated to be 0.8 percent based on information derived from the as-built plans. Figure 14 shows a plan view of the culvert crossing and its proximity to Lake Superior and Figure 15 and Figure 16 show ground level photos of the culvert.

Step 3—Identify Environmental Factors That May Impact Infrastructure Components

Precipitation (and the resulting stream flow) is the primary environmental factor affecting culvert design that is expected to be affected by climate change and is the focus of this study.

Step 4—Decide on Climate Scenarios and Determine the Magnitude of Changes

It is generally believed that precipitation intensity levels will go up over time with climate change, since a warmer atmosphere is capable of holding more water vapor. Three future precipitation scenarios were considered for this adaptation assessment based on projected climate changes. The projections of future climate were developed using outputs from global climate models (GCM) that were translated to projections for the nearest weather station to Culvert 5648 using a software tool called SimCLIM. GCMs are computer models of the Earth's climate system calibrated to historic climate conditions. Future climate projections are developed by feeding plausible scenarios of future greenhouse gas emissions into the models and observing the impacts on climate variables like temperature and precipitation.

[14] MnDOT, 2013b
[15] The headwall is the wall at either end of the culvert, perpendicular to the stream.
[16] The wing walls are the walls leading diagonally up to the culvert entrance or away from its outlet.

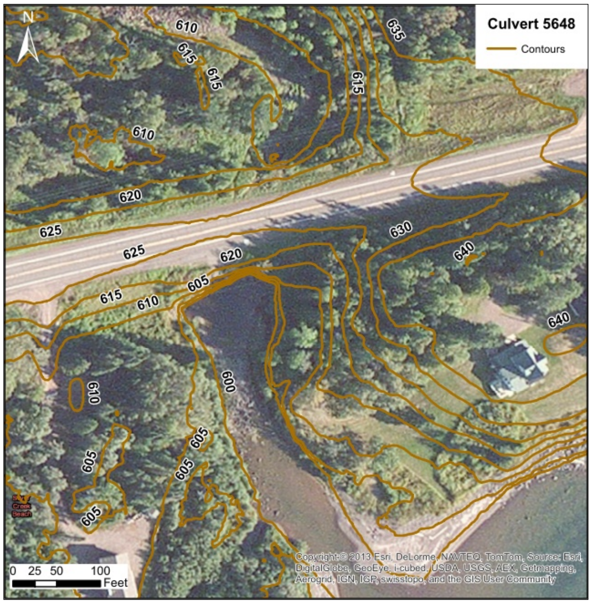


Figure 14: Plan View of Culvert 5648 Showing Elevation Contours

Figure 15: Photo of Culvert 5648, Upstream Side

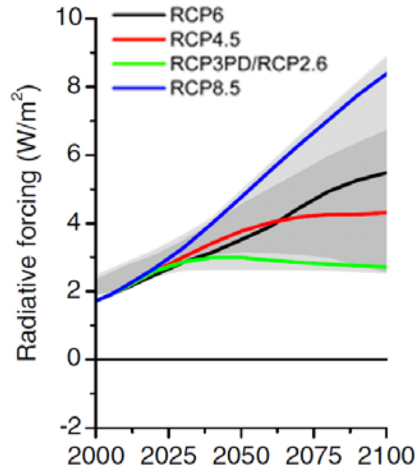
Figure 16: Photo of Culvert 5648, Downstream Side

The three greenhouse gas emissions scenarios used in this study were selected to bound the range of possible future climate conditions. The scenarios pivot off the future emission trajectories, known as representative concentration pathways (RCP), that were used in the United Nations' Intergovernmental Panel on Climate Change's (IPCC) 5th Assessment Report (AR5) [17] on climate science. The specific scenarios included:

- **Low emissions scenario:** RCP4.5
- **Medium emissions scenario:** RCP6.0
- **High emissions scenario:** RCP8.5

[17] IPCC, 2013

An even lower emissions scenario, RCP2.6, was considered for the analysis but the CAC felt this scenario was highly optimistic and therefore unlikely to actually occur. Figure 17 provides a graph showing the assumed radiative forcing [18] levels throughout the remainder of this century under the three RCPs used on this project and RCP2.6. The higher the radiative forcing values, the more warming occurs.



Source: IPCC, 2014

Figure 17: RCP Radiative Forcing Assumptions

With respect to GCMs, dozens of research institutions have developed their own models, each with a slightly different take on how the Earth's climate system functions. Thus, for any given emissions scenario, each individual climate model will produce a somewhat different precipitation projection. A total of 22 GCMs were queried in this study to provide a broad perspective on the range of possible future conditions. [19] Using the SimCLIM software tool, the range of GCM outputs for each scenario was developed and the median output from that range used to provide the precipitation values employed in this analysis.

All three scenarios considered 24-hour precipitation depths; the storm duration most relevant to the watershed being studied and one readily generated from climate models. Storm return periods [20] analyzed included the two-, five-, 10-, 25-, 50-, 100-, and 500-year events. Projections were obtained for three time periods through the year 2100, the anticipated end of the facility's design life.

When designing culverts using rainfall runoff models, current practice is to use precipitation frequency statistics developed from historical data by the National Oceanographic and Atmospheric Administration (NOAA) [21] on their Atlas 14 project. It was recognized during the course of this study that, due to differences in statistical techniques, there is a discrepancy in current precipitation depths between NOAA Atlas 14 and values derived from the climate models. To correct for this bias, instead of using the raw precipitation depths directly from the climate models, the percentage change in precipitation levels between the modeled present day conditions and those in the future were recorded and those percentage changes applied to the official NOAA Atlas 14 values.

Table 4 through Table 6 show the projected precipitation levels for the drainage area of Culvert 5648 under the low, medium, and high scenarios. The current NOAA Atlas 14 value is also shown for reference in each case. The NOAA value used was derived from a frequency analysis of the annual maxima series at the centroid of the watershed. The projected data, used to the scale the NOAA values, was obtained for the Two Harbors weather station (located approximately four miles from the culvert). The range of 24-hour precipitation values for each scenario and return period are also shown in the tables along with the percent change between observed and projected precipitation depths.

Step 5—Assess Performance of the Existing Facility

Assessing the performance of a culvert first requires detailed hydrologic and hydraulic modeling of the watershed in the vicinity of the facility to understand expected peak flows. These peak flows can then be used to evaluate the culvert's performance relative to its design standards.

[18] Radiative forcing is a measure of the Earth's greenhouse effect and refers to the amount of solar energy radiated off the surface that is captured by the atmosphere and leads to warming.
[19] The specific models used include ACCESS1-3, CanESM2, CCSM4, CESM1-BGC, CMCC-CM, CMCC-CMS, CNRM-CM5, CSIRO-Mk-3-6, GFDL-ESM2G, GFLDL-ESM2M, HadGEM2-ES, INMCM4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC-ESM, MIROC-ESM-CHEM, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, and NorESM1-M.
[20] A return period, or recurrence interval, is defined as the inverse of the probability of occurrence for a flood event in a given year; i.e., a 100-year storm would be a storm that has a one percent chance of occurring during any given year.
[21] Note that some culverts, particularly large ones, are also designed using U.S. Geological Survey regression equations.

Table 4: 24-Hour Precipitation Depths at Culvert 5648, Low Scenario

24-Hour Storm Return Period	Atlas 14 Precipitation Depth (in)[1]	Low Scenario Precipitation Depth (in)					
		2040		2070		2100	
		% Increase	Depth	% Increase	Depth	% Increase	Depth
2-year storm	2.48	3.08%	2.56	4.72%	2.60	5.48%	2.62
5-year storm	3.26	3.12%	3.36	4.77%	3.42	5.55%	3.44
10-year storm	3.89	3.22%	4.02	4.93%	4.08	5.74%	4.11
25-year storm	4.8	3.43%	4.96	5.25%	5.05	6.11%	5.09
50-year storm	5.53	3.63%	5.73	5.55%	5.84	6.46%	5.89
100-year storm	6.31	3.85%	6.55	5.90%	6.68	6.86%	6.74
500-year storm	8.26	4.47%	8.63	6.85%	8.83	7.96%	8.92

[1] *Source: NOAA, 2014b*

Table 5: 24-Hour Precipitation Depths at Culvert 5648, Medium Scenario

24-Hour Storm Return Period	Atlas 14 Precipitation Depth (in)[1]	Medium Scenario Precipitation Depth (in)					
		2040		2070		2100	
		% Increase	Depth	% Increase	Depth	% Increase	Depth
2-year storm	2.48	4.57%	2.59	7.60%	2.67	10.81%	2.75
5-year storm	3.26	4.63%	3.41	7.69%	3.51	10.95%	3.62
10-year storm	3.89	4.78%	4.08	7.95%	4.20	11.33%	4.33
25-year storm	4.8	5.09%	5.04	8.46%	5.21	12.05%	5.38
50-year storm	5.53	5.38%	5.83	8.95%	6.02	12.75%	6.23
100-year storm	6.31	5.72%	6.67	9.51%	6.91	13.55%	7.16
500-year storm	8.26	6.64%	8.81	11.04%	9.17	15.73%	9.56

[1] *Source: NOAA, 2014b*

Table 6: 24-Hour Precipitation Depths at Culvert 5648, High Scenario

24-Hour Storm Return Period	Atlas 14 Precipitation Depth (in)[1]	High Scenario Precipitation Depth (in)					
		2040		2070		2100	
		% Increase	Depth	% Increase	Depth	% Increase	Depth
2-year storm	2.48	8.51%	2.69	17.33%	2.91	25.90%	3.12
5-year storm	3.26	8.62%	3.54	17.57%	3.83	26.29%	4.12
10-year storm	3.89	8.91%	4.24	18.17%	4.60	27.18%	4.95
25-year storm	4.8	9.48%	5.26	19.34%	5.73	28.93%	6.19
50-year storm	5.53	10.03%	6.08	20.45%	6.66	30.60%	7.22
100-year storm	6.31	10.66%	6.98	21.74%	7.68	32.54%	8.36
500-year storm	8.26	12.37%	9.28	25.26%	10.35	37.89%	11.39

[1] *Source: NOAA, 2014b*

Hydrologic Modeling

Peak flows through the culvert were modeled for various storm events (two-, five-, 10-, 25-, 50-, and 100-year storms) and climate scenarios using the U.S. Department of Agriculture (USDA)-Natural Resources Conservation Service (NRCS) WinTR-20 program.[22] The TR-20 program utilizes NRCS hydrologic analysis methodology to calculate runoff using the following inputs: drainage area, land cover, soils, time of concentration, and precipitation.

Land cover can be expected to change over the period of analysis as land development occurs in the drainage area. Analysis of both existing and future land cover conditions was necessary to evaluate current flows and predicted future flows at Culvert 5648. Existing land cover was obtained from the latest (2011) National Land Cover Dataset (NLCD). Future land cover assumed a build-out of current zoning. This was accomplished by reclassifying the Lake County zoning districts within the drainage area to match the classifications of NLCD 2011 as summarized in Table 7.

Table 7: Translation between Lake County Zoning Districts and NLCD Classifications

Zoning Code	Zoning Code Meaning	NLCD Class
R-1	Residential 10 acre minimum lot, 300’ minimum lot width.	Developed, Open Space[1]
R-2	Residential 5 acre minimum lot , 200’ minimum lot width.	Developed, Open Space
R-3	Residential 2.5 acre minimum lot, 200’ minimum width.	Developed, Open Space
R-4	Residential 2 acre minimum lot size, 200’ minimum width.	Developed, Open Space

[1] Developed, Open Space areas include some structures, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.

When developing the future land cover assumptions, attention was paid to the runoff curve numbers[23] for each land cover type. If the curve number of the existing land cover was higher than that of the potential future land use, a conservative assumption was made to maintain the existing land cover classification. Overall, throughout the drainage area, the existing land cover resulted in a curve number (CN) value of 75, while the future land use had an increase of 2.1 for a final value of 77. The observed precipitation depths were run utilizing existing land use conditions, while the derived precipitation depths were run with the future land cover to determine the corresponding peak flows.

The time of concentration was calculated following the longest flow path from the most distant boundary of the watershed to the point of interest. A time of concentration value of approximately nine hours was used for existing and future condition models.

The hydrologic analysis also considered a range of temporal rainfall distributions for the evaluation of flows at the culvert to determine the appropriate values. The rainfall distribution selected was the NOAA temporal distribution for the 24-hour duration storm corresponding to the study area.

Table 8 shows the model outputs comparing current peak flows to projected future peak flows. In order to validate the model results, a comparison was performed between the existing condition TR-20 model discharges and the regional regression estimates developed by USGS.[24] These regional regression curves are applicable to non-urban areas statewide with drainage areas between one and 43 square miles. Since the regression equations are empirically derived and regionally specific, they provide a reasonable basis for calibration of the theoretical model.

[22] USDA-NRCS, 2009

[23] Curve numbers are a numeric approximation of a soil and land cover combination’s ability to produce overland runoff. The numbers range from a high end of 100, where all precipitation will be transferred to overland runoff, to a low end of near zero, which represents a condition where no overland runoff will be created.

[24] Lorenz, Sanocki, and Kocian, 2010

Table 8: TR-20 Projected Peak Flows at Culvert 5648

24-Hour Storm Return Period	Existing Discharges (cfs)	Low Scenario Discharges			Medium Scenario Discharges			High Scenario Discharges		
		2040 (cfs)	2070 (cfs)	2100 (cfs)	2040 (cfs)	2070 (cfs)	2100 (cfs)	2040 (cfs)	2070 (cfs)	2100 (cfs)
2-year storm	770	1070	1100	1120	1090	1160	1230	1180	1370	1550
5-year storm	1350	1760	1810	1830	1800	1900	2000	1930	2190	2460
10-year storm	1880	2360	2420	2450	2420	2540	2660	2580	2920	3250
25-year storm	2690	3260	3350	3390	3340	3500	3670	3550	4010	4460
50-year storm	3370	4010	4120	4170	4113	4300	4500	4360	4920	5480
100-year storm	4140	4810	4940	5000	4930	5170	5420	5240	5940	6610
500-year storm	6090	6870	7060	7150	7040	7410	7800	7520	8590	9630

Hydraulic Modeling and Performance of the Existing Culvert

Hydraulic culvert analyses were conducted to evaluate the performance of Culvert 5648 under current and future peak flows using a HEC-RAS model developed using elevations derived from LIDAR data. Since the hydraulic performance of a culvert depends on its design, an assumption had to be made regarding the likely design of the planned replacement culvert to be built in 2018. When conducting an analysis of a new facility or a facility planned for replacement, the base case design for the analysis should be whatever design would most likely be implemented if climate change were not being considered and only historical data were to be used for engineering the facility.

If the existing facility meets current design criteria, the base case can be to simply replace the existing facility in kind. Current MnDOT design criteria state that, for a large culvert over a non-navigable waterway, a three feet minimum clearance (freeboard) between the 50-year flood stage and the low point on the large culvert is desirable in many cases. [25] The actual clearance requirements, however, are determined on a case by case basis. Additional criteria state that the allowable headwater must be non-damaging to upstream property, be non-damaging to the roadway, meet stage increase criteria set forth by regulatory agencies, and should not cause disruption to traffic flow. In addition, if velocity is six feet per second or greater at the outlet a check should be made that scour will not occur. If scour may occur, outlet protection should be provided. For culverts located on public waters where fish passage has been identified as an issue, the culvert velocity should be consistent with the natural channel velocity at the two year event or be two feet per second or less.[26]

Culvert 5648 meets the MnDOT allowable headwater depth design criteria for passing the 50-year storm without overtopping, however, the existing culvert design does not comply with current fish passage requirements. In addition, velocities at the culvert exit are much higher than the velocities in the natural channel creating a scour pool at the culvert exit. Due to these deficiencies, it was decided that the existing culvert would most likely not be replaced-in-kind even if climate change were not considered. Thus, a base case culvert design was developed that addresses the velocity issues and fish passage requirements.

The base case design, a cross-section of which is shown in Figure 18, involves replacement of the existing culvert structure with a two-cell culvert having a 14-foot span (width) by 14 foot rise (height). The estimated cost for this design is $710,000. Both culvert cells were designed to be sunk two feet into the stream bed to comply with the fish passage provision. The amount that a culvert is buried will vary at each site. In areas

[25] MnDOT, 2013a
[26] MnDOT, 2000

without fish passage issues, culverts are not buried while in areas where fish passage is important culverts are buried one foot or more.

