A RISK-BASED ASSESSMENT TOOL TO PRIORITIZE ROADWAY CULVERT ASSETS FOR CLIMATE CHANGE ADAPTATION PLANNING

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A RISK-BASED ASSESSMENT TOOL TO PRIORITIZE ROADWAY CULVERT ASSETS FOR CLIMATE CHANGE ADAPTATION PLANNING

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God has cared for these trees, saved them from drought, disease, avalanches, and a thousand straining, leveling tempests and floods; but he cannot save them from fools...

~ John Muir (1901)

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GLOSSARY

Adaptive capacity:	The "ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences." (IPCC 2007)
Climate impact exposure:	The geospatial arrangement of changes in climate such that different spatial areas (and the assets in those areas) are subjected to different physical manifestations changes in climate.
Condition data:	Data that describes the physical condition of various aspects of an infrastructure asset.
Criticality:	The relative importance of a transportation infrastructure asset with respect to other similar assets, based upon several specified characteristics.
Performance data:	Data that describes the functional performance of a culvert asset and its ability to perform at its intended design specifications.
Risk:	Traditionally refers to random adverse events with probabilities of occurrence that can be statistically calculated (Knight 1921), and is determined as a combination of (1) the *likelihood* of an adverse event, and (2) the *consequences* of that adverse event.

Uncertainty:	Randomness in events that cannot be predicted by statistical probability (Lofstedt and Boholm 2009), or more broadly, “any departure from the unachievable ideal of complete determinism.” (Walker et al. 2003)
Vulnerability:	“The degree to which a system is susceptible to, and unable to cope with, adverse” events (IPCC 2007); characterized as a function of that system’s: (1) sensitivity to climate impacts, (2) adaptive capacity, and (3) exposure to climate impacts (Adejuwon et al. 2001).

LIST OF SYMBOLS AND ABBREVIATIONS

AADTT	Average Annual Daily Truck Traffic
AAM	Ancillary Asset Management
AASHTO	American Association of State Highway and Transportation Officials
ABP	Assumption Based Planning
ACA	Advanced Condition Assessment
ADT	Average Daily Traffic
AGCM	Atmospheric General Circulation Model
AHP	Analytical Hierarchical Process
AOGCM	Atmospheric-Oceanic General Circulation Model
AOR	Adjusted Overall Rating
AR1	First Assessment Report (IPCC)
AR4	Fourth Assessment Report (IPCC)
BCA	Basic Condition Assessment
BIRM	Bridge Inspector’s Reference Manual
BMS	Bridge Management System
CAP	Culvert Asset Prioritization
CCAAF	Culvert Climate Adaptation Assessment Framework
CCIAV	Climate Change Impact Adaptation and Vulnerability
CFC	Chlorofluorocarbon
CIM	Culvert Inspection Manual
CMIP3	Coupled Model Intercomparison Project – Phase Three

CMM	Culvert Management Manual
CMS	Culvert Management System
CONUS	Contiguous United States
DAP	Dynamic Adaptive Planning
DEFRA	Department for Environment, Food and Rural Affairs (UK)
DOT	Department of Transportation
DSS	Decision Support System
EC	Economic Criticality
EFRI	Engineering Forensics Research Institute
EMIC	Earth Model of Intermediate Complexity
FAF	Freight Analysis Framework
FHWA	Federal Highway Administration
FLH	Federal Lands Highway
GCM	General Circulation Model
GDP	Geo Data Portal
GEV	Generalized Extreme Value (statistical distribution)
GHG	Greenhouse Gas
GIS	Geographic Information System
HPMS	Highway Performance Monitoring System
HS	Health and Safety
IAMC	Integrated Assessment Modeling Consortium
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization

LCSR	Large Culvert Sufficiency Rating
LRFD	Load and Resistance Factor Design
LTAP	Local Technical Assistance Program
MCDA	Multicriteria Decision Analysis
MDT	Montana Department of Transportation
MMD	Multi-Model Dataset
MnDOT	Minnesota Department of Transportation
MRUTC	Midwest Regional University Transportation Center
MSU	Montana State University
NARCCAP	North American Regional Climate Change Assessment Program
NBI	National Bridge Inventory
NCEP	National Centers for Environmental Prediction
netCDF	Network Common Data Format
NHPN	National Highway Planning Network
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NYSDOT	New York State Department of Transportation
OAR	Overall Average Rating
ODOT	Oregon Department of Transportation, or Ohio Department of Transportation
OGCM	Oceanic General Circulation Model
OP	Operational
ORITE	Ohio Research Institute for Transportation and the Environment

PCMDI	Program for Climate Model Diagnosis and Intercomparison
PDSI	Palmer Drought Severity Index
PMS	Pavement Management System
R-CAP	Robust Culvert Asset Prioritization
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
REU	Research Experience for Undergraduates
SAW	Simple Additive Weighting
SCM	Simple Climate Models
SMS	Safety Management System
SQL	Structured Query Language
SRES	Special Report on Emission Scenarios
STRAHNET	Strategic Highway Network
TAM	Transportation Asset Management
TAR	Third Assessment Report (IPCC)
TRB	Transportation Research Board
UNFCCC	United Nations Framework Convention on Climate Change
USGCRP	United States Global Change Research Program
USGS	United States Geologic Survey
VDOT	Virginia Department of Transportation
WG2	Working Group II (IPCC)
WSDOT	Washington State Department of Transportation
WTI	Western Transportation Institute

SUMMARY

In 2007, the United Nations Intergovernmental Panel on Climate Change (IPCC) reported that "warming of the climate system is unequivocal," suggesting that these changes will result in regional climate impacts, including an increase in the frequency of heavy precipitation. There is growing concern in the United States and abroad that these changes may have serious adverse impacts on communities and their civil infrastructure systems. In response, governments and agencies have begun to investigate adaptation: actions taken to reduce the vulnerability or increase the resiliency of natural and human systems in light of expected climate change. In the transportation sector, adaptation planning has predominantly pursued risk-based strategies that seek to identify climate impacts, and assess infrastructure vulnerabilities across multiple asset types, in network-level planning. However, given the complexity of the myriad asset types of which engineered civil infrastructure systems are composed, these frameworks may not adequately address the unique concerns of these various individual asset types.

This research develops a risk-based framework to assess and prioritize at a network-level the risks of highway culvert assets to the projected impacts of climate change, specifically focusing on increases in extreme precipitation, and the associated potential for flooding. This research then applies the framework in a series of case studies using culvert management data provided by four state DOTs, and national climate change projection and infrastructure datasets. In doing so, this research develops a new characterization of infrastructure climate change risk, based upon the catastrophe model, to address the need for qualitative and mixed-methods approaches to risk given the uncertain nature of climate change, and the sometimes sparse inventory and attribute data for various assets. This characterization proposes three “dimensions” of infrastructure climate risk (climate change impact exposure, asset climate impact vulnerability, and asset criticality) to assign culvert asset priorities. The research develops a method to project the geospatial extent and changes in magnitude of extreme precipitation events; it also develops two simple measures of culvert vulnerability to increased flow conditions based upon data collected as part of general culvert management activities.

With its results, this research demonstrates that existing data sources can be reasonably combined in an analytical assessment framework to identify climate change impact risks to highway culvert assets, providing an additional resource to the existing climate change adaptation planning toolkit in the transportation infrastructure sector, and also laying a foundation for further refinement of these methods. Specifically, the results of this research demonstrate that existing climate change projection data, when used alongside culvert inventory and attribute data, provides a reasonable means by which to analyze the projected exposure of culvert assets to climate change impacts. This research also demonstrates that existing culvert management data provides a reasonable foundation upon which to assess the relative vulnerability of culverts to increased flow conditions, although additional research is necessary to develop these methods. The structure of the proposed framework provides a viable means by which quantitative climate change projections, asset vulnerability, and asset criticality data can be combined in a mixed-methods approach to qualitatively characterize climate change impact risks to highway culvert assets despite uncertainty in climate change projections and other inputs.

