MnDOT Flash Flood Vulnerability and Adaptation Assessment Pilot Project

DISTRICT 6 VULNERABILITY ASSESSMENT

NOVEMBER 2014

This document is part of a series of short reports based on the full Flash Flood Vulnerability and Adaptation Assessment Pilot Project.

This report was developed by the Minnesota Department of Transportation in accordance with a grant from the Federal Highway Administration (FHWA). The statements, findings, conclusions and recommendations are those of the author(s) and do not necessarily reflect the views of FHWA or the U.S. Department of Transportation.

The project was managed by the following staff from the Minnesota Department of Transportation: Bryan Anderson, Sara Dunlap, Marylin Jordahl-Larson, Gregory Pates, Philip Schaffner and Mark Schoenfelder

The full report was prepared by Parsons Brinckerhoff with contributions from Catalysis Adaptation Partners, LLC.

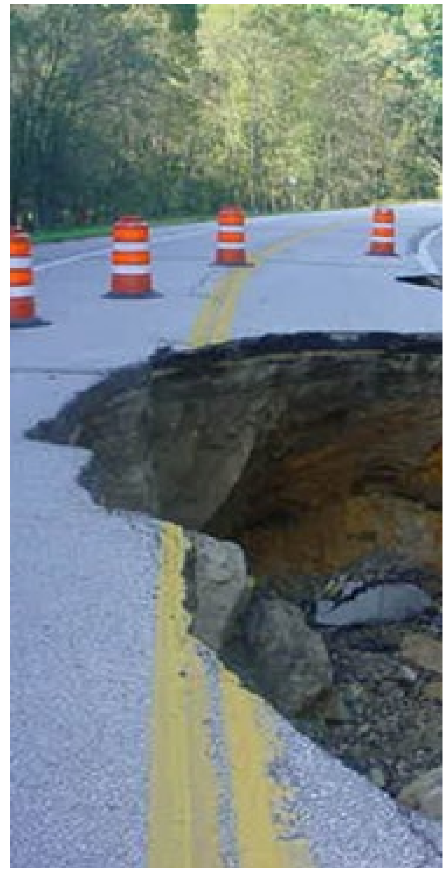
PARSONS BRINCKERHOFF

U.S. Department of Transportation
Federal Highway Administration

Catalysis Adaptation Partners LLC

SYSTEM-WIDE VULNERABILITY ASSESSMENT - MNDOT DISTRICT 6

Introduction



Minnesota's climate is changing. Extreme precipitation events and associated flooding are becoming more frequent and severe.

Flooding presents a challenge to fulfilling the Minnesota Department of Transportation's mission to, "Plan, build, operate, and maintain a safe, accessible, efficient, and reliable multimodal transportation system..." 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.

This document discusses the system-wide vulnerability assessment in District 6. This assessment was part of a broader pilot project investigating the vulnerability of highway infrastructure to climate change in two of MnDOT's eight districts. All components of the pilot project are available at www.mndot.gov/climate and are described in the project's executive summary.

The system-wide vulnerability assessment used the Federal Highway Administration's Climate Change and Extreme Weather Vulnerability Assessment Framework[1] (the "Framework") as a guide. 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. Section 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 describes how this was done consistent with the definition of vulnerability provided in the Framework report. Section 3 then presents the results of the vulnerability assessment.

Section 1: Selection of Assets

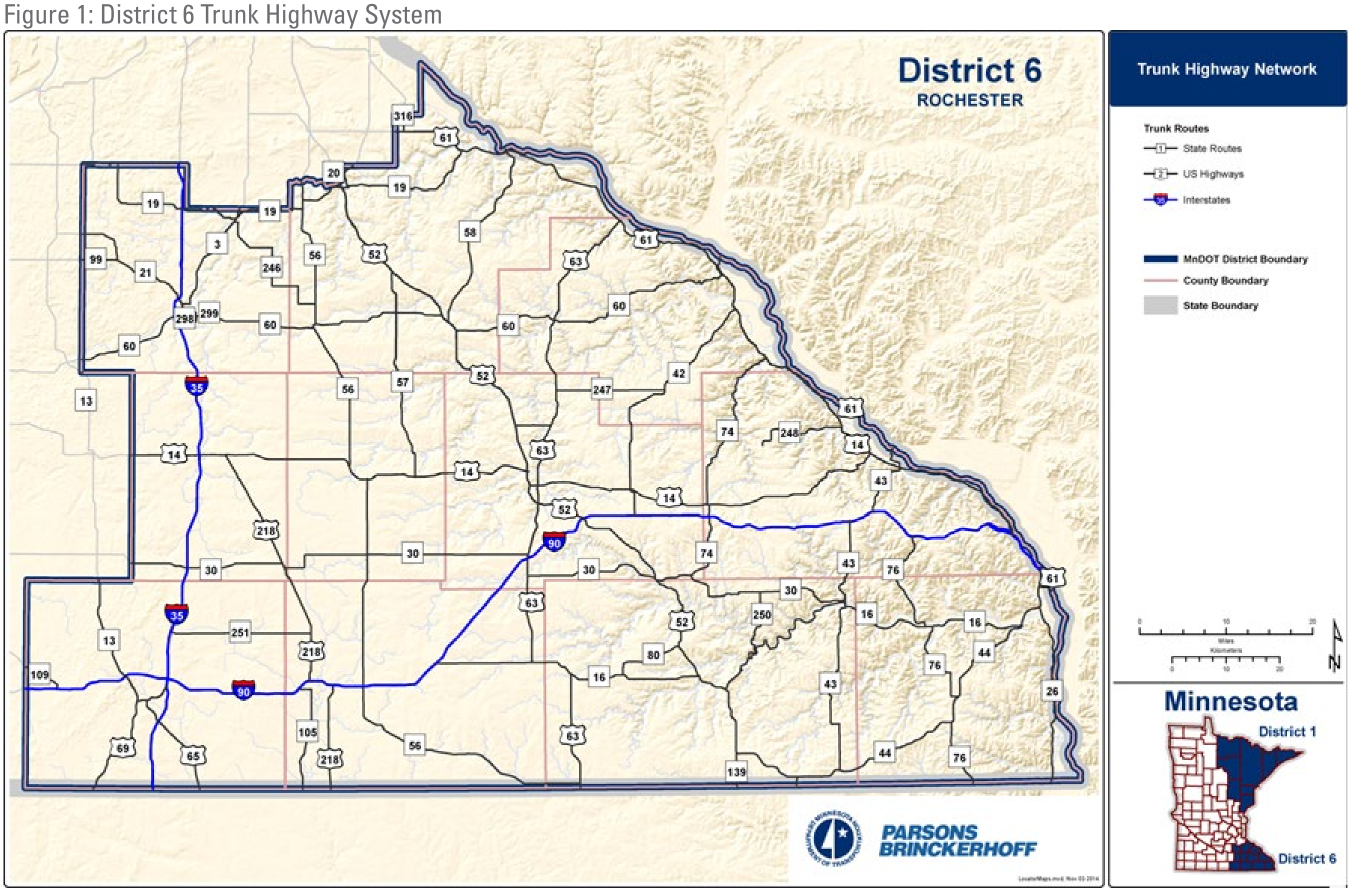
The state's trunk highway system was the roadway network selected for analysis in each district. The trunk highway system comprises the entirety of the state owned and maintained road infrastructure and includes all interstates, US routes, and signed state roads. Figure 1 shows the trunk highway system in District 6. This study considered 176 bridges, 361 large culverts, 377 pipes, and 44 roads paralleling streams in District 6.

1: https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/task_3.2/

Section 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 2, 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.