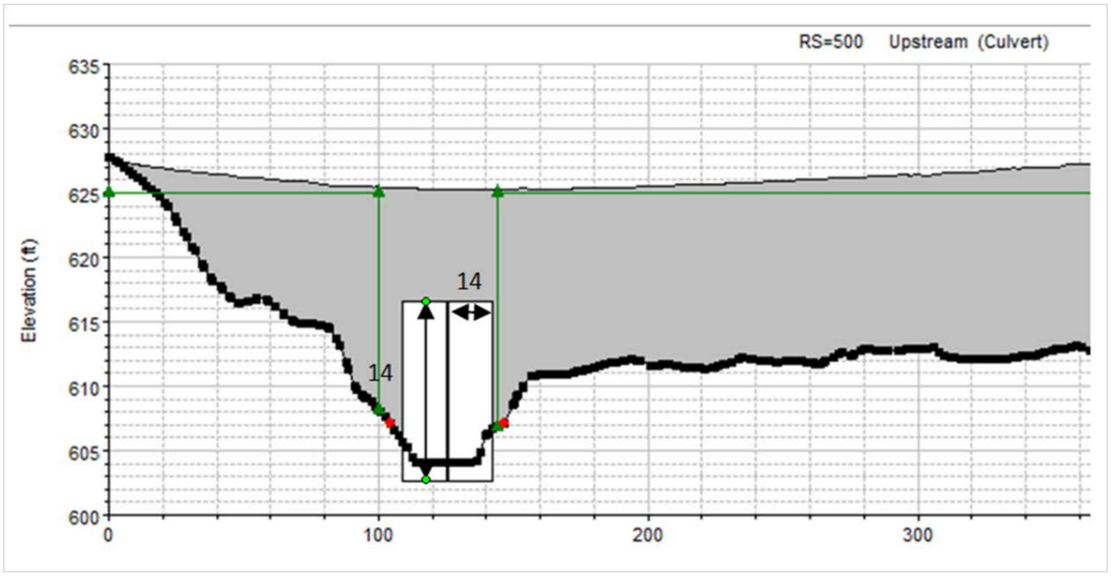


Figure 18: Upstream Cross-Section of the Base Case Design for Culvert 5648

Figure 19 provides a stage-discharge curve (a graphic representation of headwater elevations[27] at different flow levels) for the base case design. The curve shows that that MnDOT 50-year storm allowable headwater depth design criterion for culverts is readily met under current climate. The curve also illustrates that the three foot freeboard requirement is met by the base case design for both the low and medium climate scenarios. However, some of the additional design criteria such as velocities and prevention of damage to the roadway are not met under these climate scenarios so a series of adaptation options were developed that were capable of handling projected flows.

Step 6—Develop Adaptive Design Options

Since the existing structure does not meet the design criteria under all climate scenarios, adaptation alternatives were developed. Adaptation options were developed taking into consideration the different climate scenarios discussed in Step 5. The designs were based on year 2100 peak flow projections so that the facility would uphold design criteria throughout its assumed 75 to 100 year lifespan.

Option One

Option One is optimized to meet design criteria for the low climate scenario in 2100. It involves replacement of the existing culvert with a two-cell 16 foot span (width) by 14 foot rise (height) culvert. This assumes the culvert will be sunk into the stream bed two feet; thus, the water opening height will be 12 feet. Figure 20 provides a cross-section of the Option 1 design.

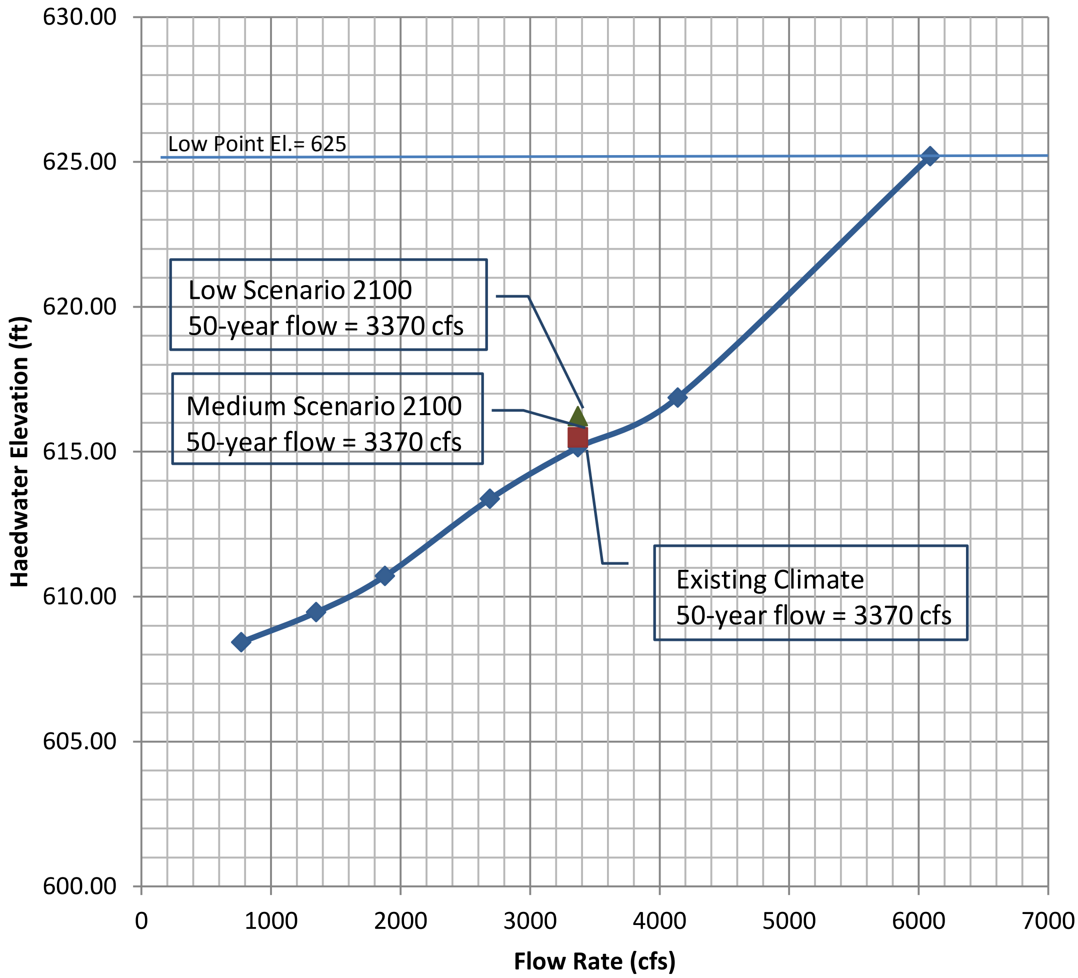
The work as estimated includes:

- Traffic control
- Riprap for the outfall scour pool
- Erosion control and stream diversion
- Guardrail
- Demolition , excavation, and structural backfill
- New culvert cells and culvert end section

[27] Headwater elevation is the level of water immediately upstream of the inlet (upstream end) of a culvert or any other conduit.

- Pavement restoration

The estimated project cost is $770,000.



Note: Headwater elevation is the level of water immediately upstream of the inlet (upstream end) of a culvert or any other conduit.

Figure 19: Stage-Discharge Curve for the Base Case Design for Culvert 5648

Option Two

Option Two is optimized to meet design criteria for the medium climate scenario in 2100. Although a larger culvert design would likely be feasible, after discussions with District 1 staff, it was revealed that there is pressure to convert culverts along MN 61 to bridges to further improve fish passage beyond what a culvert can provide. Thus, this option includes the replacement of the existing culvert with a 52 foot simple span bridge. The bridge would have abutments with a one percent slope on both sides. For the bridge model, the roadway alignment was assumed to remain the same as the current culvert.[28] Due to the length of the bridge span, the deck depth is three feet. The design follows MnDOT bridge design criteria for crossings of non-navigable waterways. Figure 21 provides a cross-section of the Option 2 design.

[28] It is likely that the road alignment might need to change somewhat in order to maintain traffic flow during construction, however, any minor changes to the alignment are not expected to result in major changes to the hydraulic performance measures presented in this study.

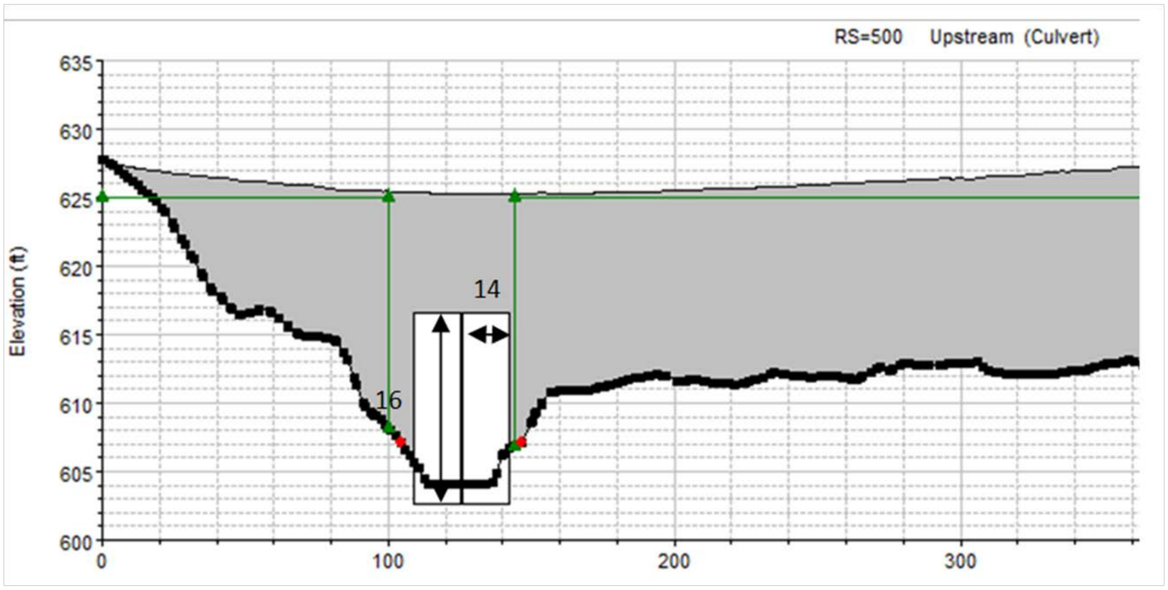


Figure 20: Upstream Cross-Section of Design Option 1 for Culvert 5648

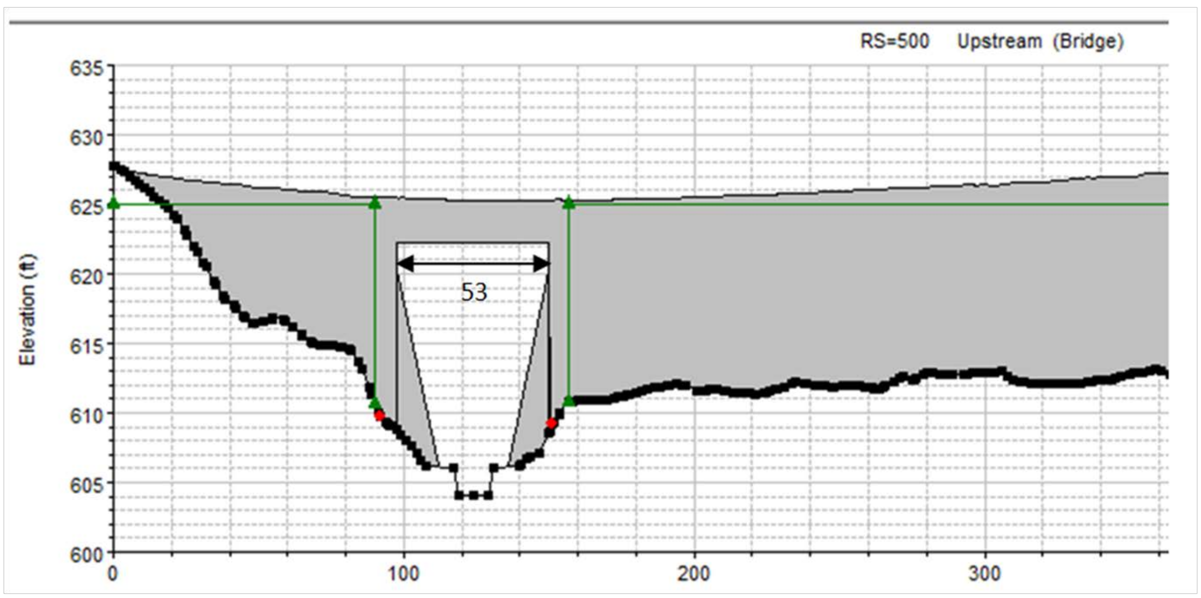


Figure 21: Upstream Cross-Section of Design Option 2 for Culvert 5648

The work as estimated includes:

- Traffic control
- Riprap for abutment protection
- Erosion control and stream diversion
- Demolition , excavation, and structural backfill
- Guardrail
- New 52 foot simple span bridge

The estimated project cost is $1,130,000.

Option Three

Option Three is optimized for the high climate scenario in 2100. In keeping with the emerging practice of replacing culverts with bridges to satisfy fish passage requirements, it includes the replacement of the existing culvert with a 57 foot simple span bridge. Similar to Option Two, the bridge would have abutments with a one percent slope on both sides and the roadway alignment is assumed to be the same as the existing facility. Due to the length of the bridge span, the deck depth is 3.4 feet. Figure 22 provides a cross-section of the Option 3 design.

The work as estimated includes:

- Traffic control
- Riprap for abutment protection
- Erosion control and stream diversion
- Demolition , excavation, and structural backfill
- Guardrail
- New 57 foot simple span bridge

The estimated project cost is $1,210,000.

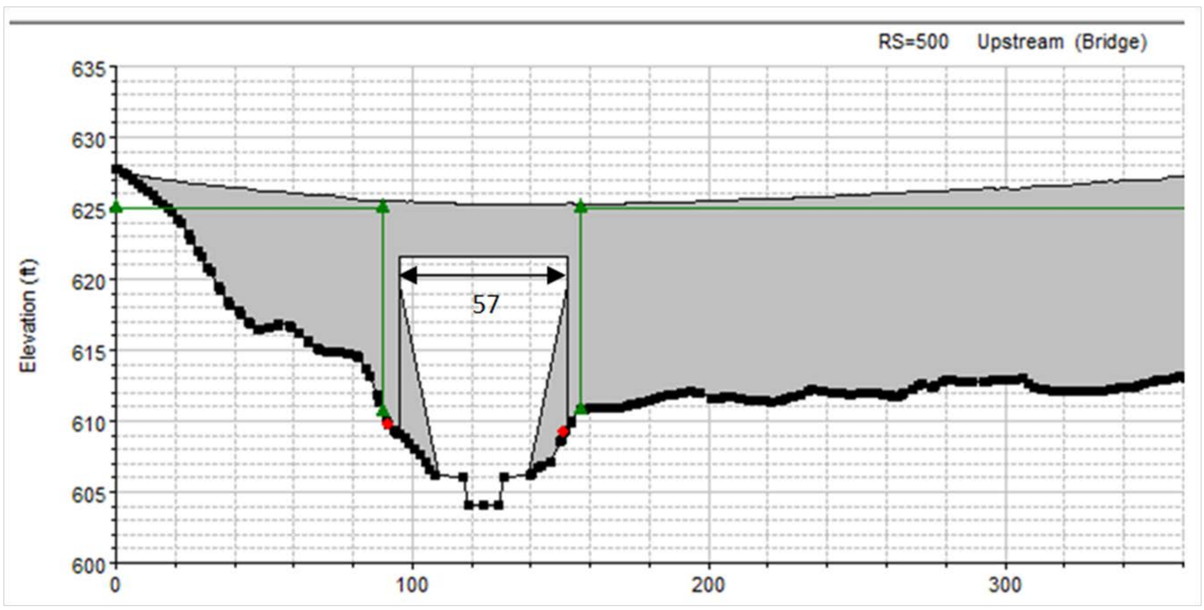


Figure 22: Upstream Cross-Section of Design Option 3 for Culvert 5648

Step 7—Assess Performance of the Adaptive Design Options

The degree of flooding was analyzed for each adaptive design option using the 50-year storm event under each climate scenario. The degree of flooding is an important input for the benefit-cost analysis that allows impacts to be quantified across the scenarios and adaptation options.

Figure 23 shows the stage-discharge curves for the different adaptation options along with the base case curve. These curves illustrate the performance of each option under the range of flows that could be experienced with the climate change scenarios studied. Each of the adaptation options prevents overtopping of the roadway at the 50-year flow rate under the climate scenarios they were designed to accommodate. The three foot freeboard requirement is also met in each instance with the exception of Option 3 which passes the 50-year storm with only about one foot of freeboard.