CHAPTER 1

INTRODUCTION

For centuries, humans have built infrastructure to meet the needs of society – water, power, mobility, and others. It has been noted that the design of infrastructure components are heavily influenced by the environment within which they are built (Meyer 2008). Traditionally, design standards have considered environmental conditions to be characterized by some natural variability over time, but that such variability is dispersed around some expected, average value. To ensure that designs are robust in the face of normal environmental variability and extreme events (e.g., heavy precipitation, flooding, high winds, temperature extremes) design standards incorporate elements such as factors of safety or region-specific design criteria. These considerations are not new – evidence suggests that even during the Roman Empire, bridge builders incorporated elements into their designs to account for extreme conditions such as flooding (Smith 1993).

In recent decades, however, there has been increasing evidence that the global climate is changing. In 2007, the United Nations Intergovernmental Panel on Climate Change (IPCC) reported that "warming of the climate system is unequivocal, as is now evident from observed increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level." (IPCC 2007)

In the coming decades, it is expected that these changes will result in regional climate impacts, including permafrost thawing, increased tropical cyclone intensity, shifting tropical storm tracks, and an increase in the frequency of heat waves and heavy precipitation (IPCC 2007). It has even been suggested that the IPCC's projections of these future impacts are, in fact, conservative in their assessment of the timing and the extent of climate change impacts (Tin 2008). As a result of these findings, there is growing concern both in the United States (National Research Council 2010; USGCRP 2009) and abroad (Department of Climate Change 2009; Department of Climate Change & Energy Efficiency 2011; IPCC 2010; UKCIP 2000) that these changes may have serious adverse impacts on communities, including their transportation and other civil infrastructure systems.

In response to these concerns, governments and agencies in charge of managing infrastructure have begun to investigate adaptation: "actions taken to reduce the vulnerability of natural and human systems or increase system resiliency in light of expected climate change." (Meyer et al. Forthcoming) In recent years, adaptation has attracted much attention in the transportation sector both domestically and abroad (Gardiner et al. 2009; Gardiner et al. 2008; ICF International and Parsons-Brinkerhoff 2011; Meyer et al. Forthcoming; Meyer and Parsons-Brinkerhoff 2009; Savonis et al. 2008; TRB 2008), and some formalized adaptation strategies have emerged.

Risk management is one approach to adaptation proposed by the Intergovernmental Panel on Climate Change (IPCC) as being well-suited to account for some of the uncertainty associated with climate change (Carter et al. 2007), and is broadly endorsed by the global climate change adaptation community as an appropriate approach (National Research Council 2010; Willows and Connell 2003). Furthermore, in a synthesis of global adaptation strategies from the transportation sector, Wall and Meyer (2013) note that "much of the transportation and infrastructure sector's approach to climate change impact analysis and adaptation planning is based on risk management practices."

1.1 Research Motivation

Adaptation planning for transportation infrastructure has, to date, predominantly consisted of developing and implementing risk-based adaptation strategies to assess the risk of infrastructure systems and assets to the projected impacts of climate change. These broad plans and frameworks have been developed for use at the federal, state, and regional levels [for example, see Bies et al. (2010); Federal Highway Administration (2012); Parsons-Brinkerhoff (2009); Victorian Government et al. (2007)]. These types of frameworks provide broad guidance and seek primarily to identify climate impacts, and assess infrastructure vulnerabilities across multiple asset types to aid in network-level planning. However, the complexity of engineered civil infrastructure systems (and the myriad assets types of which they are composed) suggests that these broadly applicable adaptation frameworks may not adequately capture the unique concerns and impacts associated with various individual asset types. Therefore, although these frameworks may provide an adequate overall structure for assessing network-level adaptation needs, more focused adaptation frameworks are needed that can address the unique concerns of individual asset types, while still maintaining network-level applicability.