Figure 1: District 6 Trunk Highway System



VULNERABILITY DEFINITION

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

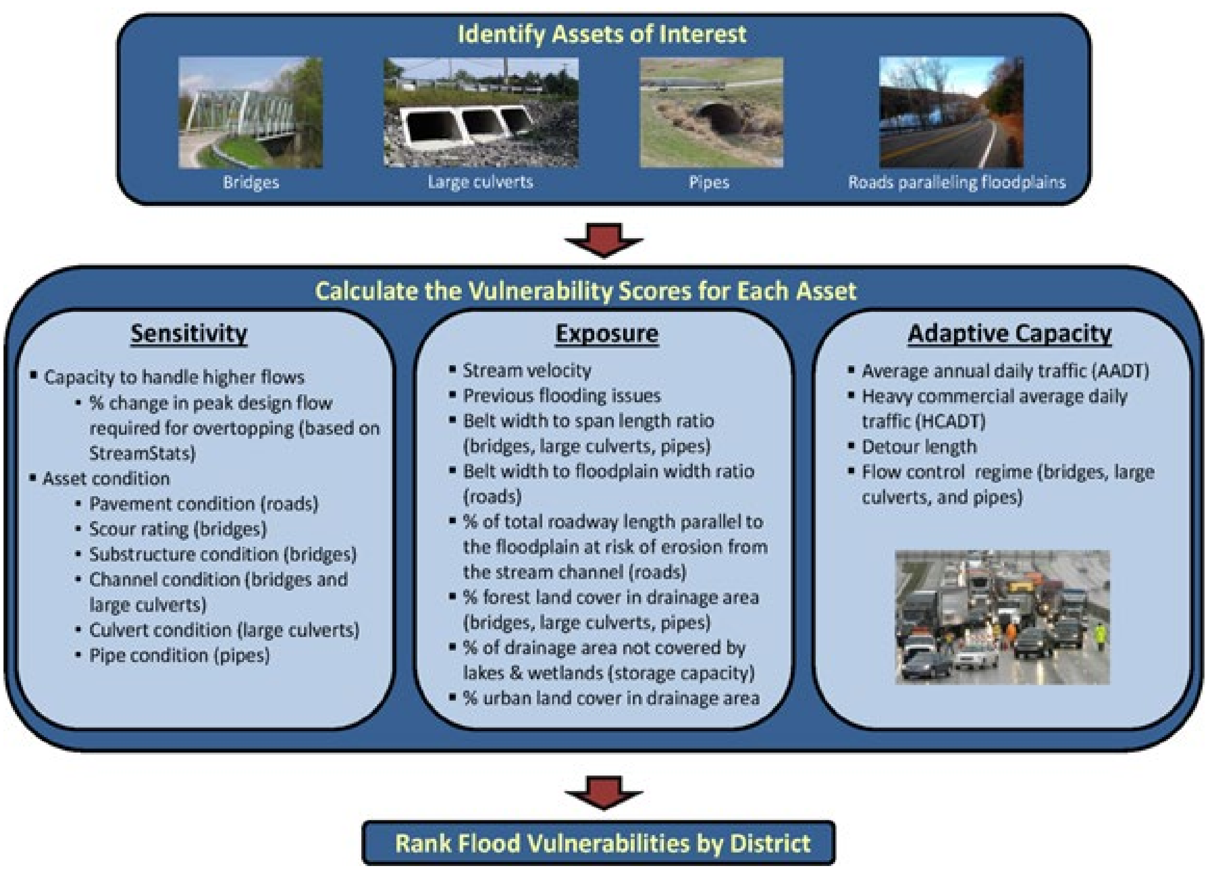
- **Exposure:** The degree to which an asset may be affected by a climate stressor.
- **Sensitivity:** How well an asset impacted by a climate stressor is able to cope with the impacts.
- **Adaptive Capacity:** How resilient the transportation system as a whole is if the asset were to be taken out of service.

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

METRICS

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 list 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.

Figure 2: Approach to Flood Vulnerability Analysis



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.

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.

Figure 3: Locations of previous flooding identified by District staff

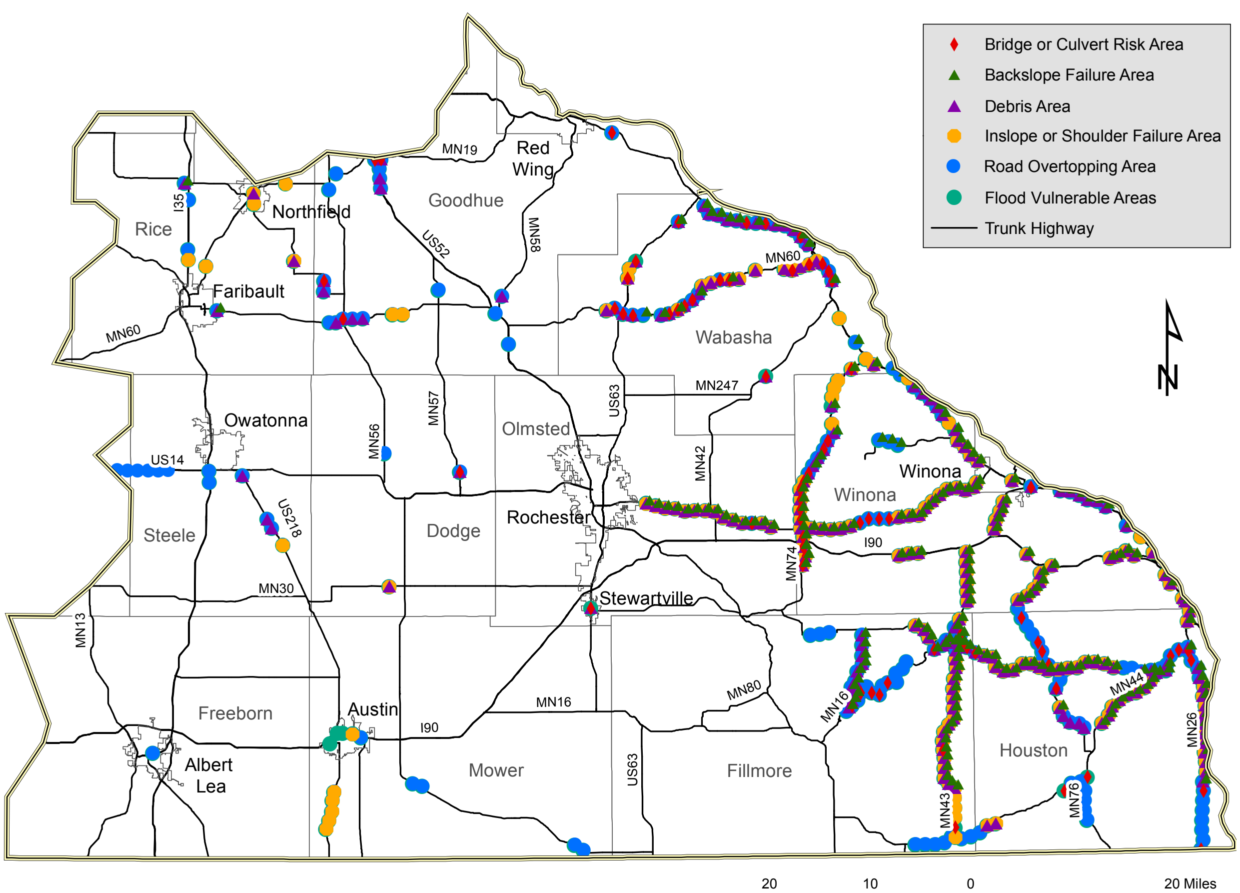


Table 1: Description and Summary of Metrics Used to Quantify Flood Vulnerability

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

1: Belt width refers to the lateral width of stream meanders

Metric	Description	Rationale for Inclusion	Data Source	Asset Type Applied To			
				Bridges	Large Culverts	Pipes	Roads Paralleling Streams
Sensetivity							
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	
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	

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

SCORING

Once all the metrics had been calculated, the next step was to combine the information into a single overarching vulnerability score for each asset. Table 2 (page 10) 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 Technical Advisory Committee (TAC).

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 (page 11) 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).

An additional analysis was conducted after the completion of the full report that used only exposure and sensitivity metrics. This analysis better isolates assets that are more at risk of flooding (regardless of role within the network). Appendix B shows how removing the purely traffic volume dependent adaptive capacity considerations affected an asset's tier (higher tier refers to greater vulnerability).

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

Table 2: Example Vulnerability Scoring Process for a Hypothetical 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

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.

Table 3: Weights Assigned by Metric

Metric	Asset Type Applied To			
	Bridges	Large Culverts	Pipes	Roads Paralleling Streams
Exposure				
Stream velocity	20%	20%	20%	10%
Previous flooding issues	35%	35%	35%	30%
Belt width1 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 area2	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%

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 occur at the district level. It is helpful to have a summary of the greatest vulnerabilities by district to inform these activities.
- In the future, additional districts around the state may have similar vulnerability assessments completed. If the analysis was set up to compare results between districts, new results would need to be generated for all districts based on the updated vulnerability assessments.