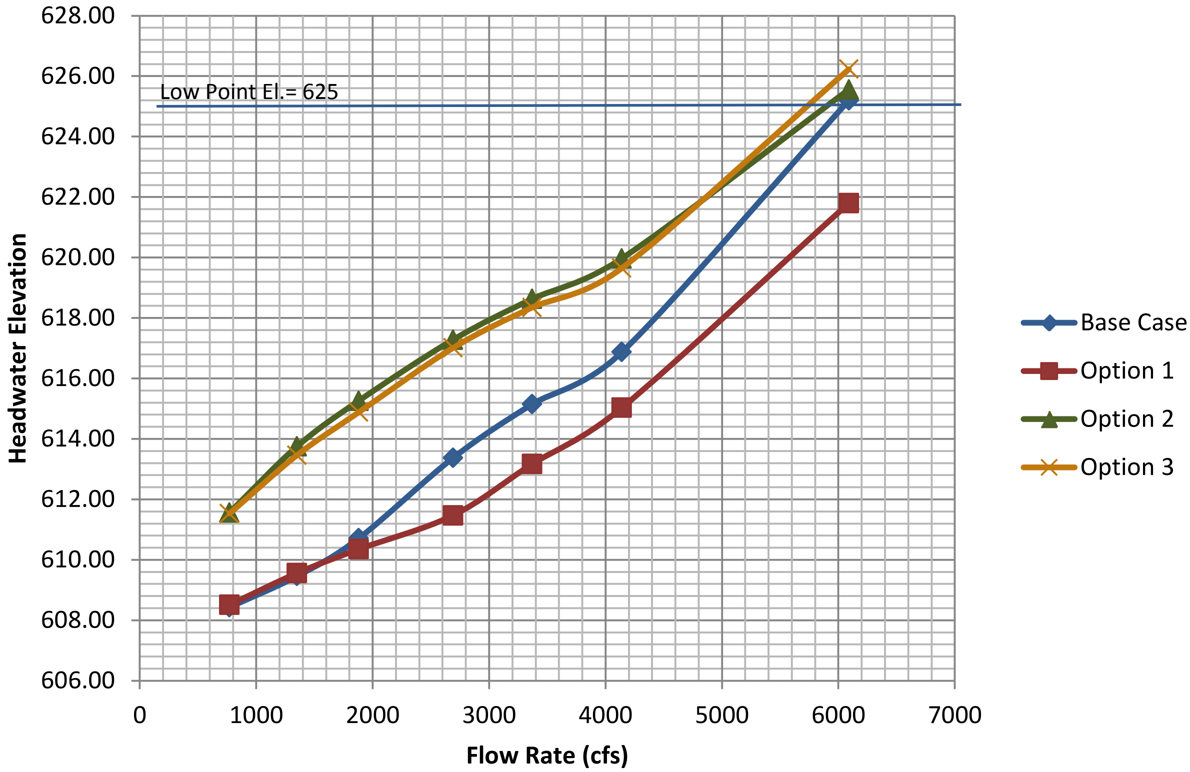


Figure 23: Stage-Discharge Curves for the Culvert 5648 Adaptation Options

Step 8—Conduct an Economic Analysis

An economic analysis was performed to determine which adaptation option, if any, would be most cost-effective under the range of possible climate scenarios evaluated. The analysis was undertaken using a software tool called COAST. COAST was initially developed with funding from the U.S. Environmental Protection Agency at the University of Southern Maine, for the purposes of furthering the development of benefit-cost analysis of climate adaptation actions, based on user-specified scenarios of climate change.

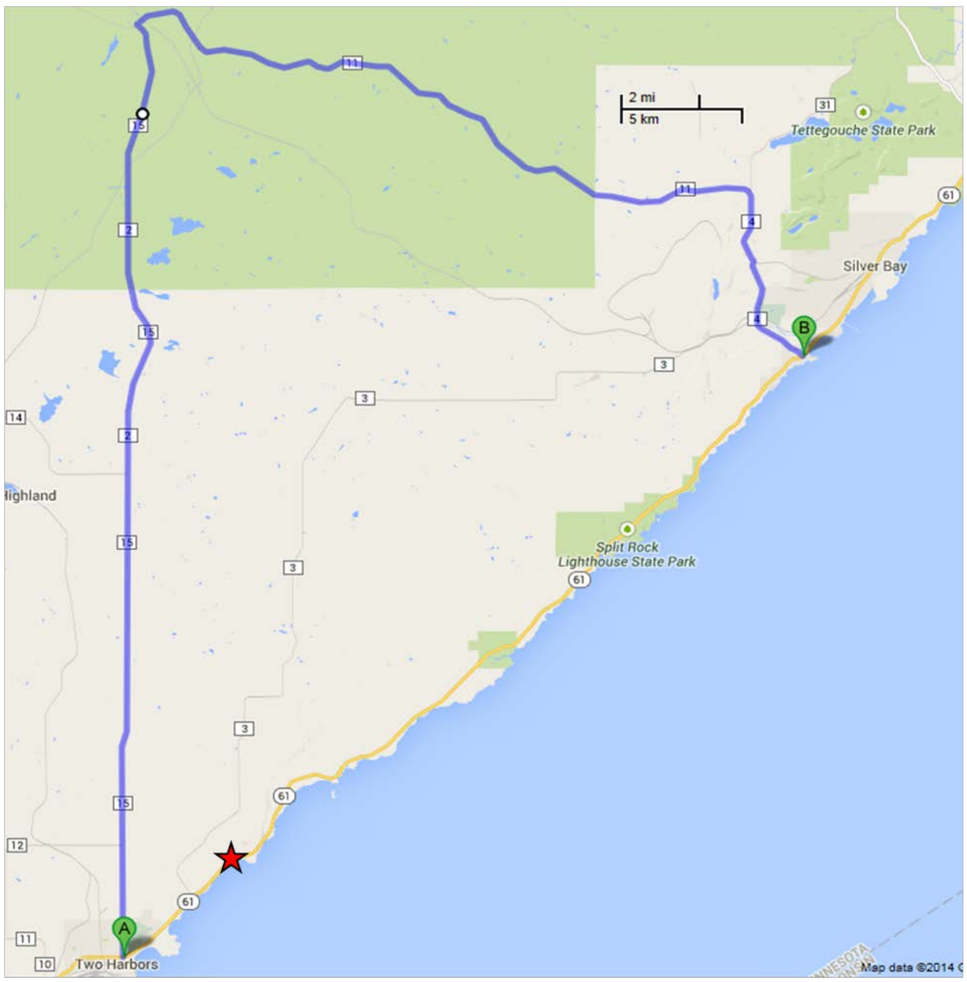
The COAST software is designed to calculate expected cumulative damages to transportation facilities over time, using curves relating water depths to their probabilities and water depths to damage costs incurred (depth-damage functions). Water levels at the facility are assessed using the heights and probabilities (return periods) provided in the depth-probability tables shown above. Every time the facility is flooded, damage is calculated according to the depth-damage function and summed for all such events over time. Each design option has its own depth-damage function.

Damage costs accounted for the depth-damage functions include:

- **Physical damage repair costs:** Estimates of the cost to repair each adaptation option given various levels of damage. These costs include the costs for parts and labor along with contingency and mobilization factors.
- **Incremental travel time costs to motorists from the detour:** Time is valuable and there is a cost imposed on motorists when a trip takes longer because of the need to detour a damaged facility. An estimate of the costs of lost time for detouring Culvert 5648 was developed by considering the additional 42 minutes of travel time required to take the detour route (shown in Figure 24) then comparing this with traffic

volumes and MnDOT recommended travel time values for motorists and freight.[29] In addition, there is also an increase in vehicle operating costs (fuel, wear and tear, etc.) due to the 24 additional miles required to detour the facility. This cost was computed using MnDOT recommended operating costs[30] and added to the travel time costs to arrive at a total estimated detour cost of approximately $140,000 per day. The length of time the detour is likely to be in place for various levels of damage was also accounted for and used to multiply the daily detour cost to arrive at a total detour cost per flooding incident. The maximum number of days a detour would be required was assumed to be 15 days for each option.

- **The potential for injury to motorists:** When a culvert fails, there is a possibility for accidents and associated injuries. An estimated cost of injury of $80,000 per flood event was included to reflect this possibility. The value chosen was approximately the same as the MnDOT recommended costs for a crash with moderate injuries (Type C).[31] This value was selected to balance the likelihood that no accident will occur with the unlikely (but still possible) chance of an accident with fatalities.



Source of background image: Google Maps

Figure 24: Detour Route for Culvert 5648

[29] MnDOT, 2014a
[30] Ibid
[31] Ibid

A discount rate of 2 percent was applied to future damage costs and expenditures per MnDOT recommendations.[32] The analyses began in 2020, the assumed year that construction would be completed, and were run through 2100 (the assumed end of the facility's design life).

For the purposes of this analysis, two sets of depth-damage functions were run for each adaptation option. One set, shown in Figure 25, includes the physical repair costs required to fix the facility along with the social costs for detours and injuries. A second set, shown in Figure 26, considered just the physical repair costs. This second assessment was undertaken to evaluate if the conclusions from the economic analysis would be different if MnDOT considered only direct agency costs.

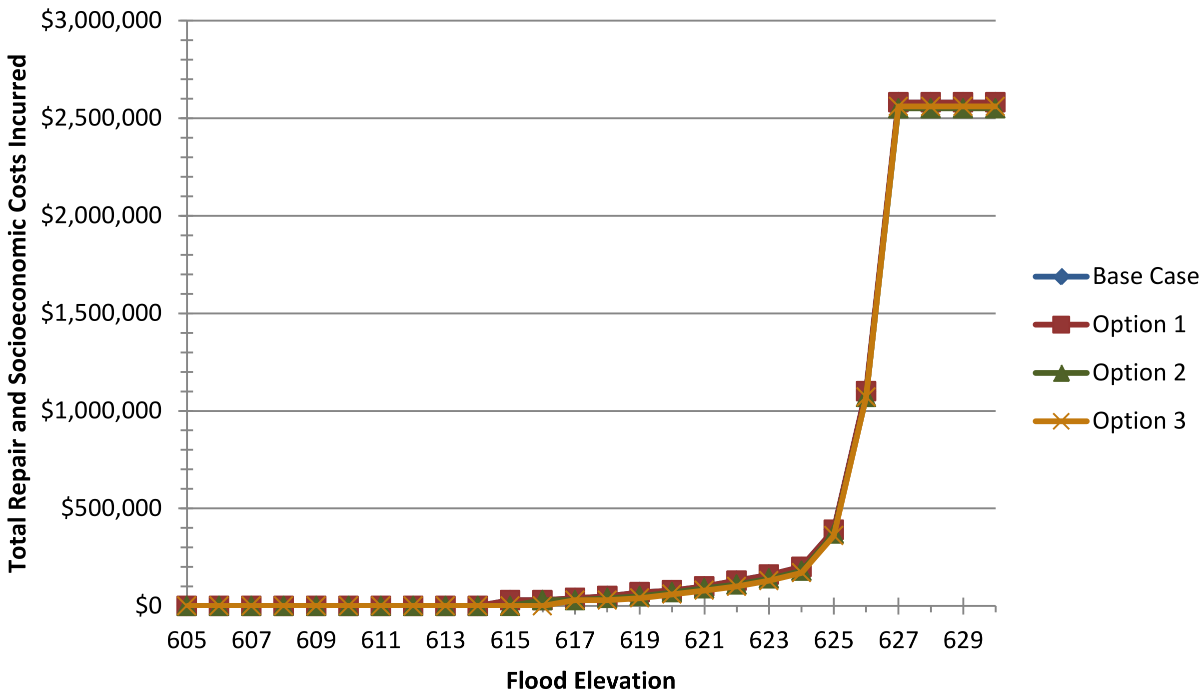


Figure 25: Depth-Damage Functions for the Culvert 5648 Design Options *With* Social Costs

The consultant team performed a total of 72 model runs (36 with social costs included and 36 without) for Silver Creek. These model runs calculated the differences in expected life cycle repair expenses between the design options given projections of rainfall patterns and flood levels over time. The construction costs of each option were then added in to provide a complete picture of expected outlays likely to be accumulated under each design.

Results of the analysis comparing the expected total life cycle costs (including construction) can be found in Table 9 through Table 14. Figure 27 and Figure 28 display this information graphically.

Key findings of the analysis include:

- If social costs of detours and injuries are included, Option 1, the expanded two cell culvert, is the most cost effective design in all rainfall increase scenarios (low, medium, and high).
- If the social costs of detours and injuries are not included, replacement-in-kind of the exiting culvert (with modifications for fish passage) is the lowest cost option if the low rainfall scenario were to occur. If the medium and higher scenarios of rainfall increase were to occur, Option 1 is the most cost effective option.

[32] Ibid

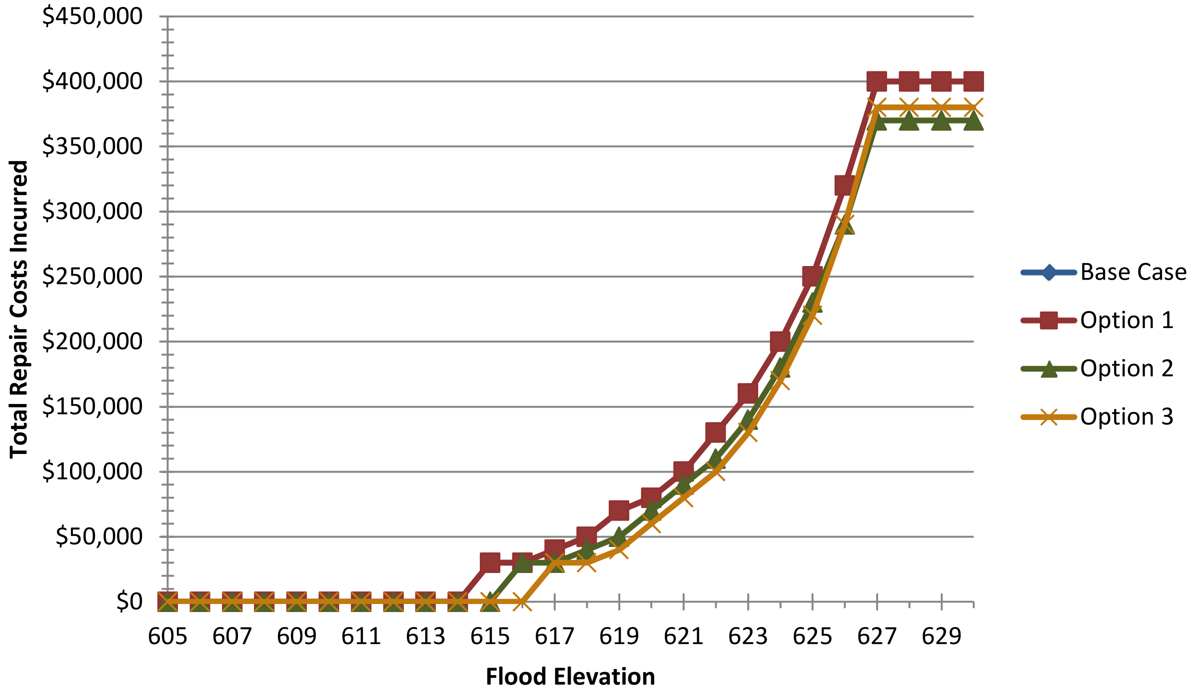


Figure 26: Depth-Damage Functions for the Culvert 5648 Design Options *Without* Social Costs

Table 9: Projected Life Cycle Costs for Culvert 5648 Adaptation Option *Without* Social Costs, Low Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	48,250	21,678	6,866	$643,069	$76,794	**$719,863**
Option 1: Two Cell Culvert	18,238	7,856	2,488	$697,413	$28,582	**$725,995**
Option 2: 52-Foot Bridge	69,034	31,226	9,890	$1,023,476	$110,150	**$1,133,626**
Option 3: 57-Foot Bridge	25,848	11,134	3,526	$1,095,934	$40,508	**$1,136,442**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Table 10: Projected Life Cycle Costs for Culvert 5648 Adaptation Options *Without* Social Costs, Medium Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	50,328	24,861	12,693	$643,069	$87,882	**$730,951**
Option 1: Two Cell Culvert	18,238	9,049	4,882	$697,413	$32,169	**$729,582**
Option 2: 52-Foot Bridge	72,494	55,098	20,600	$1,023,476	$148,192	**$1,171,668**
Option 3: 57-Foot Bridge	25,848	11,134	3,811	$1,095,934	$40,793	**$1,136,727**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Table 11: Projected Life Cycle Costs for Culvert 5648 Adaptation Options *Without* Social Costs, High Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	89,574	46,937	19,528	$643,069	$156,039	**$799,108**
Option 1: Two Cell Culvert	21,008	24,861	9,292	$697,413	$55,161	**$752,574**
Option 2: 52-Foot Bridge	58,645	26,751	26,740	$1,023,476	$112,136	**$1,135,612**
Option 3: 57-Foot Bridge	27,932	23,958	12,156	$1,095,934	$64,046	**$1,159,980**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Table 12: Projected Life Cycle Costs for Culvert 5648 Adaptation Options *With* Social Costs, Low Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	120,262	52,703	16,693	$643,069	$189,658	**$832,727**
Option 1: Two Cell Culvert	18,226	7,851	2,487	$697,413	$28,564	**$725,977**
Option 2: 52-Foot Bridge	69,148	31,269	9,904	$1,023,476	$110,321	**$1,133,797**
Option 3: 57-Foot Bridge	25,839	11,130	3,525	$1,095,934	$40,494	**$1,136,428**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Table 13: Projected Life Cycle Costs for Culvert 5648 Adaptation Options *With* Social Costs, Medium Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	122,352	111,568	40,147	$643,069	$274,067	**$917,136**
Option 1: Two Cell Culvert	18,226	9,041	14,708	$697,413	$41,975	**$739,388**
Option 2: 52-Foot Bridge	72,592	55,207	30,455	$1,023,476	$158,254	**$1,181,730**
Option 3: 57-Foot Bridge	25,839	11,130	3,808	$1,095,934	$40,777	**$1,136,711**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Table 14: Projected Life Cycle Costs for Culvert 5648 Adaptation Options *With* Social Costs, High Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	290,776	125,251	46,990	$643,069	$463,017	**$1,106,086**
Option 1: Two Cell Culvert	20,990	111,568	36,756	$697,413	$169,314	**$866,727**
Option 2: 52-Foot Bridge	58,740	26,785	41,520	$1,023,476	$127,045	**$1,150,521**
Option 3: 57-Foot Bridge	27,913	23,937	39,611	$1,095,934	$91,461	**$1,187,395**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