Maintaining a network-level approach while assessing the adaptation needs of individual asset types allows for a jurisdiction-wide assessment of priorities, enabling agencies to more efficiently allocate planning and programming resources. This is facilitated by identifying higher-risk assets, which may require a more in-depth project-level assessment, but also low-risk assets that may not require further assessment for adaptation. In that respect, an asset-specific network-level assessment may serve as a system-wide screening process to prioritize assets within various classes according to their climate change risks and, by extension, their adaptation needs.

1.2 Research Objective

The objective of this dissertation research is to develop a nationally applicable, risk-based framework that will enable transportation agencies to assess the vulnerabilities of highway culvert assets to the projected impacts of climate change at a network level. This overarching research objective is guided by several guidelines.

1.2.1 Guideline 1 – Focus on Highway Culvert Assets and Extreme Precipitation

This study focuses on one type of transportation asset and one type of climate change impact: the risks to roadway culverts resulting from extreme precipitation, and the associated potential for flooding. The focus on highway culverts is motivated, in part, by the particular vulnerability of culverts to flooding impacts (flow constriction is a deliberate hydraulic design element), as well as the observation that culverts "tend to go ignored until a catastrophic failure occurs." (FHWA 2007) The interplay between these two aspects of flooding vulnerability and the current state of culvert management is important as repair and replacement costs can be significant. For example, a study of 17 culvert failures in the United States found that the average repair/replacement cost was approximately $845,500, with the maximum cost found to be $4.2 million (Perrin and Dwivedi 2006). Another example, specific to the impacts of heavy precipitation and flooding, found that Tropical Storm Irene (2011) damaged, in Vermont alone, over 500 miles of highways, including approximately 960 roadway culverts (Pealer 2012).

This study's focus on extreme precipitation events is also supported by the IPCC's observation that "climate change may be perceived most through the impacts of extreme events…" (Trenberth et al. 2007). Furthermore, extreme precipitation events are noted as among the "most serious challenges to our nation in coping with climate change." (USGCRP 2009) Recent events in the Northeast United States (i.e., Tropical Storm Irene and Hurricane Sandy), the Gulf Coast region (i.e., Hurricane Katrina), and Colorado (widespread flooding, September and October 2013) underscore the potential severity of extreme precipitation impacts on transportation and highway drainage infrastructure.

1.2.2 Guideline 2: Maintain a Risk-Based Approach to Adaptation Assessment

A key aspect of the framework developed in this study is that it maintains the risk-oriented and risk-based approaches of the broader adaptation strategies and frameworks discussed above. The reasons for this are many. First, dozens of frameworks developed by the global transportation and infrastructure sectors [for a full list see, Wall and Meyer (2013)] have utilized the principles of risk and risk-management in assessing adaptation. Therefore, developing a risk-based framework in this study will maintain consistency with the current state of practice.

At a more fundamental level, however, risk and risk-management are already familiar to the transportation and infrastructure sectors (TRB 2008), which use such approaches in day-to-day management and design practices. For example, the AASHTO

LRFD Bridge Design Specifications (2004) “incorporates risk into the calculations of bridge design parameters.” (Meyer 2008) Furthermore, design criteria such as the 100-year flood are inherently risk-based parameters as they attach some likelihood of occurrence to an event of a certain impact or magnitude.

In addition, the most recent federal transportation legislation (*Moving Ahead for Progress in the 21st Century*, or MAP-21), requires that states develop “risk-based, performance-based asset management plan[s] for preserving and improving the condition of the [National Highway System].” (FHWA 2012) This suggests that asset management (which is concerned with the condition and performance of assets, as may be relevant to climate change adaptation assessment and planning) will become increasingly prevalent in the transportation sector, and will also become increasingly risk-based.