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.

Section 3: Findings

Figures 4 and 5 provide graphs showing the breakdown of asset types within each vulnerability tier in District 6 both with and without adaptive capacity considerations. Bridges and roads paralleling streams were the asset types that had the greatest proportions of highly vulnerable Tier 1 and Tier 2 assets. Figures 6 and 7 show the same information presented in terms of the number of assets by tier.

Appendix A contains a suite of maps displaying the locations of assets and their vulnerability tiers. 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). That said high vulnerability facilities are located throughout the district. Appendix B contains maps that display vulnerability data when adaptive capacity weights are removed.

Additional Information

More information about the pilot project including case studies and proposed adaptation options can be found at www.mndot.gov/climate.

Figure 4: Vulnerability by Asset Type District 6

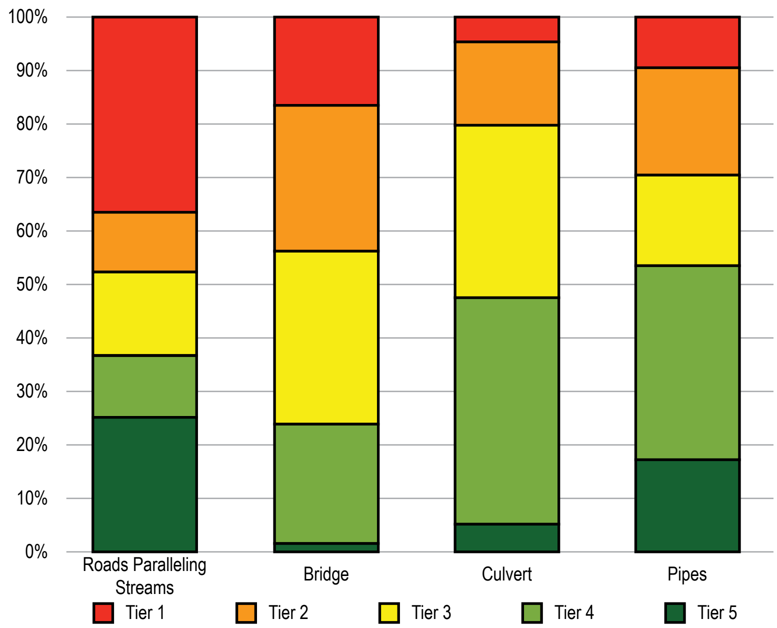


Figure 5: Vulnerability by Asset Type (Exposure & Sensitivity only) District 6

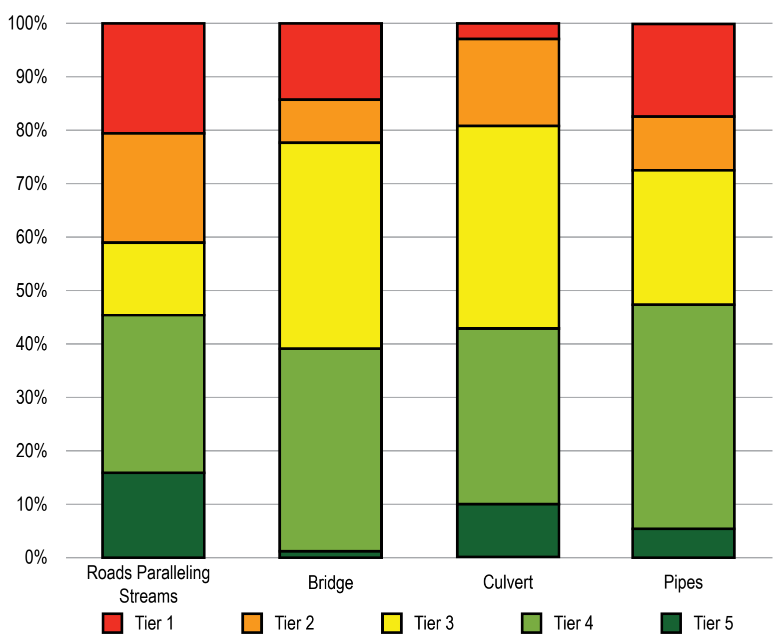


Figure 10: Vulnerability Tiers by Type, District 6

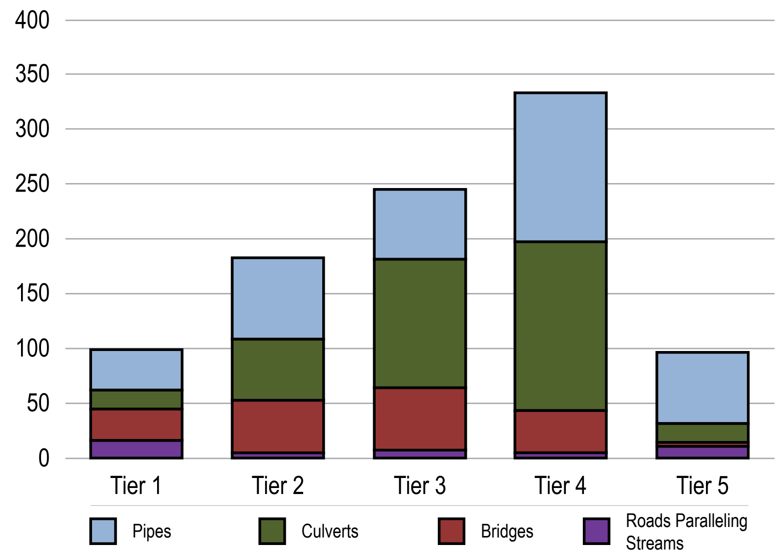
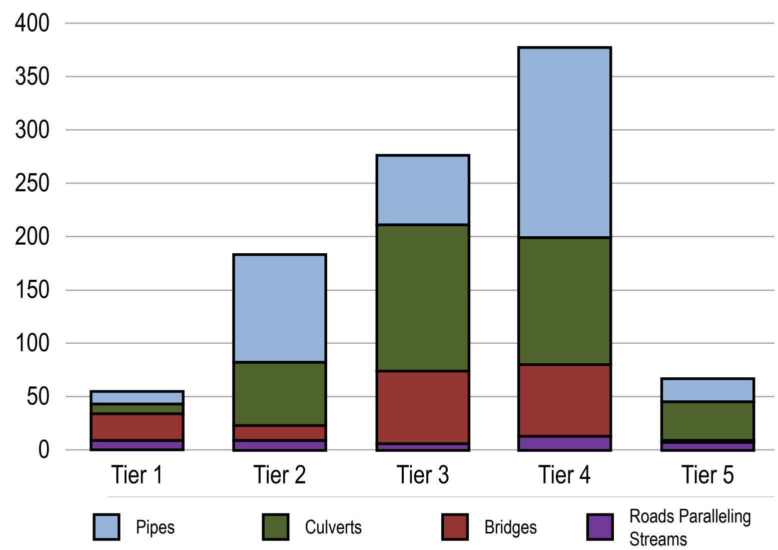
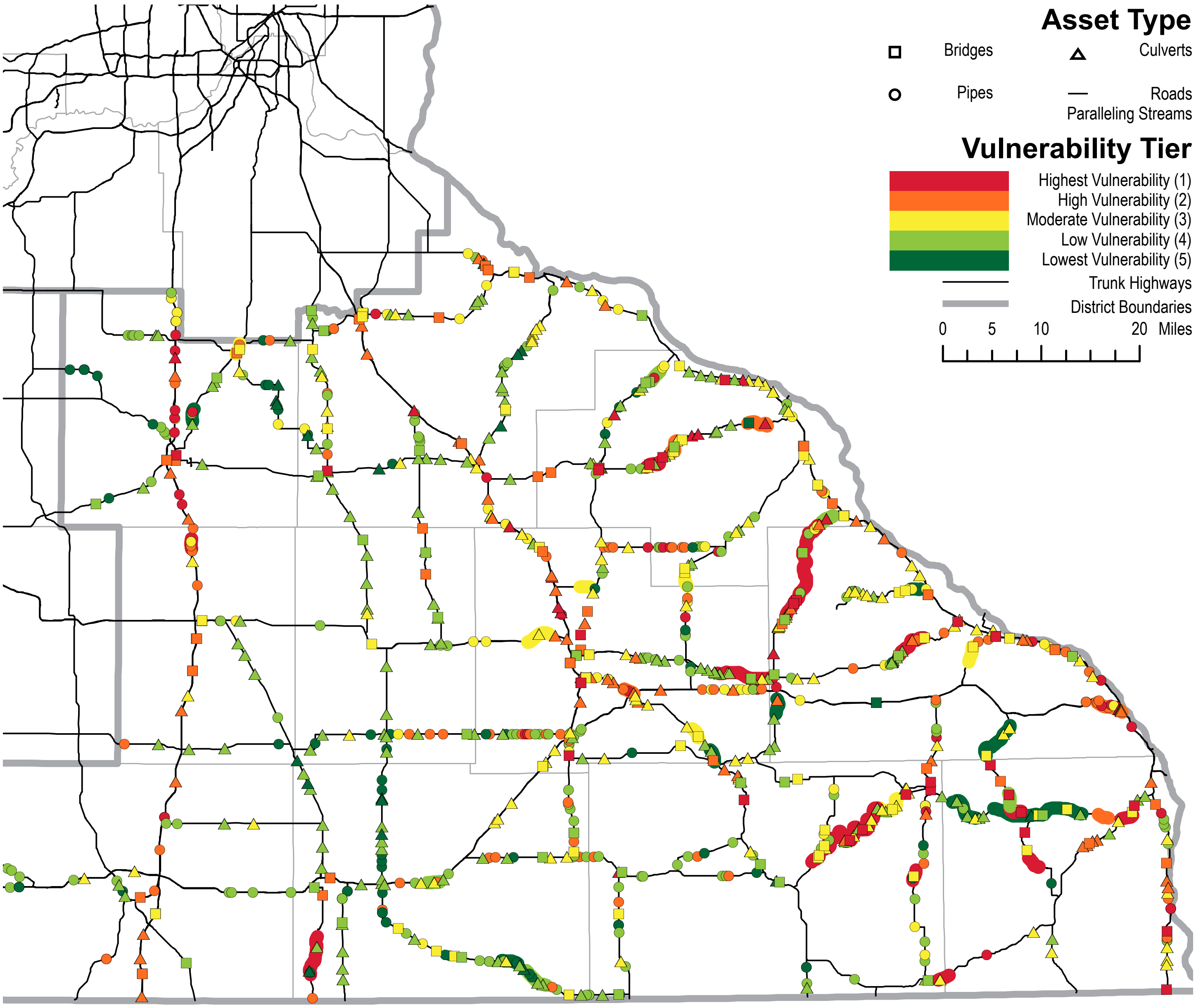