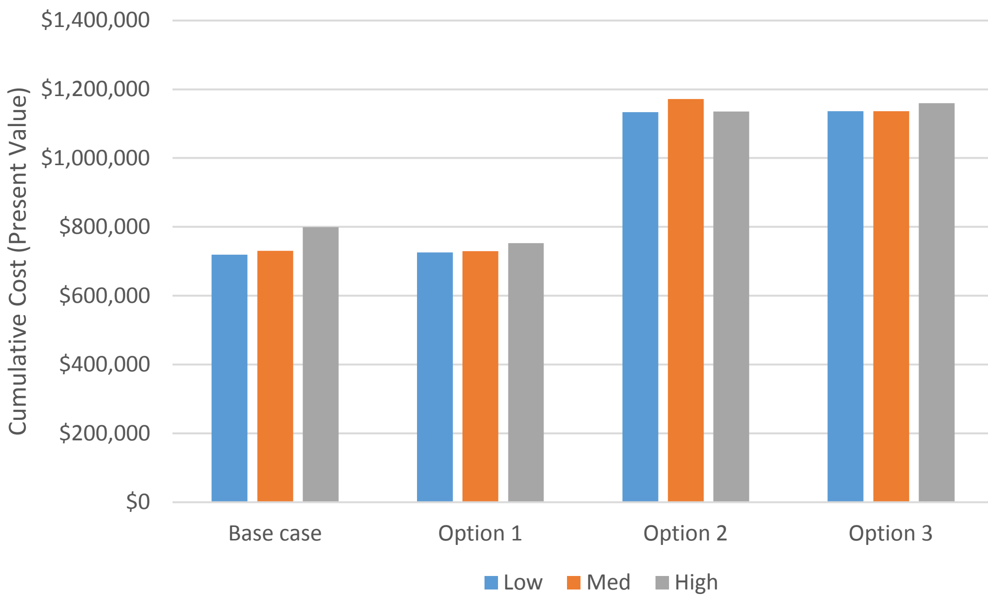


Figure 27: Cost Effectiveness of Culvert 5648 Adaptation Options *Without* Social Costs

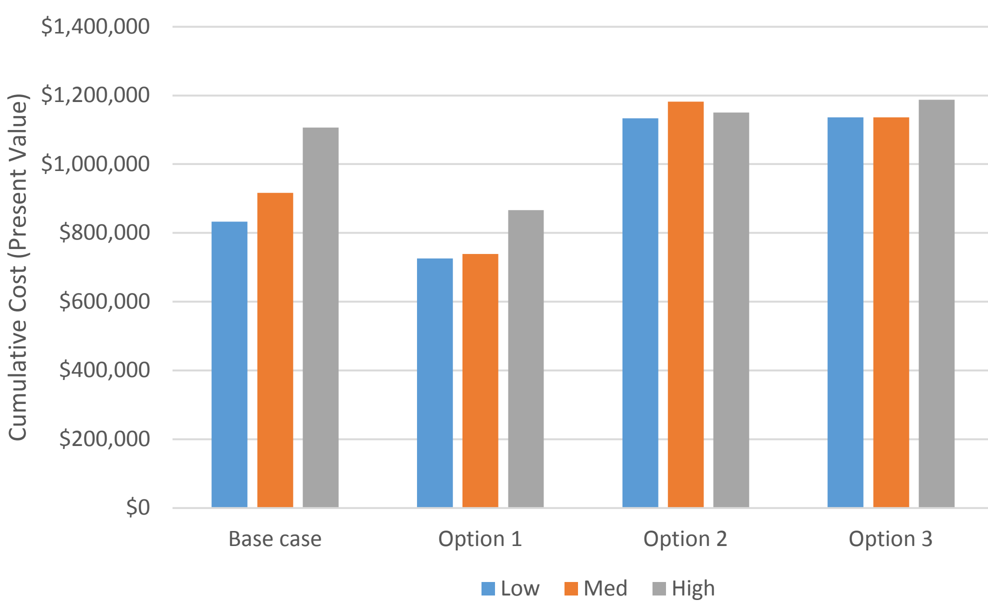


Figure 28: Cost Effectiveness of Culvert 5648 Adaptation Options *With* Social Costs

Thus, different conclusions are arrived at depending whether one considers social costs. It is recommend that social costs be included in the analysis which points to Option 1 being the preferred option under the range of climate scenarios tested. That said, although the economic analysis can point the way to the most cost-effective option, decision-makers should consider other social or political criteria not included in the modeling before deciding on a course of action. These considerations are offered in the next step.

Step 9—Evaluate Additional Decision-Making Considerations

Potential additional decision-making considerations that are of concern for the Silver Creek site would include fish passage design requirements, maintenance of traffic, and on-going maintenance needs of the selected alternative. The pilot study project did not fully delve into all of these issues but specific points of consideration could include whether a culvert option can provide both a sustainable platform for channel bed sediments and meet the low flow velocity and depth requirements for fish passage. Finally, from a long-term maintenance standpoint, the selection of a bridge option is going to encumber the district with an additional structure in need of regular inspections, while a culvert option will have its own maintenance needs that may be more or less of a concern.

Each of these factors, along with other possible factors related to sustainability, permitting, project feasibility and practicality, ongoing maintenance needs, capital funds availability, and project risk should be considered along with the cost-effectiveness results, to select a design the provides the greatest value to MnDOT and the community.

Step 10—Select a Course of Action

Based upon the results of the benefit-cost analysis, Option 1 would be recommended for the site. However, there are known additional decision-making considerations for this site that include fish passage requirements. The pilot study was not developed to enough detail to determine the applicability of the culvert structure to the local fish passage requirements, thus a specific recommendation could not be made. Meeting of these additional requirements will directly impact the Department's ability to permit and construct an individual option and may supersede the recommendations of this analysis.

Step 11—Plan and Conduct Ongoing Activities

After construction, facility performance should be monitored and recorded in an asset management database. Specific items that should be recorded include frequency of overtopping, duration of closures, whether injuries resulted from the overtopping, and any damage costs. Instances where an adaptive design prevented the incurrence of costs relative to a traditional design should also be noted and a tally maintained of costs avoided; eventually this can be used to determine whether the additional costs incurred for the adaptation were justified. All of this information will aid in future decision-making for this and other assets.

3.3.3 US 63 Culvert (#5722) over Spring Valley Creek

The case study of Culvert 5722 provides an example of how a facility-level adaptation assessment can be conducted for an asset that is not currently programmed for replacement.

Application of the General Adaptation Process for Engineering

Step 1—Describe the Site Context

Culvert 5722 carries US 63 over Spring Valley Creek and is located in the southeast portion of the state within the small town of Spring Valley (see Figure 29). US 63 is an important regional roadway linking the mid-sized cities of Rochester and Waterloo, Iowa and many rural communities in between. AADT at the facility is currently 5,700 vehicles per day and HCADT is currently 610 trucks per day.

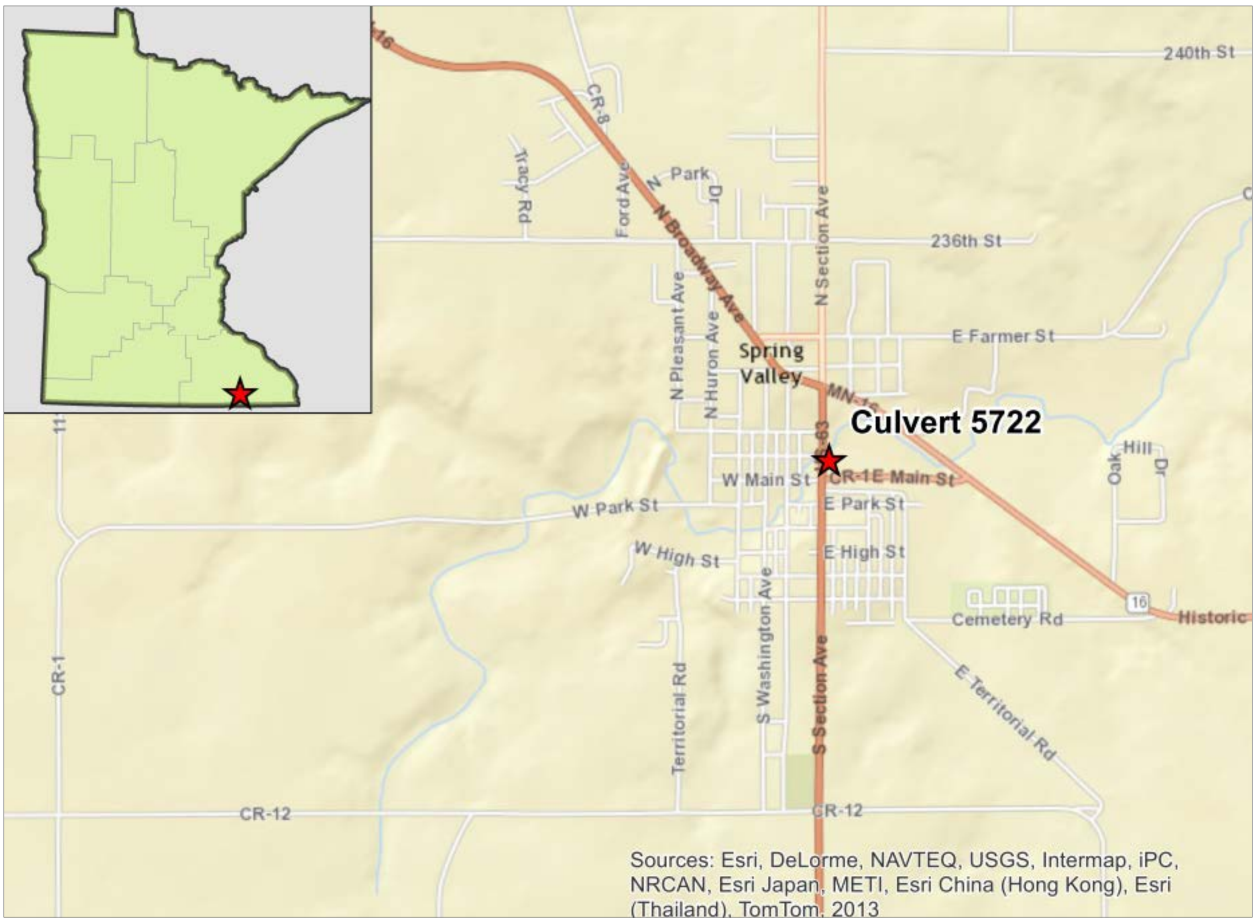
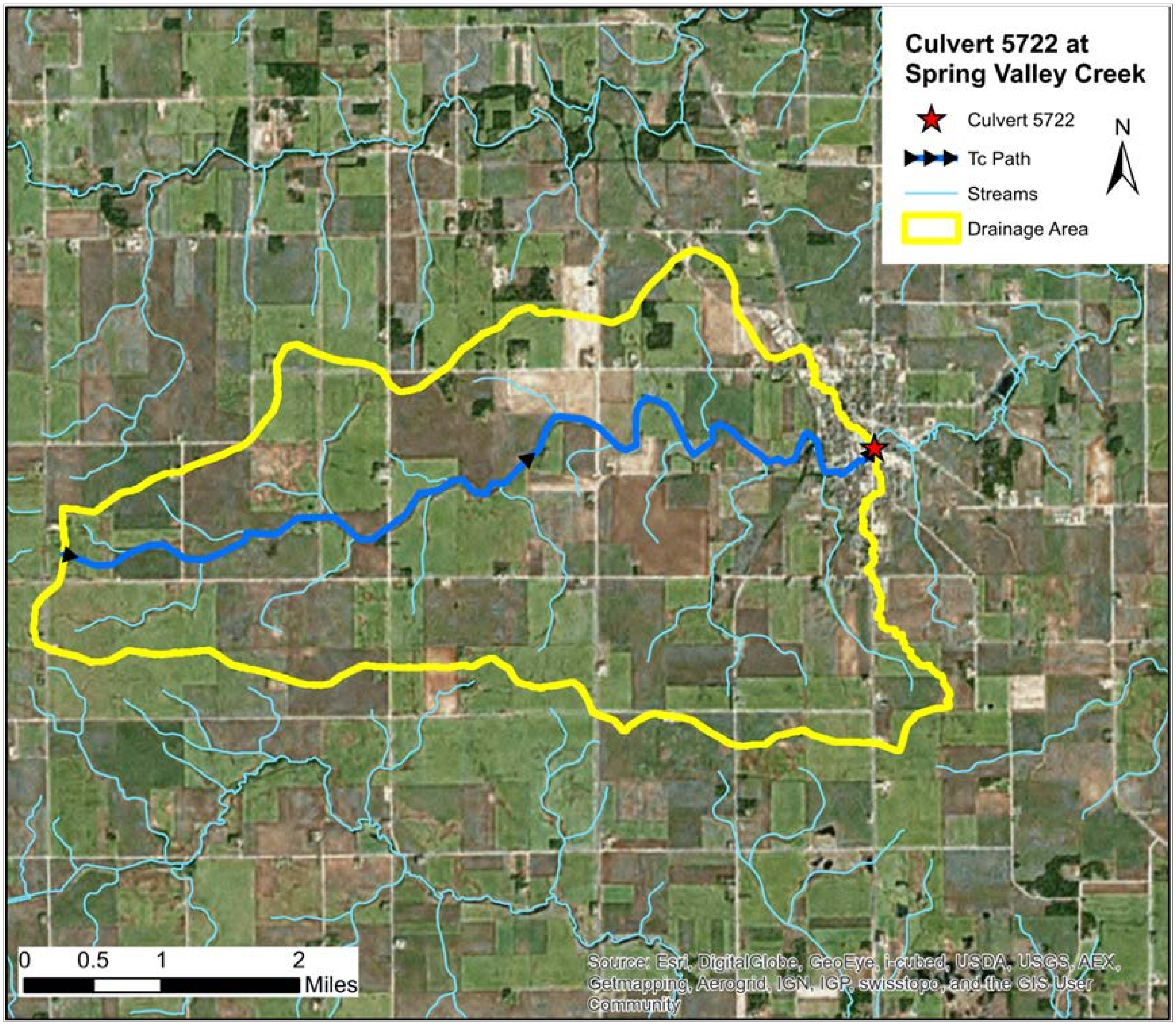


Figure 29: Location of Culvert 5722

Hydrologic Setting

Spring Valley Creek is a small creek that cuts through the town of Spring Valley. Within the center of town, just upstream of the study culvert, there are numerous roadways that cross over the stream and a car dealership building cantilevered over the creek. The segment upstream of the culvert is constrained by the buildings and roadways surrounding the stream. Immediately upstream of the culvert there are retaining walls extending off the culvert wing walls. The downstream area is more natural and has vegetated banks with a floodplain.

Figure 30 shows the drainage area for water flowing to the culvert being analyzed. The total drainage area to the culvert is 13.93 square miles.



Note: The Tc path line shown denotes the path used to compute the time of concentration for this facility. Time of concentration is the time needed for water to flow from the most hydrologically remote point of the drainage area to the discharge point of the drainage area.

Figure 30: Drainage Area to Culvert 5722 Showing Time of Concentration (Tc) Path

Step 2—Describe the Existing Facility

Culvert 5722 is a three-cell culvert with each barrel having a 12 foot span (width) by six foot (1.8) rise (height). The barrels extend 67 feet and it is skewed 35° relative to the road as seen on the plan view in Figure 31. The culvert was originally built in 1937. The latest inspection report notes that the culvert was repaired in 1996, but describes the presence of scattered vertical cracks in the structure and spalling with exposed rebar on the culvert barrel. Figure 32 and Figure 33 are photos of the upstream and downstream ends of the culvert taken in 2014.