Given these considerations, the use of risk as an underlying approach to adaptation assessment in this study will align with current approaches to handling general uncertainty in the transportation and infrastructure sectors, and may more readily enable the interface of asset management and adaptation planning activities in the future.

1.2.3 Guideline 3: Structure Framework for National Applicability

A final goal of this study is to develop an adaptation assessment framework that is nationally applicable. MAP-21 outlines national goal areas for performance management, which include infrastructure condition and environmental sustainability, among others (FHWA 2012). Although climate change adaptation is not identified under the current legislation, it is closely related to infrastructure condition and environmental sustainability concerns, and could be considered in future legislation. Furthermore, it is possible that states could proactively choose to evaluate climate and extreme weather concerns as part of the currently identified performance management areas. However, the development of such performance-based goals also necessitates the establishment of national performance measures. Seeking to promote national applicability in an adaptation assessment framework may enable the framework’s use in identifying performance goals, or in measuring performance based upon those goals, today or at some time in the future. This requires not only the use of nationally available data, but also the flexibility of the framework to adapt to state- or region-specific data and concerns, while maintaining a consistent overall structure, approach, and outcome.

1.3 Dissertation Organization

This research study is organized into six chapters (in addition to the introduction). Chapter 2 beings by discussing observed changes in the climate system, both globally and in the United States, to provide background information and further motivate this research. It then discusses the driving forces of global climate change, including a discussion of climate modeling, the use and development of emission scenarios, and climate projection downscaling techniques. It then introduces the projected changes in both global and United States climate. Chapter 2 concludes with a discussion of the nature and sources of uncertainty in projecting climate change impacts.

Chapter 3 reviews the evolution and development of climate change adaptation strategies. This begins with a general introduction to the concepts of adaptation and uncertainty planning techniques. It then discusses the evolution of climate change assessment and adaptation, which includes an introduction and discussion of the concept of risk and of risk-management practices. It then focuses on risk-based adaptation frameworks from the infrastructure and transportation sectors, synthesizing commonalities and discussing barriers and limitations. This chapter provides a foundation for the use of risk-based approaches in developing the adaptation assessment framework in this study.

Chapter 4 focuses the discussion to highway culvert assets. It introduces culvert inspection and management systems in the United States in the broader context of asset management. It then discusses several culvert condition and performance assessment frameworks relevant to culvert asset management, but which also may be useful in determining culvert vulnerabilities to increased precipitation. It then discusses the nature of culvert failures and potential indicators of failure. This chapter provides a foundation for focusing this study's adaptation assessment framework on culvert assets and assessing their vulnerabilities to increased flow conditions.

Chapter 5 introduces the study methodology. This begins with introducing the framework developed in this study, the Culvert Climate Adaptation Assessment Framework (CCAAF). It also introduces the case study approach used to evaluate and draw conclusions about the efficacy of the framework for national implementation. The constituent components of the CCAAF are then discussed in detail with respect to their structure and development. This includes: a discussion of the types and sources of data used in the case studies; the development of precipitation exposure, vulnerability, and criticality analyses; and the combination of these analyses in a prioritization analysis that produces a series of indices to rate culverts as high, medium, or low risk.

Chapter 6 presents and discusses the results of the four case studies that implement the CCAAF. This includes results from the precipitation exposure analysis, the vulnerability analysis, and the criticality assessment. Chapter 6 concludes by presenting and discussing the final prioritization index results that rate the culvert risks to the projected impacts of climate change; it also compares the analysis results among the four case-study DOTs, as well as among multiple analysis methods used within the CCAAF.

Chapter 7 offers several conclusions about this research study. This begins with a discussion of several key contributions of this dissertation research. It then discusses the overall structure of the CCAAF and the qualitative approach to risk, including the new characterization of risk offered. It then discusses the contribution of several of the individual steps in the CCAAF that were developed for this research study (e.g., infrastructure relevant climate impact projections, culvert vulnerability measures). It then discusses climate change adaptation and the CCAAF in the broader context of infrastructure asset management. The chapter concludes with a discussion of future research needs based upon the findings of this dissertation research.