Figure 11: Vulnerability Tiers by Type (Exposure & Sensitivity only) District 6



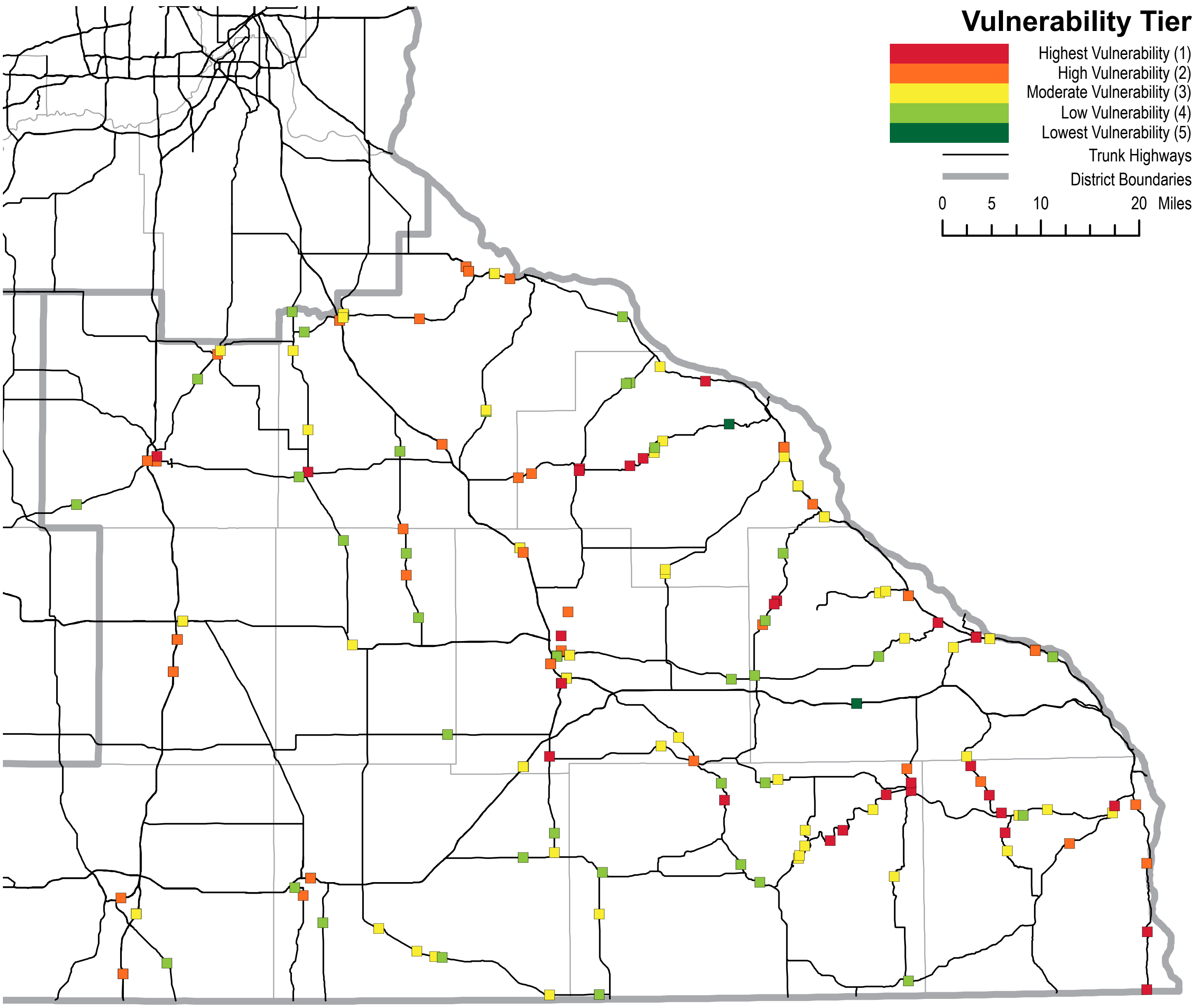
APPENDIX A | ASSET VULNERABILITY MAPS

District 6 Asset Vulnerability Assessment | Weighted by Exposure, Sensitivity & Adaptive Capacity