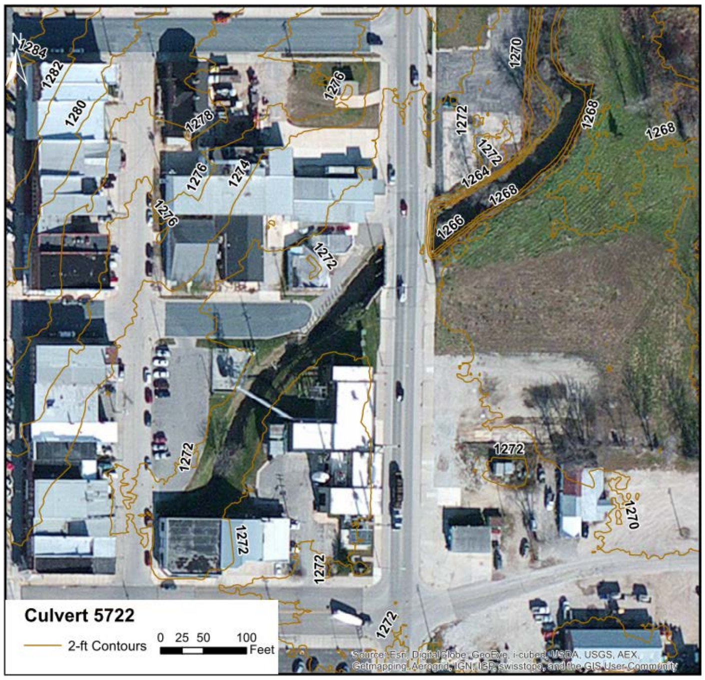


Figure 31: Plan View of Culvert 5722 Showing Elevation Contours

Figure 32: Photo of Culvert 5722, Upstream Side

Figure 33: Photo of Culvert 5722, Downstream Side

Step 3—Identify Environmental Factors That May Impact Infrastructure Components

As in the case study of Culvert 5648 at Silver Creek, precipitation is the primary climate stressor of interest in the design of Culvert 5722.

Step 4—Decide on Climate Scenarios and Determine the Magnitude of Changes

To promote consistency in climate adaptation assessments, the same technique for generating climate scenarios was used for Culvert 5722 as was used for the previous case study of Culvert 5648 at Silver Creek. Readers are referred back to Step 4 of that study for details on the process for scenario generation. In the case of Culvert 5722, SimCLIM climate projections were obtained from the Grand Meadow weather station, located approximately 11 miles from the study site. The range of 24-hour precipitation values for each scenario (low, medium, and high) and return period is shown in Table 15 through Table 17 along with the percent change between observed and projected precipitation depths.

Table 15: 24-Hour Precipitation Depths at Culvert 5722, Low Scenario

24-Hour Storm Return Period	Atlas 14 Precipitation Depth (in)[1]	Low Scenario Precipitation Depth (in)					
		2040		2070		2100	
		% Increase	Depth	% Increase	Depth	% Increase	Depth
2-year storm	2.79	3.66%	2.89	5.59%	2.95	6.50%	2.97
5-year storm	3.7	3.01%	3.81	4.61%	3.87	5.37%	3.90
10-year storm	4.49	2.89%	4.62	4.42%	4.69	5.14%	4.72
25-year storm	5.69	2.92%	5.86	4.47%	5.94	5.20%	5.99
50-year storm	6.7	3.03%	6.90	4.64%	7.01	5.40%	7.06
100-year storm	7.81	3.21%	8.06	4.91%	8.19	5.71%	8.26
500-year storm	10.8	3.76%	11.21	5.75%	11.42	6.69%	11.52

[1] *Source: NOAA, 2014a*

Table 16: 24-Hour Precipitation Depths at Culvert 5722, Medium Scenario

24-Hour Storm Return Period	Atlas 14 Precipitation Depth (in)[1]	Medium Scenario Precipitation Depth (in)					
		2040		2070		2100	
		% Increase	Depth	% Increase	Values	% Increase	Depth
2-year storm	2.79	5.42%	2.94	9.00%	3.04	12.79%	3.15
5-year storm	3.7	4.47%	3.87	7.44%	3.98	10.59%	4.09
10-year storm	4.49	4.28%	4.68	7.13%	4.81	10.15%	4.95
25-year storm	5.69	4.33%	5.94	7.20%	6.10	10.26%	6.27
50-year storm	6.7	4.50%	7.00	7.49%	7.20	10.66%	7.41
100-year storm	7.81	4.76%	8.18	7.91%	8.43	11.26%	8.69
500-year storm	10.8	5.58%	11.40	9.28%	11.80	13.23%	12.23

[1] *Source: NOAA, 2014a*

Table 17: 24-Hour Precipitation Depths at Culvert 5722, High Scenario

24-Hour Storm Return Period	Atlas 14 Precipitation Depth (in)[1]	High Scenario Precipitation Depth (in)					
		2040		2070		2100	
		% Increase	Depth	% Increase	Depth	% Increase	Depth
2-year storm	2.79	10.08%	3.07	20.44%	3.36	30.48%	3.64
5-year storm	3.7	8.33%	4.01	16.99%	4.33	25.42%	4.64
10-year storm	4.49	7.98%	4.85	16.30%	5.22	24.40%	5.59
25-year storm	5.69	8.07%	6.15	16.46%	6.63	24.64%	7.09
50-year storm	6.7	8.39%	7.26	17.11%	7.85	25.61%	8.42
100-year storm	7.81	8.86%	8.50	18.08%	9.22	27.07%	9.92
500-year storm	10.8	10.40%	11.92	21.26%	13.10	31.94%	14.25

[1] *Source: NOAA, 2014a*

Step 5—Assess Performance of the Existing/Proposed Facility

Assessing the performance of a culvert first requires detailed hydrologic and hydraulic modeling of the watershed in the vicinity of the facility to understand expected peak flows. These peak flows can then be used to evaluate the culvert's performance relative to its design standards.

Hydrologic Modeling

Peak flows through the culvert were modeled for various storm events and climate scenarios using the same type of WinTR-20 program used for the Silver Creek case study. As in that case study, analysis of both existing and future land cover conditions was necessary to evaluate current flows and predicted future flows at the culvert. Existing land cover conditions were obtained from the latest, 2011, National Land Cover Dataset and are shown in Figure 34.

Derivation of future land cover involved developing a build out of zoned land uses within the drainage area. This involved consulting the zoning ordinances for the three jurisdictions with zoning authority in the drainage area: Mower County, Fillmore County, and the town of Spring Valley. In the Mower and Fillmore County portions of the drainage area, the zoning is agricultural, so existing land cover was assumed to remain in place for the future. Within the town of Spring Valley, there remains some vacant land zoned for development; these areas were assumed to be built out in the future land cover projections. Overall, the existing land cover resulted in a curve number value of 80. Future land use had an increase of 0.5 but, using the whole number rounding convention traditionally employed when reporting curve numbers, the value remained 80.

A time of concentration value of 10.4 hours was used for existing and future condition models. All other hydrologic assumptions were similar to those employed in the Culvert 5648 case study and calibrations of the results were run in the same manner. Table 18 shows the model outputs comparing current peak flows to projected future peak flows at Culvert 5722.

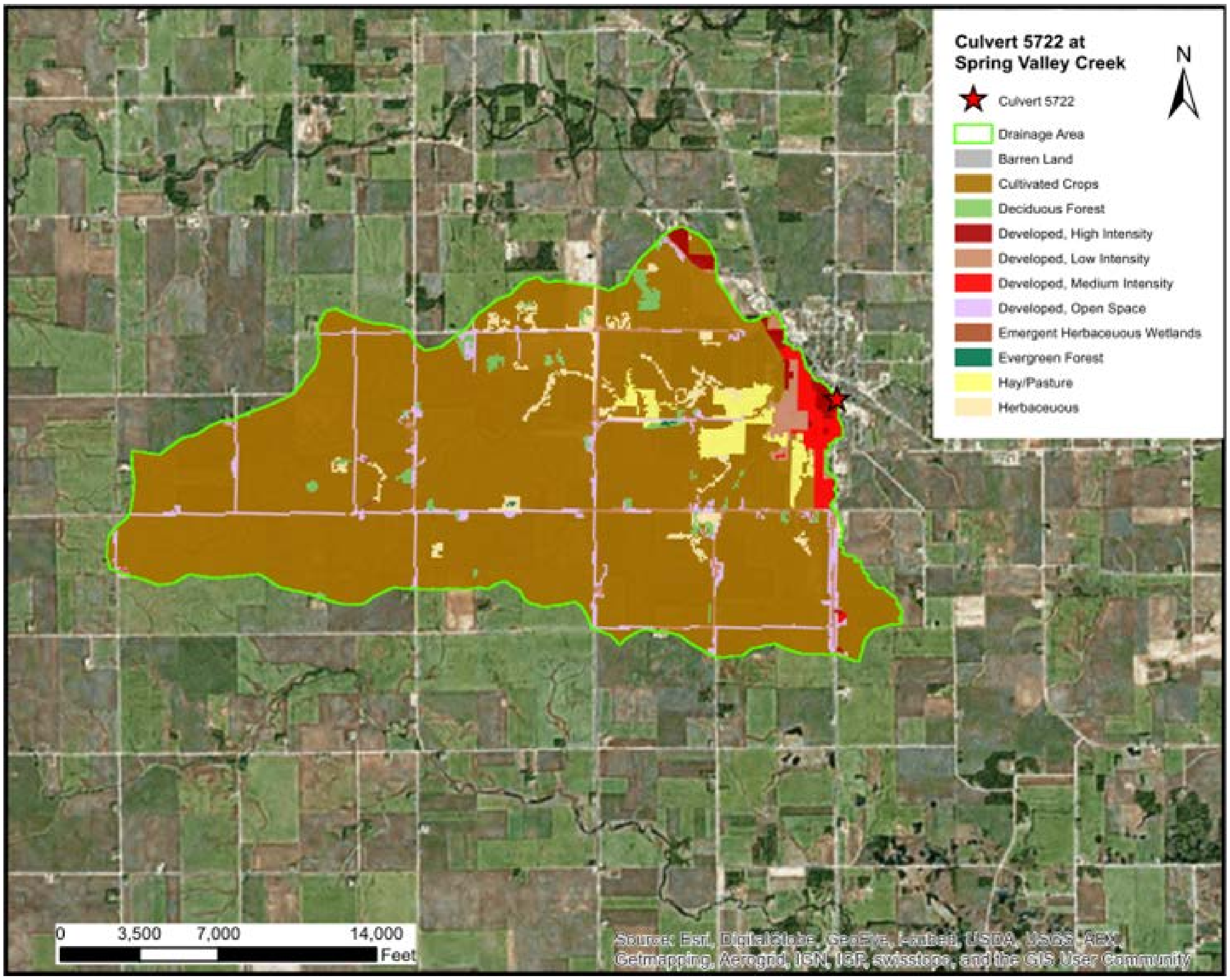


Figure 34: Existing Land Cover within the Culvert 5722 Drainage Area

Table 18: TR-20 Projected Peak Flows at Culvert 5722

24-Hour Storm Return Period	Existing Discharges (cfs)	Low Scenario Discharges			Medium Scenario Discharges			High Scenario Discharges		
		2040 (cfs)	2070 (cfs)	2100 (cfs)	2040 (cfs)	2070 (cfs)	2100 (cfs)	2040 (cfs)	2070 (cfs)	2100 (cfs)
2-year storm	850	930	965	980	960	1020	1080	1040	1210	1380
5-year storm	1390	1480	1520	1540	1520	1590	1660	1610	1810	2010
10-year storm	1880	2000	2040	2060	2030	2120	2210	2150	2390	2630
25-year storm	2670	2810	2860	2890	2860	2970	3090	3000	3330	3650
50-year storm	3340	3520	3590	3630	3590	3720	3870	3760	4170	4550
100-year storm	4100	4310	4400	4445	4390	4560	4740	4610	5100	5590
500-year storm	6160	6490	6630	6700	6620	6900	7200	6980	7800	8600

Hydraulic Modeling and Performance of the Existing Culvert

Hydraulic culvert analyses were conducted to evaluate the performance of Culvert 5722 under current and future peak flows. The existing facility was analyzed as the base case in this study since no improvements are currently planned for the asset. An existing HEC-RAS hydraulic model, developed for the Federal Emergency Management Agency's Spring Valley Flood Insurance Study,[33] was modified to accommodate existing conditions. The main modification in the model was the replacement of the bridge downstream of Culvert 5722. A smaller bridge existed at the time the model was developed. The peak flows developed through the hydrologic analysis were analyzed with the culvert model to determine the headwater elevation at the culvert for various climate scenarios. The stage-discharge curve shown in Figure 35 demonstrates that the MnDOT design criterion for culverts (that a 50-year storm should be passable with 3 feet of freeboard) is not met. Even under current climate conditions, the culvert is overtopped by storms much weaker than the 50-year design storm.

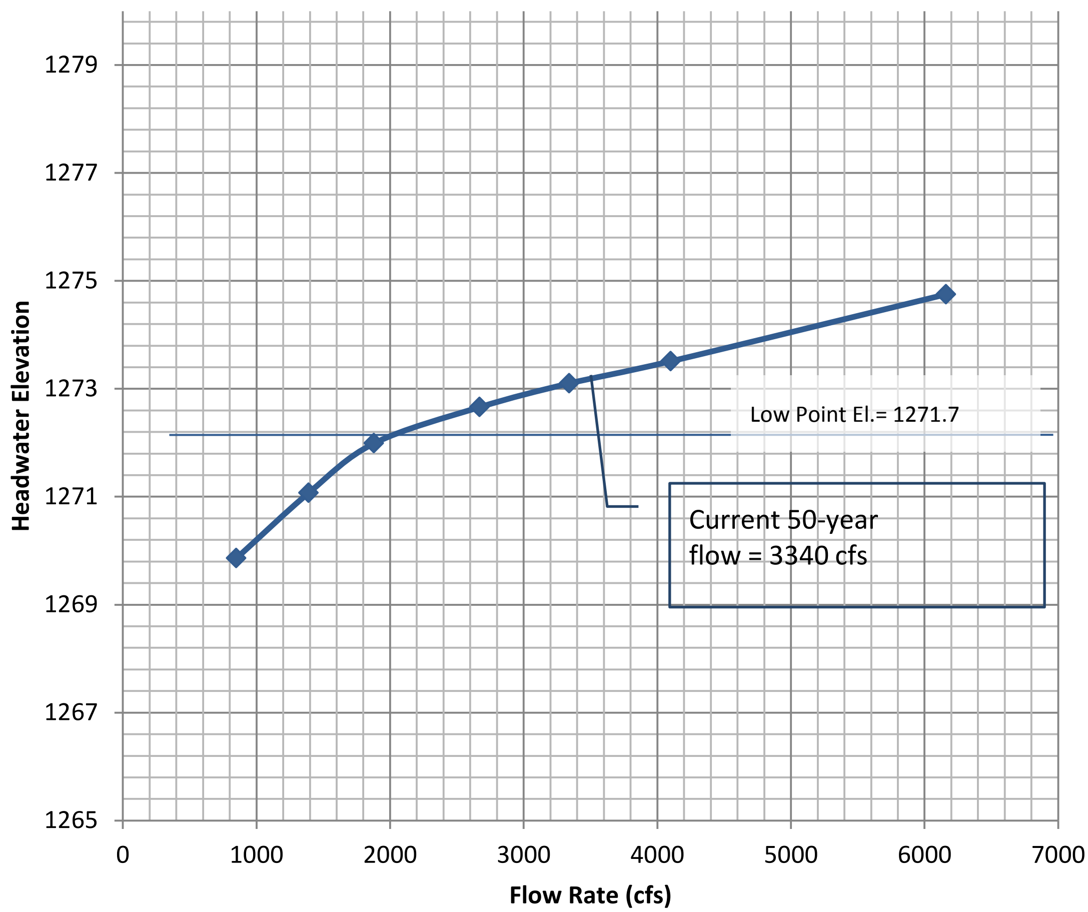


Figure 35: Stage-Discharge Curve for Culvert 5722

[33] FEMA, 1981

Step 6—Develop Adaptive Design Options

Since the existing structure does not meet design criteria for current and future conditions, a series of three adaption options were developed for the crossing. The adaptation options take into consideration the different climate scenarios discussed in Step 5. When considering the costs of the adaptation options cited below, note that the existing culvert is estimated to cost $460,000 to replace.

Option One

Option One adds two additional 12 foot span (width) by six foot rise (height) cells to the existing culvert design. Figure 36 shows cross-sections of this design option.

The work as estimated includes:

- Traffic control
- Riprap for outfall scour pool
- Erosion control and stream diversion
- Demolition, excavation, and structural backfill
- New culvert cells and culvert end section
- Pavement restoration

The estimated project cost is $690,000.