CHAPTER 2

CLIMATE CHANGE OBSERVATIONS, PROJECTIONS, AND MODELING

In order to plan for and adapt to the impacts of climate change, an understanding of the global changes in climate that are expected to occur, and how those global changes translate into regionally or locally significant impacts, must be established. Generally speaking, our understanding of the future climate system is derived from computer simulations that involve multiple coupled atmospheric-oceanic general circulation models (AOGCMs). The input variables, or boundary conditions, for the AOGCMs are defined by known climate drivers (e.g., GHG concentrations, aerosols, solar radiation, etc.) and are validated by reproducing observed historical climate conditions. Scenarios of future emission are then used to force boundary conditions in the models to produce projections of future global climate conditions under each emission scenario. These global climate projections are then downscaled into regional projections of future conditions with higher spatial resolutions.

This chapter discusses each of the above mentioned steps in greater detail and provides a background of the climate projection and modeling efforts that form the foundation of impact and adaptation assessments.

2.1 Observed Changes in Climate

In the synthesis of the *IPCC Fourth Assessment Report: Climate Change 2007 (AR4)*, the IPCC states that “warming of the climate system is unequivocal, as is now evident from observed increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level." (IPCC 2007) This section summarizes the observed changes in global climate as evidence that the earth's global climate system is changing. This section also summarizes the observations of climate change in the United States as motivation for the need to adapt to such changes. This discussion and summary is not intended to be an exhaustive introduction to all observed changes; predominant observed changes were selected. These include temperature (averages and extremes), precipitation (averages and extremes), sea-level rise, and extreme events (tropical cyclones, extra- and sub-tropical storms).

2.1.1 Observed Changes: Temperature, Sea-Level, Precipitation, and Extreme Events

Table 2.1 summarizes several major observed changes in climate, both globally and in the United States. Additional global trends are then discussed in the next section.

Table 2.1 Observed Changes in Climate, Globally and the United States

Climate Stressor	Global	United States
Temperature		
Average	• Surface temperatures increased 0.74±0.18°C from 1906-2005[1] • This rate of increase in the last 50 years is double that from the last 100 years[1]	• More than 2°F increase since 1969[4]
Extreme	• Reduced number of frost days in mid-latitude regions[1] • Increase in warm extremes and decrease in number of daily cold extremes in 70%-75% of land regions[1]	• Change in 90th percentile temperature days since 1950[5] : o Maximum temp: +3% o Minimum temp: +5% • Increasing trend in the heat wave index since the 1960s[5] o Rise in extremely high nighttime temperatures[5]

Table 2.1 (Continued)

Climate Stressor	Global	United States
Sea Level Rise	• 1961 to 2003: Average increase of 1.8± 0.5 mm/yr[2] • 1993 to 2003: Average increase of 3.1± 0.7 mm/yr[2] o 1.6± 0.5 mm/year from thermal expansion of ocean[2] o 0.8-1.6 mm/yr from changes in cryosphere (e.g., melting sea/glacial ice) [3]	• Regionally variable • Ranges from +9.65 mm/year to -17.12 mm/year[6]
Precipitation		
Average	• Regionally variable o Generally increased in Northern latitudes from 1900-2005**[1]** o Generally decreased in the tropics since 1970**[1]**	• 5% per year average increase in average annual rainfall from 1958 to 2008[4] • 7% increase in total precipitation during 20th century[5]: o SE and SW areas have generally become drier[4] o NE and Northern Midwest areas have generally become wetter[4]
Extreme	• "Increases in the number of heavy precipitation events (e.g., 95th percentile) within many land regions, even those where there has been a reduction in total precipitation amount..."**[1]**	• Amount of precipitation falling in the heaviest 1% of rain events increased nationally by 20% during the 20th century[5] • Regional increases in precip falling in heaviest 1% of rain events, ranges: o Days: 58% (NE) to 12% (Pacific NW)[4] o Amount: 67% (NE) to 9% (SE & California) [4]
Extreme Events		
Hurricanes / Cyclones	• Large natural variability "masks" any distinct trends**[1]** • Some evidence of increase in tropical storm intensity and duration since 1970s**[1]**	• Increase in Atlantic tropical cyclone activity and destructive power (intensity, duration, frequency) since 1970[4,5]
Winter & Sub-tropical storms	• Net increase in mid-latitude storms since approx. 1950**[1]** • Poleward shift in storm tracks, particularly in northern hemisphere land**[1]**	• Northward shift in tracks of heavy snowstorms [5] • Downward trend in Southern & lower-Midwestern snowstorm frequency between 1901-2000[5] • Upward trend in Northeast and upper-Midwest snowstorm frequency between 1901-2000[5]