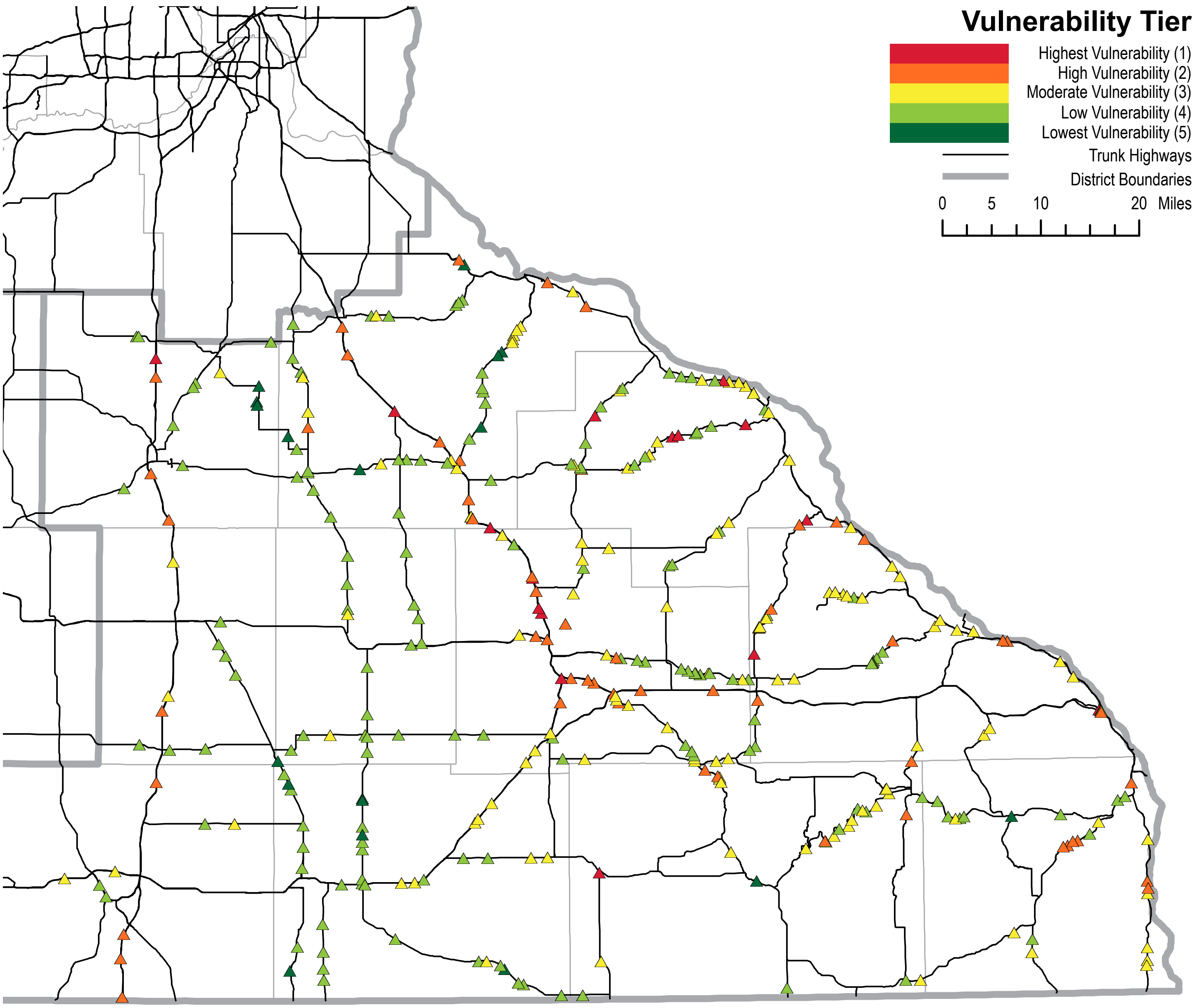
Highly vulnerable (Tier 1 and Tier 2) assets are not necessarily in imminent danger of flooding, nor are lower vulnerability (Tier 4 and Tier 5) assets immune to flooding. These values are indicators of the relative vulnerability of assets compared with other assets in the same district.

District 6 Bridge Vulnerability Assessment | Weighted by Exposure, Sensitivity & Adaptive Capacity



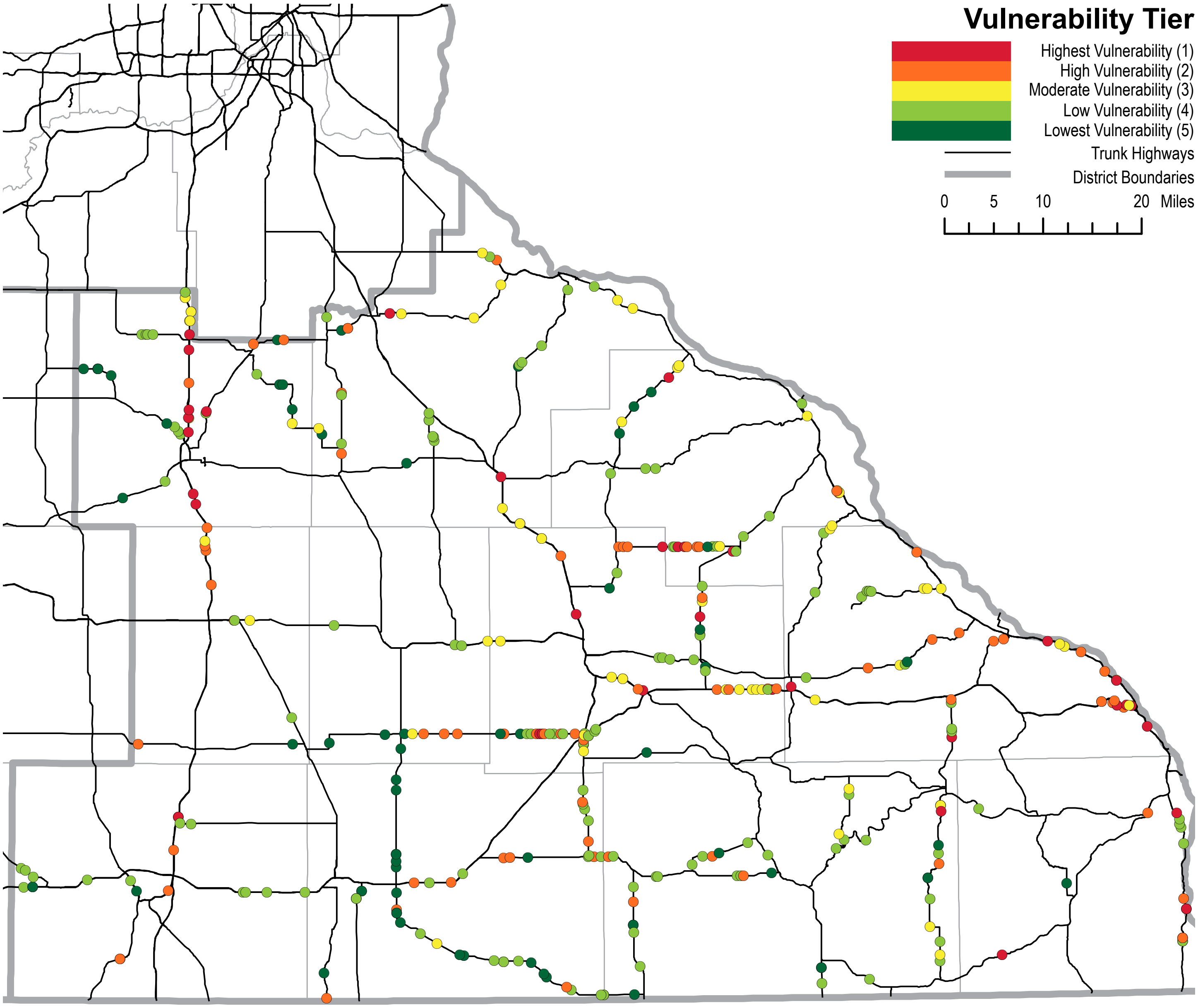
Highly vulnerable (Tier 1 and Tier 2) assets are not necessarily in imminent danger of flooding, nor are lower vulnerability (Tier 4 and Tier 5) assets immune to flooding. These values are indicators of the relative vulnerability of assets compared with other assets in the same district.

District 6 Culvert Vulnerability Assessment | Weighted by Exposure, Sensitivity & Adaptive Capacity