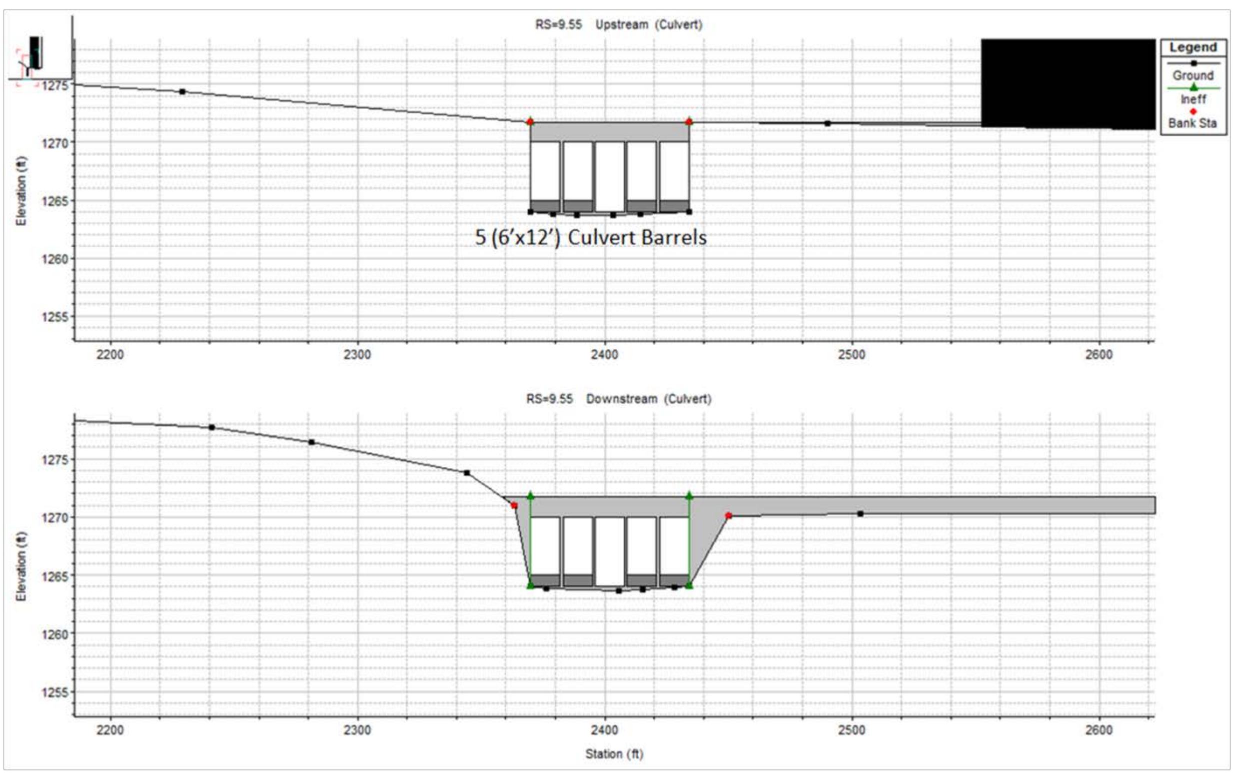


Figure 36: Cross-Sections of Design Option 1 for Culvert 5722

Option Two

Option Two includes the same structural changes as in Option One, but adds a floodplain enhancement upstream of the culvert to give the river room to spread out. This has the effect of lowering peak flow elevations. The work as estimated includes all the items mentioned above for Option One and the additional costs of the floodplain enhancements (including property acquisition and the demolition of one structure). The total estimated project cost is $1,640,000. Figure 37 shows cross-sections of this design option.

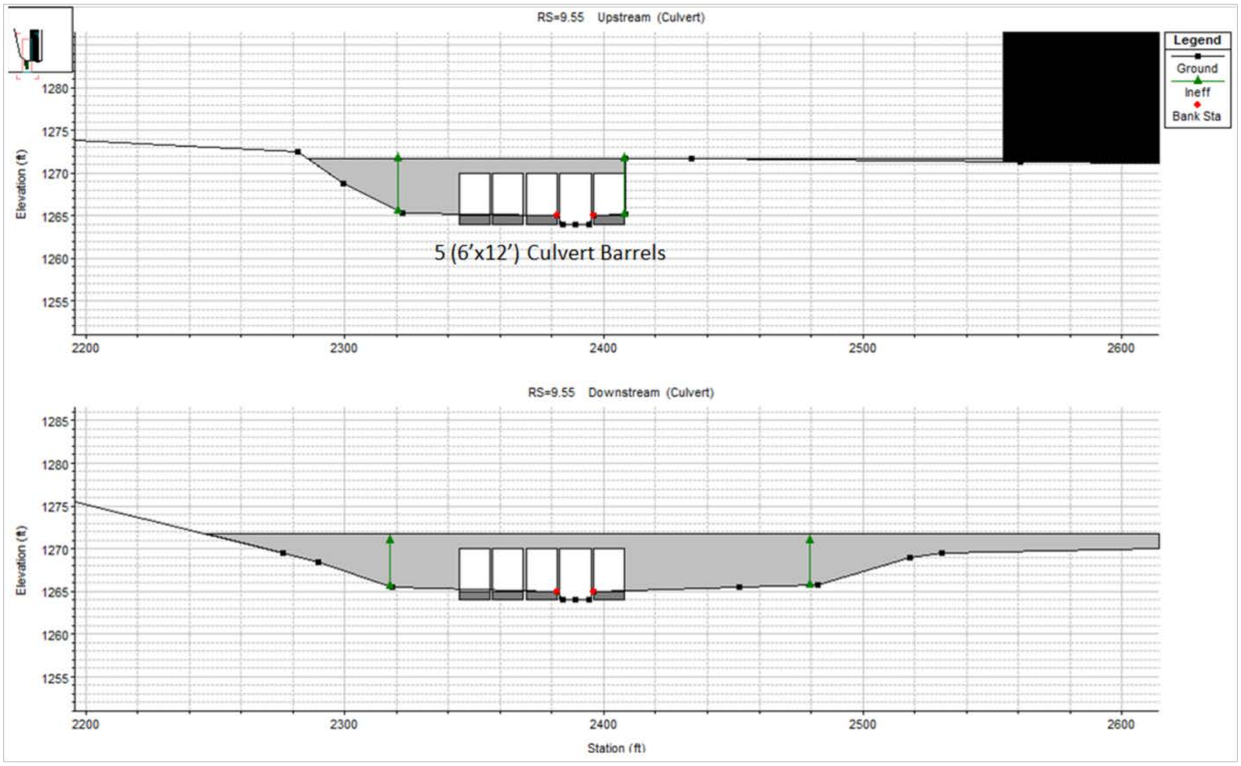


Figure 37: Cross-Sections of Design Option 2 for Culvert 5722

Option Three

Option three replaces the existing culvert with a three span bridge with each span being 28 feet in length. This option was designed to meet MnDOT design criteria for the 50-year storm in 2100. The bridge would have abutments with a one percent slope on both sides and two piers. The lowest deck elevation is 1,275.1 feet and the highest point is 1,276.8 feet. In total, the roadway will need to be raised approximately five feet either side of the bridge. The raising of the roadway will necessitate the closing and/or re-design of some intersections with local streets. Figure 38 shows cross-sections of this design option.

The work as estimated includes:

- Traffic control
- Riprap for abutment protection
- Erosion control and stream diversion
- Demolition, excavation, and structural backfill
- A new 28 foot multi-span bridge
- Associated road elevating and retaining wall construction

The estimated project cost is $4,210,000.

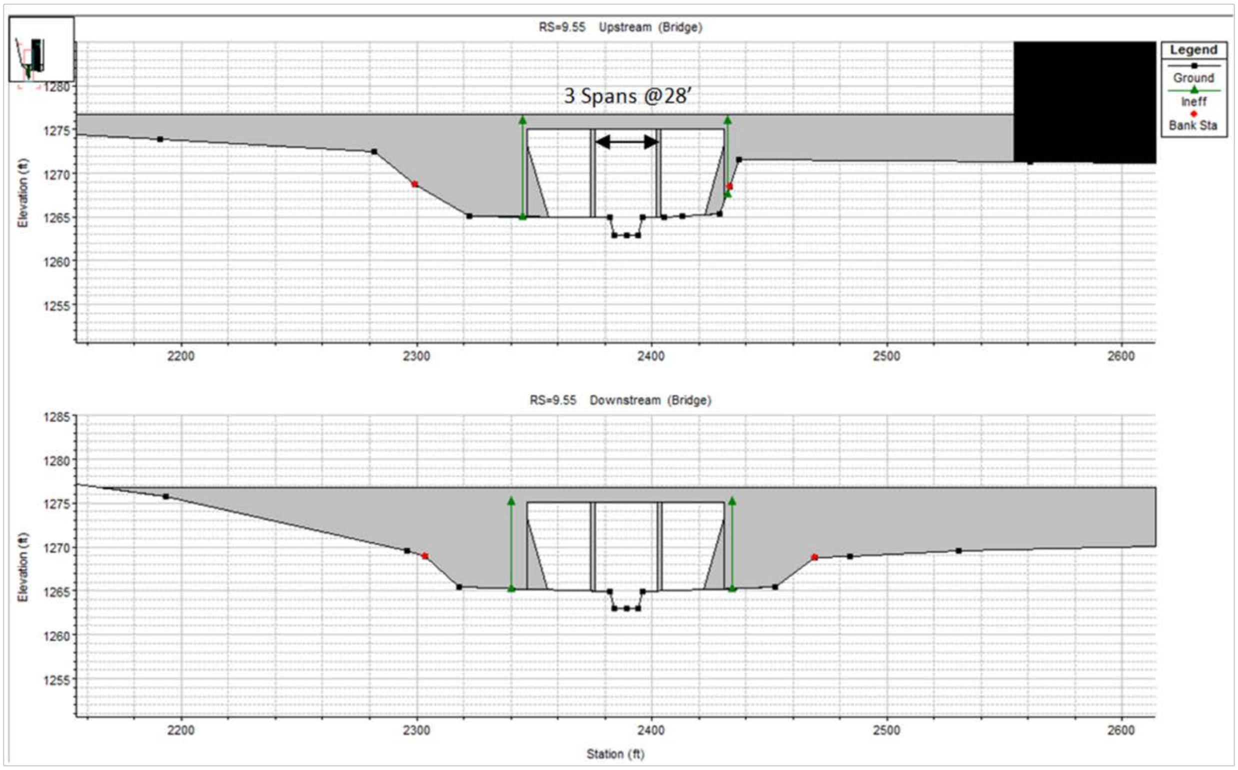


Figure 38: Cross-Sections of Design Option 3 for Culvert 5722

Step 7—Assess Performance of the Adaptive Design Options

The degree of flooding was analyzed for each adaptive design option using the 50-year storm event for all three scenarios. Figure 39 presents the stage-discharge curves for the different adaptation options. Although an improvement over the existing culvert, Option 1 and Option 2 do not meet the MnDOT design criteria—overtopping during even the present day 50-year storm. Option 3, on the other hand, does not overtop under the 50-year storm even under the high climate change scenario in 2100. That said, there is some erosion in the three foot freeboard requirement under this set of conditions but this could be acceptable in this context.

Step 8—Conduct an Economic Analysis

The consultant team performed an economic analysis for the Spring Valley Creek crossing using the COAST tool (see Step 8 of the Culvert 5648 case study for a description of the basic functioning of the tool). Since no improvements at Spring Valley are currently programmed, it was assumed that any adaptation options would not be completed until 2025. One other important item of note is that, for the purposes of the study, it was assumed that the base case existing asset would be replaced in kind in the year 2037 when the existing facility reaches the end of its design life. In all cases, the analyses were run until the year 2100 when it is expected that the design life of the adaptation options will be drawing to a close. As at Silver Creek, a total of 72 model runs were performed; 32 with social costs included and 32 without.

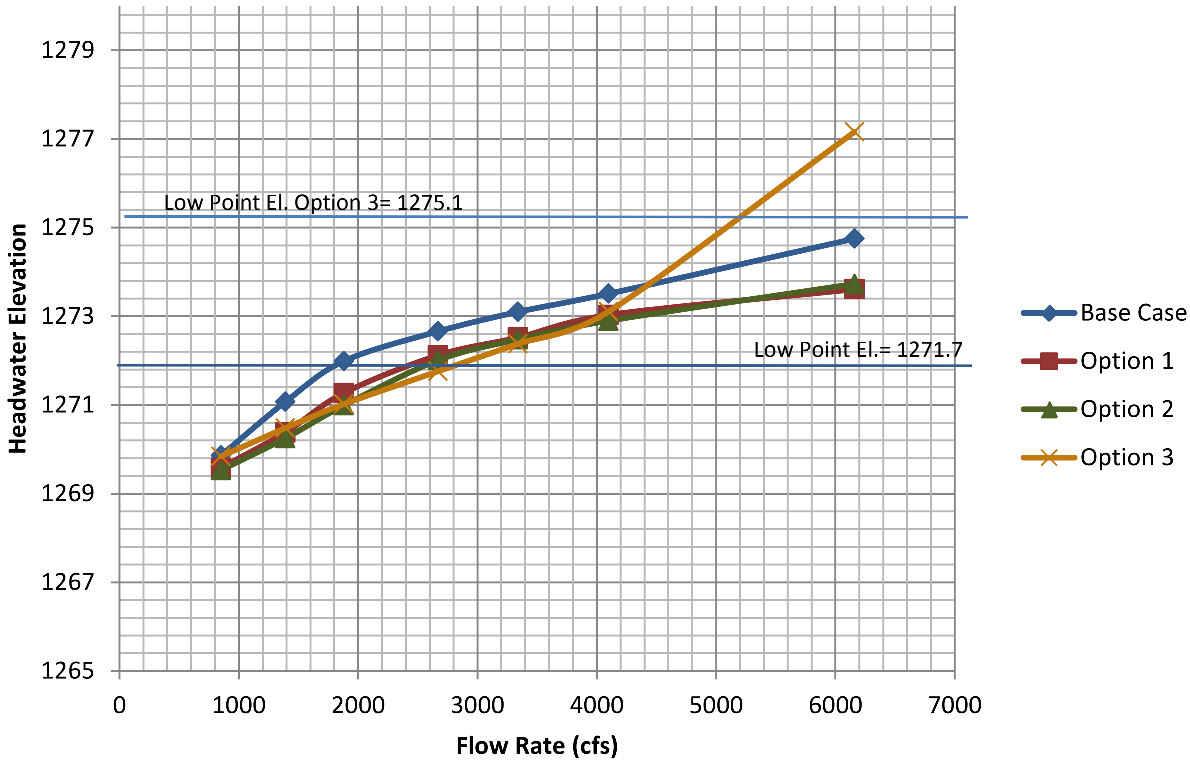
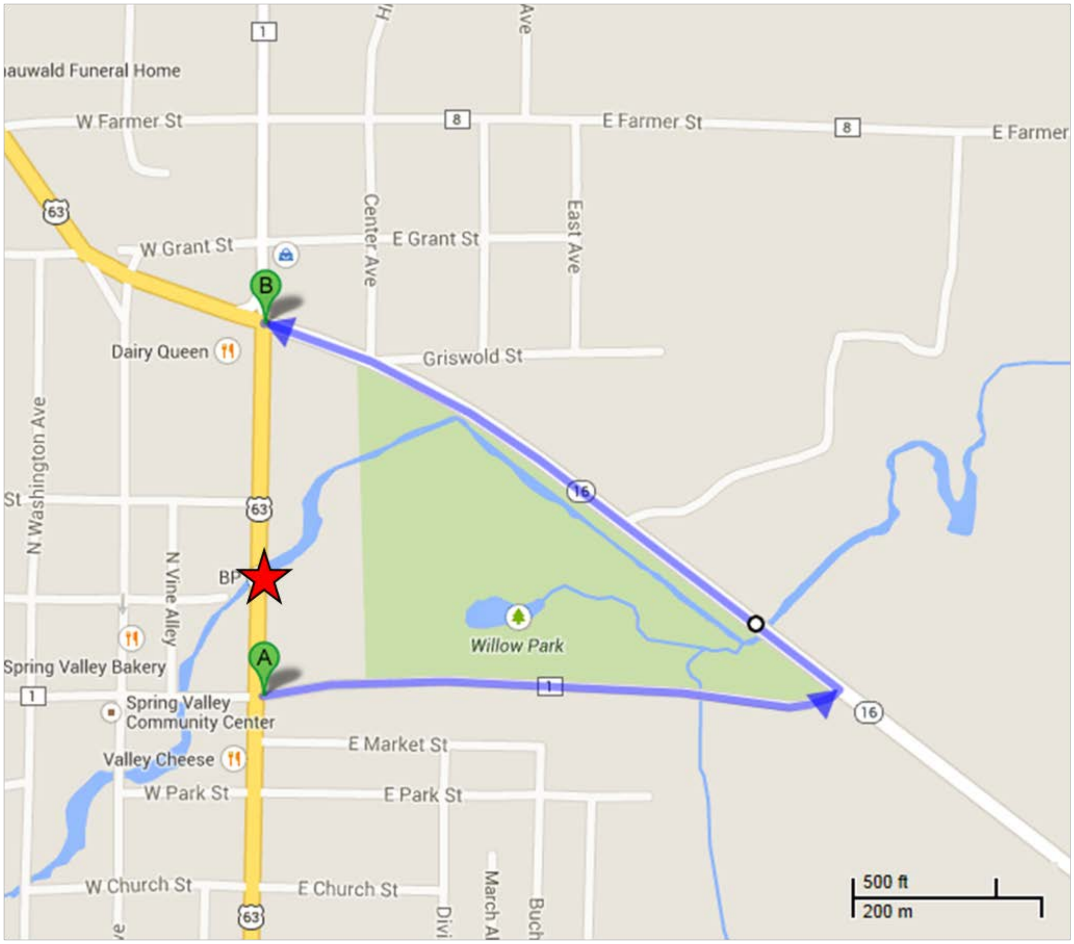


Figure 39: Stage-Discharge Curves for the Culvert 5722 Adaptation Options

The factors considered to generate the depth-damage functions for Culvert 5722 were the same as those considered in the previous case study. However, at approximately $4,000 per day, the detour costs were much lower than with Culvert 5648 because, as shown in Figure 40, the detour route was much shorter (0.6 miles) and added only 1.5 minutes of travel time. The maximum duration of the detour was assumed to be 15 days for the base case, Option 1, and Option 2. However, for Option 3, the maximum duration of the detour was assumed to be 60 days to reflect the possibility of foundation failure of the bridge and the long time that would be required to repair such damage. Figure 41 presents the depth-damage functions for each design option with social costs considered and Figure 42 presents the depth-damage functions excluding those costs.