1. Trenberth et al. (2007)
2. Bindoff et al. (2007)
3. Lemke et al. (2007)
4. USGCRP (2009)
5. Kunkel et al. (2008)
6. Zervas (2009)

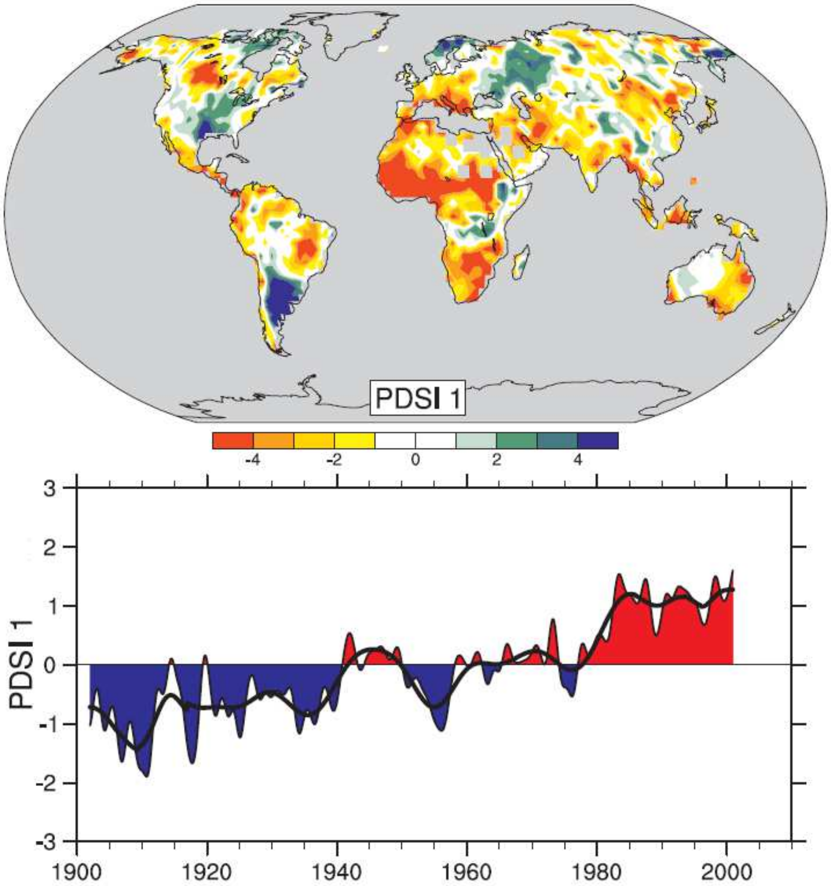
2.1.2 Other Global Trends: Snow Cover, Sea Ice, Permafrost, and Drought

Changes in snow cover and frozen ground extents serve as strong indicators of a changing climate. The IPCC (Lemke et al. 2007) notes that “snow cover has decreased in most regions, especially in spring and summer.” (p. 329) In the northern hemisphere, satellite observations for the period from 1966 to 2005 indicate that total snow cover decreased in all months except November and December; historical observations of the southern hemisphere indicate minor changes or no changes (Lemke et al. 2007). Decreases in snow coverage area are largely attributed to changes in temperature; where snow coverage area has increased, changes in precipitation were the dominant cause (Lemke et al. 2007).