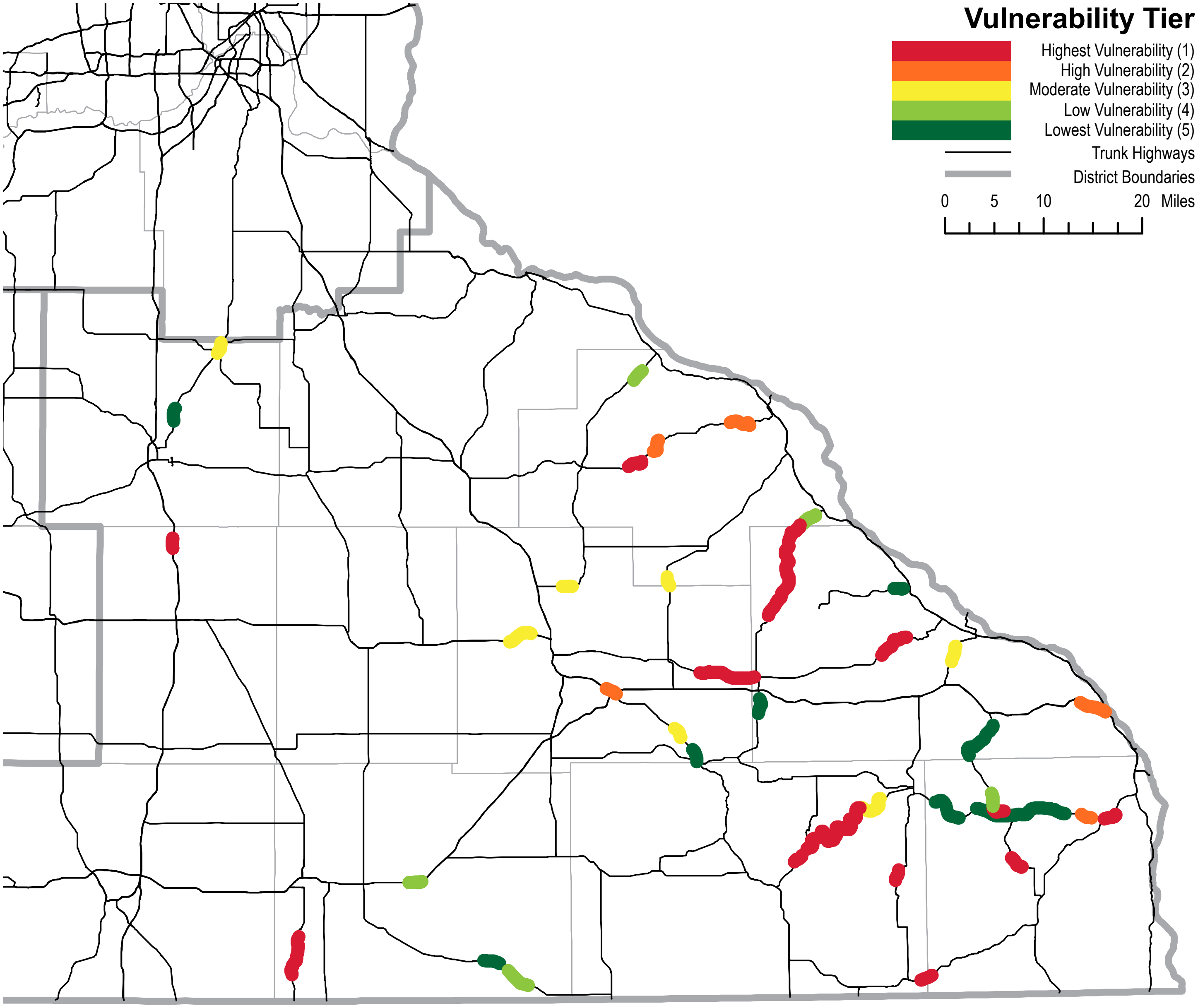
Highly vulnerable (Tier 1 and Tier 2) assets are not necessarily in imminent danger of flooding, nor are lower vulnerability (Tier 4 and Tier 5) assets immune to flooding. These values are indicators of the relative vulnerability of assets compared with other assets in the same district.

District 6 Pipe Vulnerability Assessment | Weighted by Exposure, Sensitivity & Adaptive Capacity



Highly vulnerable (Tier 1 and Tier 2) assets are not necessarily in imminent danger of flooding, nor are lower vulnerability (Tier 4 and Tier 5) assets immune to flooding. These values are indicators of the relative vulnerability of assets compared with other assets in the same district.

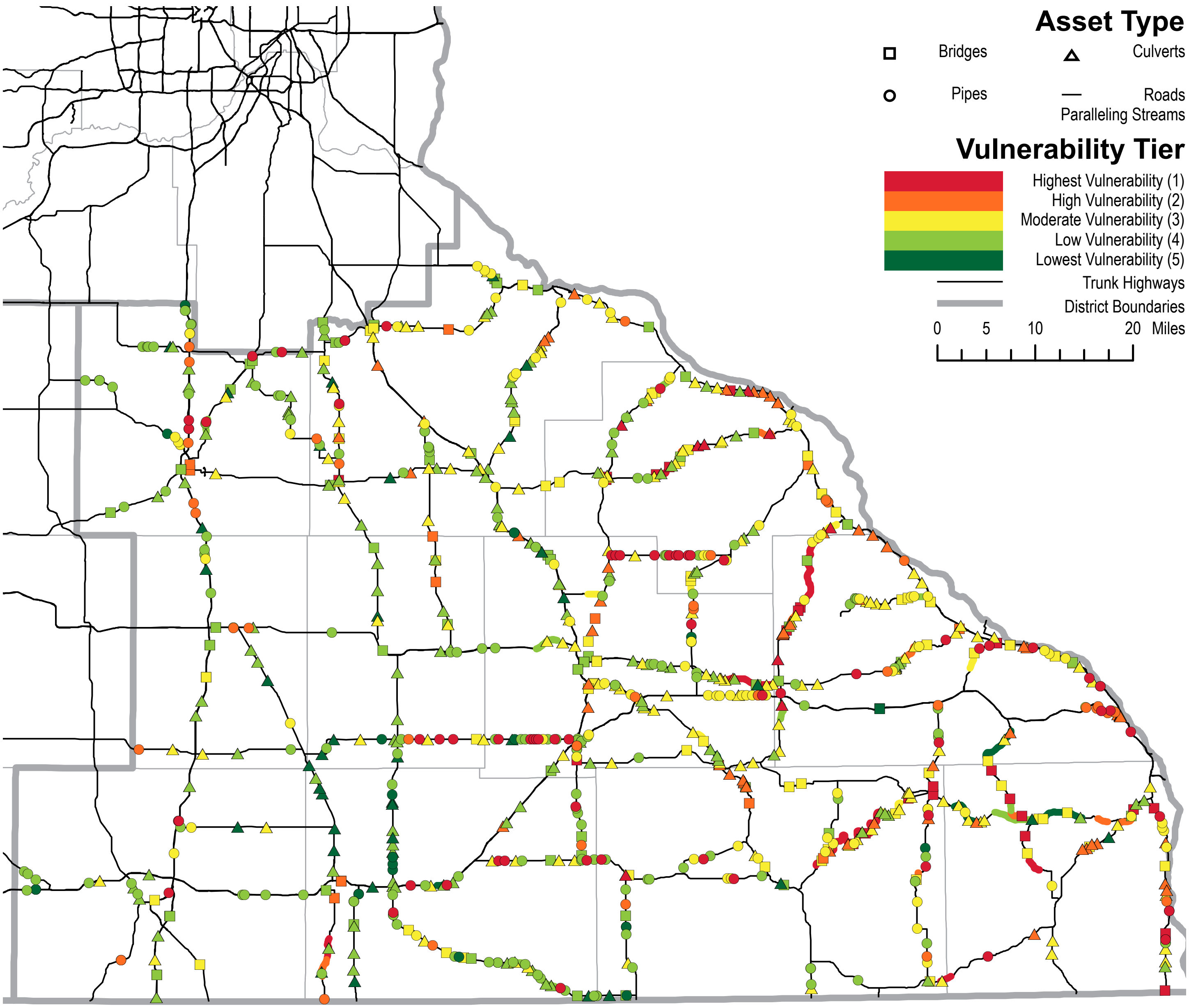
District 6 Roads Paralleling Streams Vulnerability Assessment | Weighted by Exposure, Sensitivity & Adaptive Capacity



Highly vulnerable (Tier 1 and Tier 2) assets are not necessarily in imminent danger of flooding, nor are lower vulnerability (Tier 4 and Tier 5) assets immune to flooding. These values are indicators of the relative vulnerability of assets compared with other assets in the same district.