Results of the analysis comparing the expected total life cycle costs (including construction) can be found in Table 19 through Table 24. Figure 43 and Figure 44 display this information graphically.

The key conclusion of the analysis is that, whether or not social costs of detours and injuries are included, Option 1, the expanded five cell culvert, is the most cost effective design in all rainfall increase scenarios (low, medium, and high). Thus, Option 1 would be the preferred option under the range of climate scenarios tested. That said, although the economic analysis identifies the most cost-effective option, decision-makers should consider other social or political criteria not included in the modeling before deciding on a course of action.



Source of background image: Google Maps

Figure 40: Detour Route for Culvert 5722

Step 9—Evaluate Additional Decision-Making Considerations

Potential additional decision making considerations that are of concern for the Spring Valley Creek culvert include upstream flood reduction benefits, total maximum daily load (TMDL)/water quality benefits, surrounding property impacts, historic and aesthetic value, maintenance of traffic, and on-going maintenance needs of the selected alternative. The pilot study project did not delve into each of these issues but specific points of consideration could include the historic railing on the existing culvert, the value of stream restoration on water quality, and the general utilization of the roadway.

A known issue is the presence of a historic railing on the current culvert structure. Regulatory requirements for the project may indicate that expansion of the existing culvert, rather than complete replacement, provides a more permissible treatment in regards to the railing. Option 2, which includes stream restoration and floodplain enhancement for the specific purpose of backwater reduction, will also provide benefits for water quality improvement due to stabilization of erosion areas and depositional opportunities for suspended solids and nutrients. This option would provide the department with water quality TMDL credits, if necessary, at a future time.

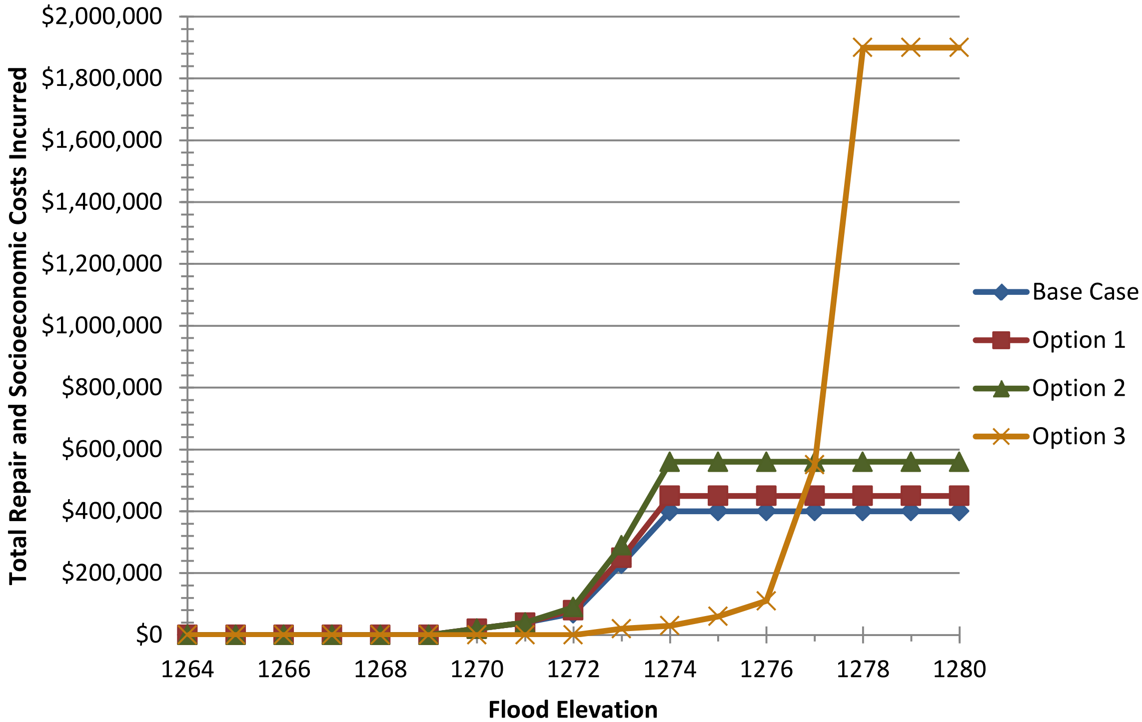


Figure 41: Depth-Damage Functions for the Culvert 5722 Design Options *With* Social Costs

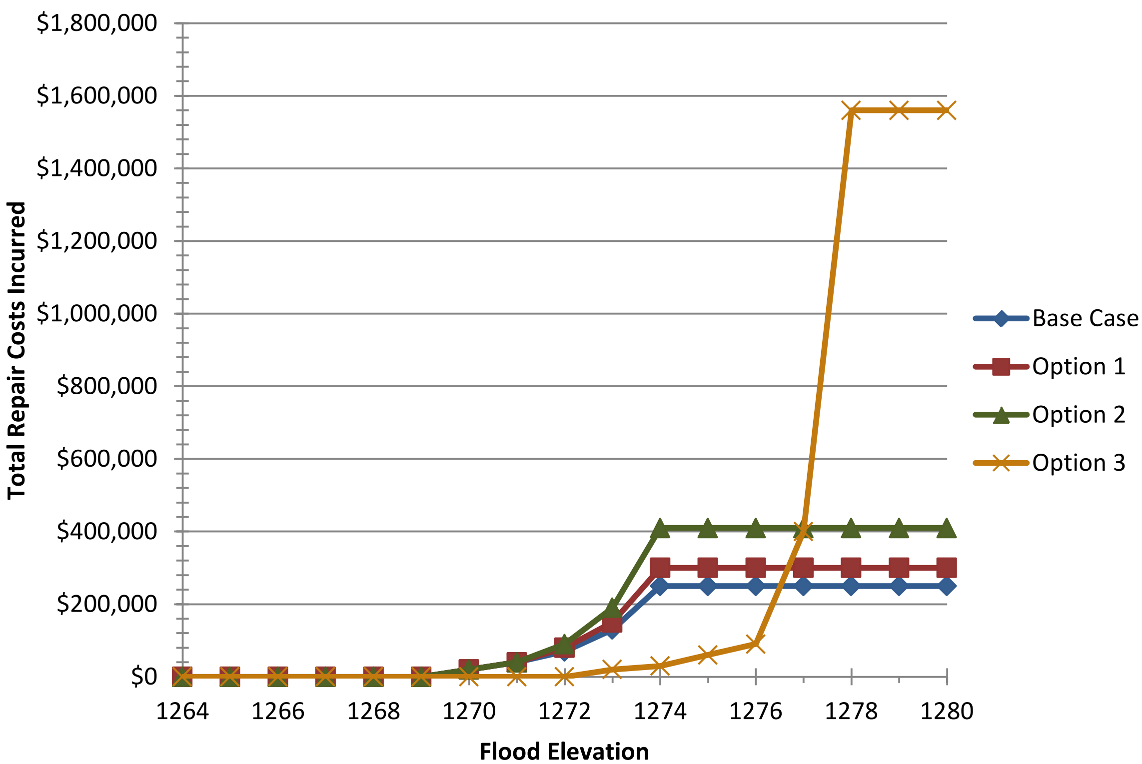


Figure 42: Depth-Damage Functions for the Culvert 5722 Design Options *Without* Social Costs

Table 19: Projected Life Cycle Costs for Culvert 5722 Adaptation Options *Without* Social Costs, Low Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	745,149	393,792	124,727	$291,712	$1,263,668	**$1,555,380**
Option 1: Add 2 cells	530,642	280,431	93,074	$566,040	$904,147	**$1,470,187**
Option 2: Add 2 cells and Floodplain Enhancement	395,233	238,715	75,609	$1,345,371	$709,557	**$2,054,928**
Option 3: 3 spaces @ 28-foot Bridge	5,636	2,979	933	$3,453,666	$9,548	**$3,463,214**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Table 20: Projected Life Cycle Costs for Culvert 5722 Adaptation Options *Without* Social Costs, Medium Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	745,149	423,625	134,176	$291,712	$1,302,950	**$1,594,662**
Option 1: Add 2 cells	530,642	247,275	93,074	$566,040	$870,991	**$1,437,031**
Option 2: Add 2 cells and Floodplain Enhancement	451,706	238,715	88,208	$1,345,371	$778,629	**$2,124,000**
Option 3: 3 spaces @ 28-foot Bridge	5,636	17,697	5,605	$3,453,666	$28,938	**$3,482,604**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Table 21: Projected Life Cycle Costs for Culvert 5722 Adaptation Options *Without* Social Costs, High Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	801,600	423,625	187,091	$291,712	$1,412,316	**$1,704,028**
Option 1: Add 2 cells	556,045	293,856	134,810	$566,040	$984,711	**$1,550,751**
Option 2: Add 2 cells and Floodplain Enhancement	451,706	337,942	107,038	$1,345,371	$896,686	**$2,242,057**
Option 3: 3 spaces @ 28-foot Bridge	5,636	2,979	933	$3,453,666	$3,463,214	**$6,916,880**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Table 22: Projected Life Cycle Costs for Culvert 5722 Adaptation Options *With* Social Costs, Low Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	1,049,983	554,889	175,752	$291,712	$1,780,624	**$2,072,336**
Option 1: Add 2 cells	662,357	350,039	116,538	$566,040	$1,128,934	**$1,694,974**
Option 2: Add 2 cells and Floodplain Enhancement	451,526	268,441	85,024	$1,345,371	$804,991	**$2,150,362**
Option 3: 3 spaces @ 28-foot Bridge	5,638	2,980	944	$3,453,666	$9,562	**$3,463,228**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Table 23: Projected Life Cycle Costs for Culvert 5722 Adaptation Options *With* Social Costs, Medium Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	1,049,983	584,722	185,201	$291,712	$1,819,906	**$2,111,618**
Option 1: Add 2 cells	662,357	367,936	116,538	$566,040	$1,146,831	**$1,712,871**
Option 2: Add 2 cells and Floodplain Enhancement	507,954	268,441	110,226	$1,345,371	$886,621	**$2,231,992**
Option 3: 3 spaces @ 28-foot Bridge	5,638	23,665	7,495	$3,453,666	$36,798	**$3,490,464**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

Table 24: Projected Life Cycle Costs for Culvert 5722 Adaptation Options *With* Social Costs, High Scenario

	Period 1 2025-2055	Period 2 2056-2085	Period 3 2086-2100	Initial Construction Costs	Total Damage/ Repair Costs by 2100	Total Life Cycle Cost by 2100
Base Case: Replace in Kind	1,106,434	584,722	307,408	$291,712	$1,998,564	**$2,290,276**
Option 1: Add 2 cells	696,224	367,936	160,647	$566,040	$1,224,807	**$1,790,847**
Option 2: Add 2 cells and Floodplain Enhancement	507,954	411,953	130,479	$1,345,371	$1,050,386	**$2,395,757**
Option 3: 3 spaces @ 28-foot Bridge	44,780	26,641	25,731	$3,453,666	$97,152	**$3,550,818**

Note: Options with the best life cycle cost-effectiveness are highlighted in green.

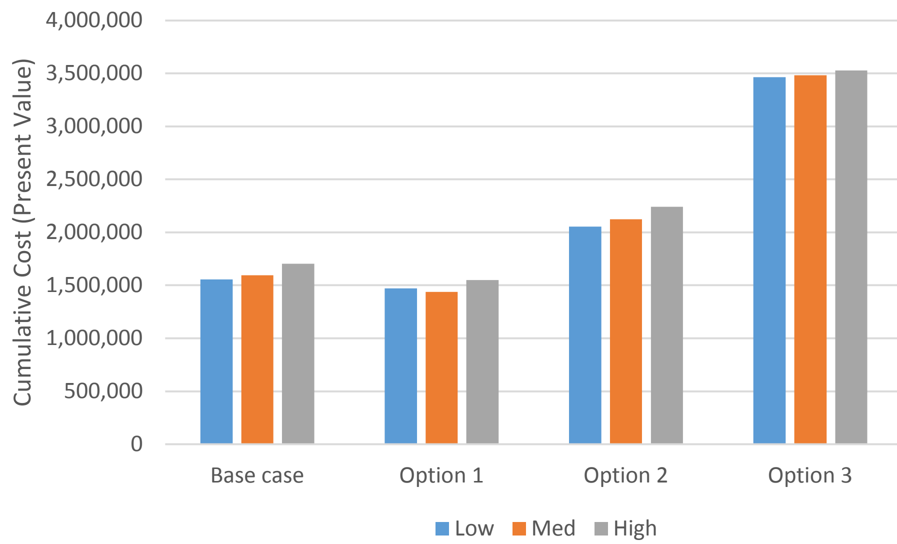


Figure 43: Cost Effectiveness of Culvert 5722 Adaptation Options *Without* Social Costs

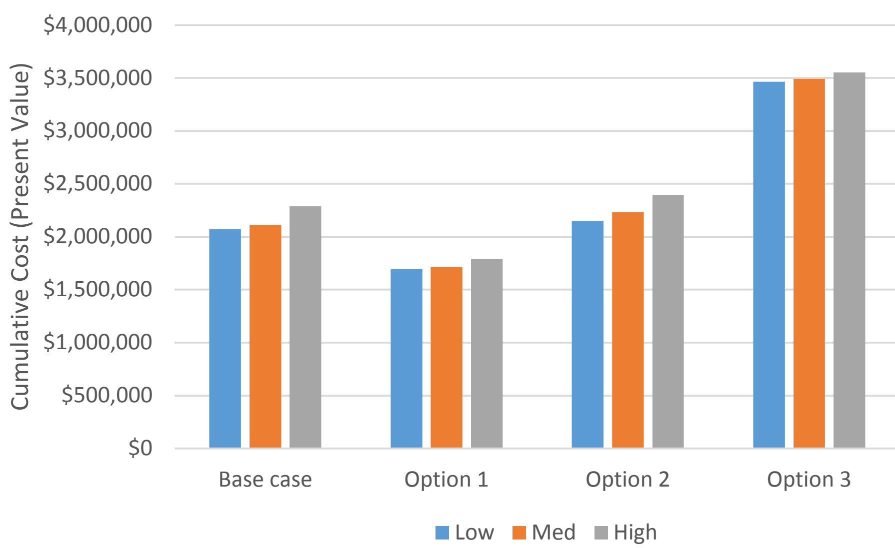


Figure 44: Cost Effectiveness of Culvert 5722 Adaptation Options *With* Social Costs

Each of these factors, along with other possible factors related to sustainability, permitting, project feasibility and practicality, ongoing maintenance needs, capital funds availability, and project risk should be considered along with the cost-effectiveness results, to select a design the provides the greatest value to the Department and the community.

Step 10—Select a Course of Action

Based upon the results of the economic analysis, Option 1 is recommended for the site. However, additional conditions such as upstream flooding of private property, TMDL credit needs, and the project permitting requirements will need to be fully considered before a final course of action can be selected.

Step 11—Plan and Conduct Ongoing Activities

After construction, facility performance should be monitored and recorded in an asset management database. As in the Silver Creek case study, specific items that should be recorded include frequency of overtopping, duration of closures, whether injuries resulted from the overtopping, and any damage costs. Instances where an adaptive design prevented the incurrence of costs relative to a traditional design should also be noted and a tally maintained of costs avoided. In the case of Culvert 5622, any changes in the flooding patterns of adjacent properties attributable to the design option chosen should also be monitored. All of this information will aid in future decision-making for this and other assets.

3.4 Action Items

Given the experience with the case study process, MnDOT is considering the following action items with respect to adaptation assessments for individual transportation facilities:

- **Project Planning and Design**
  - Consider conducting facility-level adaptation assessments on assets from the system-wide vulnerability analysis that are under-capacity (not capable of passing the 50-year design storm), have high social costs of failure (high traffic volumes or long detour routes), and are not planned for replacement.
  - Consider conducting facility-level adaptation assessment process on all major projects with potential exposure to climate change moving forward.
  - Use facility-level adaptation assessment process to justify betterments through ER funding after flooding damage occurs.
- **Capital Planning**
  - Incorporate cost-effective proactive adaptation projects from facility-level assessments into the capital plan.
- **Research**
  - Monitor updates to climate projections and advances in climate downscaling[34] methodologies.