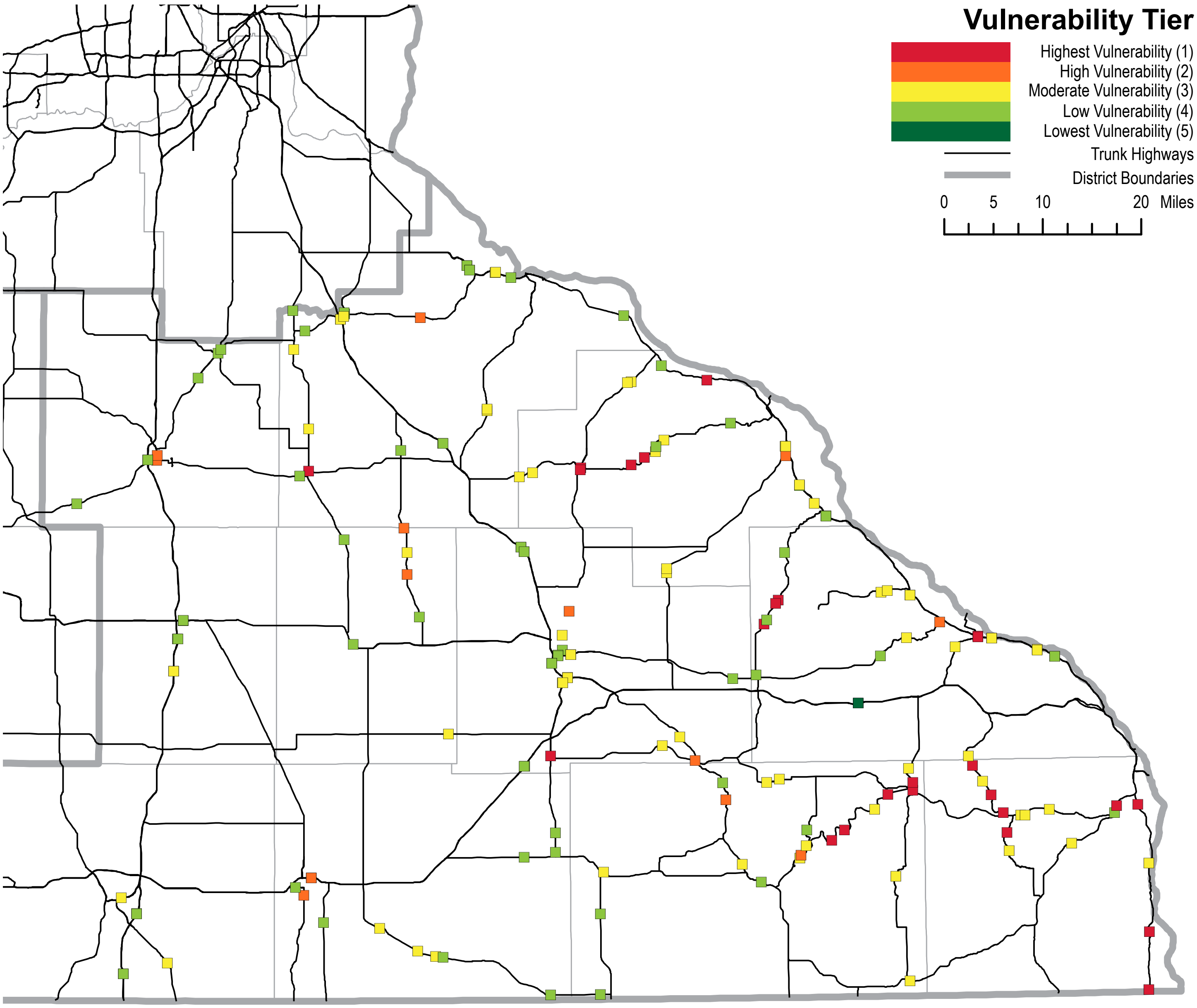
APPENDIX B | ASSET VULNERABILITY (EXPOSURE & SENSITIVITY)

District 6 Asset Vulnerability Assessment | Weighted by Exposure and Sensitivity



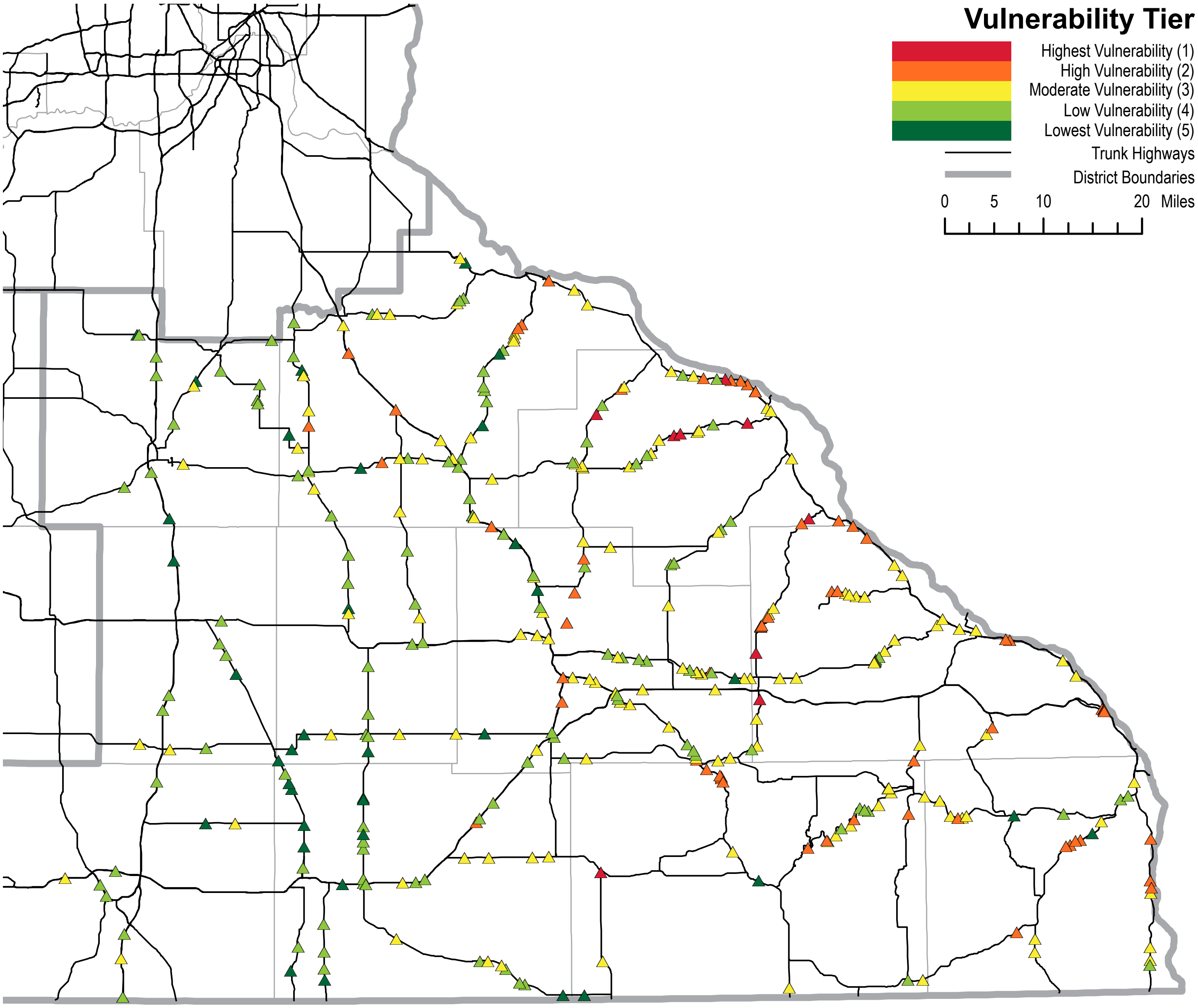
Highly vulnerable (Tier 1 and Tier 2) assets are not necessarily in imminent danger of flooding, nor are lower vulnerability (Tier 4 and Tier 5) assets immune to flooding. These values are indicators of the relative vulnerability of assets compared with other assets in the same district.

District 6 Bridge Vulnerability Assessment | Weighted by Exposure and Sensitivity



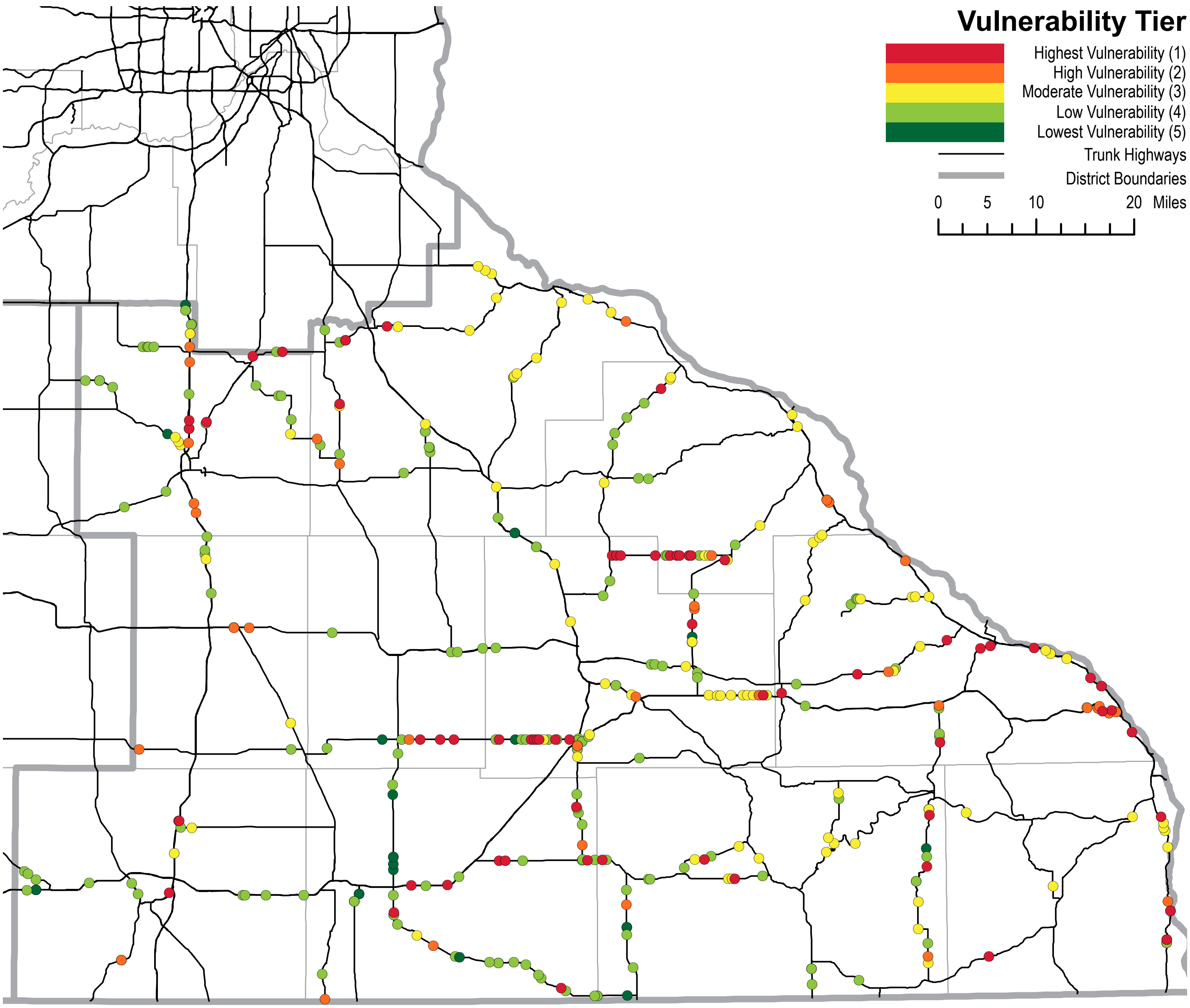
Highly vulnerable (Tier 1 and Tier 2) assets are not necessarily in imminent danger of flooding, nor are lower vulnerability (Tier 4 and Tier 5) assets immune to flooding. These values are indicators of the relative vulnerability of assets compared with other assets in the same district.

District 6 Culvert Vulnerability Assessment | Weighted by Exposure and Sensitivity



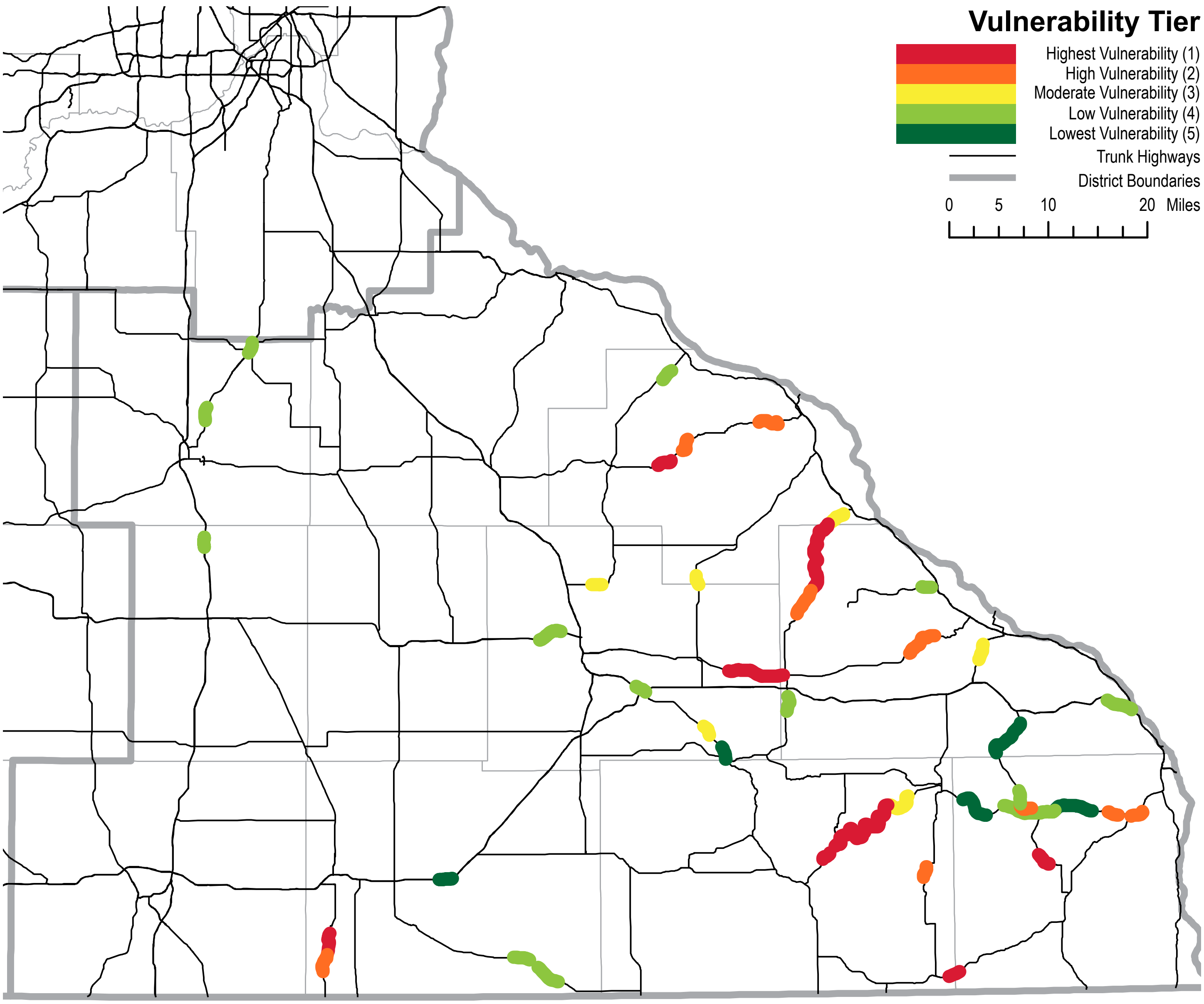
Highly vulnerable (Tier 1 and Tier 2) assets are not necessarily in imminent danger of flooding, nor are lower vulnerability (Tier 4 and Tier 5) assets immune to flooding. These values are indicators of the relative vulnerability of assets compared with other assets in the same district.

District 6 Pipe Vulnerability Assessment | Weighted by Exposure and Sensitivity



Highly vulnerable (Tier 1 and Tier 2) assets are not necessarily in imminent danger of flooding, nor are lower vulnerability (Tier 4 and Tier 5) assets immune to flooding. These values are indicators of the relative vulnerability of assets compared with other assets in the same district.

District 6 Roads Paralleling Streams Vulnerability Assessment | Weighted by Exposure & Sensitivity



Highly vulnerable (Tier 1 and Tier 2) assets are not necessarily in imminent danger of flooding, nor are lower vulnerability (Tier 4 and Tier 5) assets immune to flooding. These values are indicators of the relative vulnerability of assets compared with other assets in the same district.