[34] Downscaling refers to the process of translating coarse geographic resolution climate projections from GCMs into higher geographic resolution projections more relevant for site level analyses.

4 Lessons Learned and FHWA Vulnerability Framework Recommendations

MnDOT's approach to understanding flood vulnerabilities of the roadway system was unique, pivoting off asset data and also specific spatial analysis techniques to develop a methodology which was markedly different from other efforts conducted nationally to date. The efforts to accomplish this work required the development of new processes and methods for applying data analysis that required some trial and error and also robust dialogue on the processes applied. Lessons learned on the project range from concerns about the use of climate model generated precipitation data in decision-making to an identified unease in changing established methods for project-level decision-making. A summary of some of the lessons learned on this project are identified below. They include:

- The FHWA framework guidance on identifying system vulnerabilities needs more specifics on how system-wide analyses should be completed from a technical perspective. It is a significant effort to get to a level of specificity required for decision-making at the individual asset level.
- The FHWA vulnerability framework merges sensitivity, exposure and adaptive capacity into one score. Methods that allow for assessments for a range of risk factors both with and without adaptive capacity measures may be a more appropriate method for identifying specific risks.
- Use of climate model data to identify spatial differences in future precipitation projections at a geographic area less than statewide for the system-wide vulnerability analysis were identified as unacceptable by the CAC
- Use of climate model data to derive future precipitation levels was questioned due to the range of potential errors from generating the data. There is some level of discomfort in using that information for decision-making.
- The state of Minnesota has collected detailed LIDAR data statewide, however, the use of this data to generate drainage areas for each asset (bridge, culvert, etc.) using an ArcGIS software extension called ArcHydro was identified as problematic given the presence of "digital dams" in the dataset (i.e. instances where water is conveyed through an embankment by a culvert that is not recognized in the LIDAR data). Using this data to generate detailed drainage areas would require a major allocation of resources to accomplish. Fortunately, StreamStats was available in Minnesota to aid in this task on this study although some loss of precision was accepted given that it uses a courser elevation dataset than the statewide LIDAR data.
- There are few off the shelf methods or tools for generating information specific to each asset and drainage area. Doing this work requires development of specialized GIS processes to generate results.
- Limitations of data at the asset level which can help drive analysis similar to the work completed for this project is often limited as it is not a normal part of asset data collection. Data collected at the asset level which identifies values such as culvert slope, waterway opening, flood history, and other similar information for each asset is beneficial to the assessment process. Incorporating additional data collection effort as part of asset management methods would increase its use in vulnerability assessments.
- The uncertainty assumed as part of climate data is an uncomfortable leap for engineers who have worked primarily with statistically derived data from the past to identify asset risk.

5 Conclusions and Next Steps

MnDOT's effort to define system vulnerabilities across Districts 1 and 6 were a significant step toward defining the indictors of risk for assets on its roadway network. This effort is like no other conducted to date and the work efforts of MnDOT staff that contributed their time and efforts to conducting this work and defining potential risks to the transportation system needs to be mentioned. MnDOT's work will stand as a significant initial effort in creating a data driven analysis that identifies asset details that can be scored and compared amongst other various assets.

Work efforts on this project included the assembly of asset data for culverts and bridges from various sources and technical analysis. The work effort for this project was an intensive data analysis effort and assembling data across such a wide range of assets is a testament to MnDOT's commitment to its asset management systems and its work as steward of the transportation system.

The work effort to reach the project conclusion and the dialogue conducted to reach the end of the project point to a few key next steps to further ingrain the dialogue and assessment methodologies within MnDOT business practices. In addition to those relating specifically to the system-wide and facility level assessments mentioned earlier in the report, more general next steps to follow from this significant work effort include:

- Undertake education/dialogue throughout the agency on the flooding/climate change issues and the methodology employed in this study.
- Use the results of this study to make the case for additional funding resources from the legislature for future flood vulnerability assessment and adaptation work.
- Share results of this work with other state and local agencies and establish a collaborative effort to better define and address risks.

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Appendix A System-wide Hydraulic Model Screening Tool

The system-wide hydraulic model screening tool (the "Tool") was developed by Parsons Brinckerhoff for the purpose of computing various hydraulic parameters as related to transportation infrastructure, based upon information contained within a department of transportation's asset management database. Under the MNDOT pilot, Parsons Brinckerhoff developed individual customizations to allow the tool to interface with MNDOT's asset management database.

In the MNDOT version of the Tool, the Tool was broken into four modules to develop the hydraulic metrics selected for the system-wide vulnerability analysis. These modules include: bridge, large culverts, pipes, and roadways parallel to streams. A brief overview of each module is provided below.

Bridge Module

The Bridge Module has been developed to provide computation for the overtopping flow for both bridge high flow condition and low flow / perched bridge conditions. The module computed bridge geometry based upon a total bridge span length, a defined number of piers, an average roadway elevation at the bridge abutments, and an average channel slope.

The model solves for the waterway opening based upon a relationship between total deck thickness and span length, the average roadway elevations, the total span length, and bankfull channel geometry. The deck thickness relationship was developed by Parsons Brinckerhoff based on AASHTO data. The total span length is skew adjusted based on the information presented in the asset management database. The bankfull channel geometry is determined based upon regional regression equations with data from the Red River used for all channels with slopes less than 0.5 percent and the Allegheny Plateau curves used as a surrogate for the Superior Upland curves on all slopes over 0.5 percent. The development of better regional bankfull curves is a recommended area of improvement for the MNDOT pilot project. Lastly, the bridge abutment treatments were assumed based upon the relationship of span length to the channel bankfull width. In cases where a spill through abutment with 2H:1V riprap slopes will fit with the bankfull channel width, the spill through abutment was selected for the bridge geometry. For cases where the spill through abutment does not fit, a vertical abutment was selected to define the bridge geometry.

The high flow bridge model determines which computation method to utilize based on a comparison of the roadway sump elevation to the bridge low chord elevation (bottom of the bridge span or girders). For cases where the sump is above the bridge low chord, the high flow computational conditions are used. For cases where the sump is below the bridge low chord, the low flow / perched bridge computation conditions are used.

The high flow computations compute discharge based first upon a modified orifice flow equation. This equation is presented as Equation 5-15 in the HEC-RAS Hydraulic Reference Manual. The bridge computation is checked for convergence relative to a manning's computation at an assumed downstream cross-section. The downstream cross-section is modeled based upon the average channel slope, the bankfull channel geometry, and reductions in flow area due to bridge ineffective flow zones. If the convergence checks determine that the drawdown across the bridge is not valid for the orifice flow computation, the module replaces the solution with a pressure flow / sluice flow solution, presented as Equation 5-14 in the HEC-RAS Hydraulic Reference Manual. The low flow computations utilize the energy based computational method, with the added frictional losses due to the bridge piers.

Large Culvert Module

The culvert module was developed to compute both inlet control and outlet control conditions for various configurations of pipes. The module is capable of computing discharges for multi-cell culverts. The module does not compute low flow hydraulics and assumes that a perched culvert condition will not be a frequent occurrence. Perched culverts were not noted in the MNDOT pilot, but if infrequent could be computed offline using HY-8.

The large culvert module assumes that all culverts are constructed with headwalls and wingwalls. The module was customized for the MNDOT database to read and interpret the culvert codes (e.g. W108D) into the culvert geometrics (a 10-foot by 8-foot concrete box culvert in the example). The module utilizes the provided codes and regression relationships for common culvert sizes to compute the total waterway opening and hydraulic radius for each culvert cell. The module assumes that the slope of the culvert is equivalent to the average slope of the stream in the vicinity of the culvert crossing.

The culvert module computes inlet control for submerged conditions only (Flow Type 5). The inlet control equations utilized are presented as equation A.3 in the FHWA HDS 5 publication. Unsubmerged conditions for culvert flow will only be required for overtopping conditions with a perched culvert. As previously noted, this condition is anticipated to be rare and would be computed off-line using HY-8. Outlet control conditions for Flow Types 4, 6, and 7 are also computed in the module. These conditions are computed following equations 3.1 through 3.6b as presented in FHWA's HDS 5 publication. The culvert module solves for both inlet and outlet control conditions for each culvert crossing. Once compiled, the lower discharge result (higher energy condition at the upstream culvert approach) from inlet or outlet control is selected as the controlling condition.

Pipe Module

The pipe module is a variant of the large culvert module that has adapted to handle the specific inputs provided by the asset management database for pipe crossings. The governing hydraulic computations from each module are the same. Specific to the pipe module, the Tool utilizes regression equations developed by Parsons Brinckerhoff to determine pipe waterway opening based upon provided pipe span and type. The regression equations were developed based upon pipe data compiled for various manufacturers for elliptical pipes, steel pipe arches, reinforced concrete pipe, corrugated metal pipe, and concrete boxes. Similar to the large culvert module, the pipe module computed inlet and outlet control conditions and is capable of computing discharges for multi-cell crossings.

Roadway Parallel to Streams Module

The roadway parallel to stream module was developed to compute the required overtopping discharge for a discreet section of roadway located near a FEMA defined floodplain. The Tool utilizes Manning's Equation to compute the overtopping discharge for the predefined roadway sections. The channel and floodplain geometry at the overtopping section is developed by the tool based upon a stream's belt width near the roadway and assumed valley wall slopes. The cross-sectional geometry of the valley is constrained based upon the minimum distance of the roadway to the centerline of the stream (stream valley bisected by raised roadway embankment). The module assumes a Manning's n value of 0.1 for floodplains with slopes greater than 0.5 percent and 0.12 for slopes less than 0.5 percent.

Appendix B Scaling Schema for Categorical Metrics

Categories	Scaled Value (0-100)
Scour rating (bridges)	
A, bridge is not over waterway	Not included in study
B, bridge is closed to traffic; field review indicates that failure of piers and/or abutments due to scour is imminent or has occurred	Not included in study (only bridges that are in use are included)
C, bridge is closed to traffic for reasons other than scour. Prior to reopening, the bridge must be evaluated for scour and the scour code must be updated	Not included in study (only bridges that are in use are included)
D, bridge is scour critical; field review indicates that extensive scour has occurred at bridge foundations. Immediate action is required to provide scour countermeasures. Note: this scour code is equivalent to a critical finding.	100
E, culvert structure: Scour calculation, evaluation, and/or screening have not been made	Not included in study as a bridge (included as a large culvert)
F, bridge structure: Scour calculation, evaluation, and/or screening have not been made	50
G, scour calculation, evaluation, and/or have not been made. Bridge on unknown foundations.	50
H, bridge foundations (including piles) are well above flood water elevations	0
I, bridge screened and determined to be low risk for failure due to scour	10
J, bridge screened and determined to be scour susceptible	50
K, bridge screened and determined to be of limited risk to public, monitor in lieu of evaluation and close if necessary	20
L , scour evaluation complete and bridge judged to be low risk for failure due to scour	15
M, bridge foundations determined to be stable for calculated scour conditions; calculated scour depth from the scour prediction equations is above top of footing	10
N, bridge foundations determined to be stable for calculated scour conditions; calculated scour depth from the scour prediction equations is within limits of footings or pilings	20
O, bridge foundations determined to be stable for predicted scour conditions; Scour Action Plan requires additional action	50
P, countermeasures have been installed to correct a previously existing problem with scour. Bridge is no longer scour critical. Scour countermeasures should be inspected during routine inspections (when above water or accessible by wading), during underwater inspections, after major flows, or as recommended in the Scour Action Plan. Report any changes that have occurred to countermeasures.	70
R, bridge has been evaluated and is scour critical. Scour Action Plan recommends monitoring the bridge during high flows and closing if necessary.	95
U, bridge has been evaluated as scour critical and protection is planned in the future. In the meantime follow monitoring requirements in a Scour Action Plan.	95
Substructure condition rating (bridges)	
N, NOT APPLICABLE, Culverts	Not included in study as a bridge (included as a large culvert)
9, EXCELLENT CONDITION	0
8, VERY GOOD CONDITION (no problems noted)	5
7, GOOD CONDITION (some minor problems)	20
6, SATISFACTORY CONDITION (structural elements show some minor deterioration)	35

Categories	Scaled Value (0-100)
5, FAIR CONDITION (all primary structural elements are sound but may have minor section loss, cracking, spalling or scour)	50
4, POOR CONDITION (advanced section loss, deterioration, spalling or scour)	80
3, SERIOUS CONDITION (loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.)	90
2 , CRITICAL CONDITION (advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.)	100
1, "IMMINENT" FAILURE CONDITION (major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.)	Not included in study (only bridges that are in use are included)
0, FAILED CONDITION (out of service—beyond corrective action.)	Not included in study (only bridges that are in use are included)
Channel condition rating (bridges and large culverts)	
9, There are no noticeable or noteworthy deficiencies which affect the condition of the channel.	0
8, Banks are protected or well vegetated. River control devices such as spur dikes and embankment protection are not required or are in a stable condition.	5
7, Bank protection is in need of minor repairs. River control devices and embankment protection have a little minor damage. Banks and/or channel have minor amounts of drift.	30
6, Bank is beginning to slump. River control devices and embankment protection have widespread minor damage. There is minor stream bed movement evident. Debris is restricting the channel slightly.	50
5, Bank protection is being eroded. River control devices and/or embankment have major damage. Trees and brush restrict the channel.	75
4, Bank and embankment protection is severely undermined. River control devices have severe damage. Large deposits of debris are in the channel.	90
3, Bank protection has failed. River control devices have been destroyed. Stream bed aggradation, degradation or lateral movement has changed the channel to now threaten the bridge and/or approach roadway.	95
2, The channel has changed to the extent the bridge is near a state of collapse.	100
1, Bridge closed because of channel failure. Corrective action may put back in light service.	Not included in study (only bridges that are in use are included)
0, Bridge closed because of channel failure. Replacement necessary.	Not included in study (only bridges that are in use are included)
Culvert condition rating (large culverts)	
9, No deficiencies	0
8, No noticeable or noteworthy deficiencies which affect the condition of the culvert. Insignificant scrape marks caused by drift.	5
7, Shrinkage cracks, light scaling, and insignificant spalling which does not expose reinforcing steel. Insignificant damage caused by drift with no misalignment and not requiring corrective action. Some minor scouring has occurred near curtain walls, wingwalls, or pipes. Metal culverts have a smooth symmetrical curvature with superficial corrosion and no pitting.	20

Categories	Scaled Value (0-100)
6, Deterioration or initial disintegration, minor chloride contamination, cracking with some leaching, or spalls on concrete or masonry walls and slabs. Local minor scouring at curtain walls, wingwalls, or pipes. Metal culverts have a smooth curvature, non-symmetrical shape, significant corrosion or moderate pitting.	35
5, Moderate to major deterioration or disintegration, extensive cracking and leaching, or spalls on concrete or masonry walls and slabs. Minor settlement or misalignment. Noticeable scouring or erosion at curtain walls, wingwalls, or pipes. Metal culverts have significant distortion and deflection in one section, significant corrosion or deep pitting.	50
4, Large spalls, heavy scaling, wide cracks, considerable efflorescence, or opened construction joint permitting loss of backfill. Considerable settlement or misalignment. Considerable scouring or erosion at curtain walls, wingwalls or pipes. Metal culverts have significant distortion and deflection throughout, extensive corrosion or deep pitting.	70
3, Any condition described in Code 4 but which is excessive in scope. Severe movement or differential settlement of the segments, or loss of fill. Holes may exist in walls or slabs. Integral wingwalls nearly severed from culvert. Severe scour or erosion at curtain walls, wingwalls or pipes. Metal culverts have extreme distortion and deflection in one section, extensive corrosion, or deep pitting with scattered perforations.	90
2, Integral wingwalls collapsed, severe settlement of roadway due to loss of fill. Section of culvert may have failed and can no longer support embankment. Complete undermining at curtain walls and pipes. Corrective action required to maintain traffic. Metal culverts have extreme distortion and deflection throughout with extensive perforations due to corrosion.	100
1, Bridge closed. Corrective action may put back in light service.	Not included in study (only bridges that are in use are included)
0, Bridge closed. Replacement necessary.	Not included in study (only bridges that are in use are included)
Pipe condition rating (pipes)	
1, Excellent (like new condition)	0
2, Fair (some wear, but structurally sound)	20
3, Poor (deteriorated, consider for repair or replacement)	70
4, Very Poor (serious deterioration)	100
0, Not able to rate (not visible)	40
Previous flooding issues	
N, no	0
Y, yes	100
Detour length	
Greater than 50 miles (including cases with no detour alternative)	100
36 to 50 miles	80
21 to 35 miles	60
All shorter detour lengths	Numerically scaled between 0 and 60
Flow control regime	
Inlet/headwater controlled	0
Outlet/tailwater controlled	100