Satellite observation from 1978 to 2005 also indicates that the extent of arctic sea ice has changed at a rate of -2.7 ± 0.6% per decade, and that the extent of arctic sea ice that survives the summer months has changed at a rate of -7.4 ± 2.4% per decade (Lemke et al. 2007).

Decrease in the temperature and depth of arctic permafrost layers also suggests an arctic warming trend. “Temperature at the top of the permafrost layer has increased by up to 3°C since the 1980s in the Arctic,” and the base of the permafrost layer has been thawing at a rate between 0.02 m/year (Tibetan Plateau since the 1960s) to 0.04 m/year (Alaska since 1992) (Lemke et al. 2007).

Observations of decreased precipitation in the tropics (see Table 2.1) reinforce the observation that “droughts have become more common, especially in the tropics and subtropics since the 1970s.” (Trenberth et al. 2007) A global study using the Palmer Drought Severity Index (PDSI), which measures the cumulative deficit of surface land moisture relative to average local conditions indicates that although there is a global trend of increasing drought, there is significant regional variability and that some regions are trending towards wetter than average conditions. Figure 2.1 shows both a spatial and temporal distribution of drought conditions from 1900 to 2002 as changes in PDSI.



Source: Trenberth et al. (2007)

Figure 2.1 Observed Trends in Monthly Palmer Drought Severity Index, 1900-2002

2.2 Climate Drivers & Projected Climate Change

Climate scientists have identified that change in atmospheric greenhouse gas and aerosol concentrations, solar radiation, and land surface properties are among the key drivers affecting climate change (Solomon et al. 2007).   Changes in these factors affect the energy balance of the global climate system through radiative forcing – "the change in the net, downward minus upward, irradiance…at the tropopause due to a change in an external driver of climate change…" (IPCC 2007). That is, changes in the atmospheric concentrations of so-called radiatively active species lead to changes in the balance of incoming versus outgoing energy in the earth's atmospheric system, expressed in watts per meter squared (W/m^2). Table 2 summarizes the key findings of the IPCC (Solomon et al. 2007; Solomon et al. 2007) regarding climate change drivers. It has been noted that 55% of the anthropogenic greenhouse effect is attributed to increases in carbon dioxide (CO2) concentrations in the atmosphere, and between 15-20% and 25-30% are attributed to changes in the concentrations of methane and nitrous oxide (NO), respectively (Beniston 2004).

Table 2.2 Key External Drivers of Climate Change

Climate Driver	Pre-Industrial Concentration	Current Concentration (2005)	Radiative Forcing (Watts/m^2)
Greenhouse Gases (GHGs)			
CO2	280 ppm	379 ppm	+2.30
Methane	715 ppb	1774 ppb	-
NO	270 ppb	319 ppb	-
Aerosols	-	-	-0.5
Change in solar output	-	-	+0.12
Land use & earth surface albedo	-	-	-0.2
Black carbon snow deposits	-	-	+0.1
Change in tropospheric ozone	-	-	+0.35
Halocarbons	-	-	+0.01

The IPCC notes that the increased concentration of atmospheric carbon dioxide is primarily the result of fossil fuel usage, with some additional contribution from changes in land-use (Solomon et al. 2007). Additionally, both increases in atmospheric concentrations of methane (which has historically ranged between 320 and 790 ppb over the previous 650,000 years) and nitrous oxide are predominantly attributed to agriculture, however other sources also contribute (Solomon et al. 2007).

Aerosols such as sulfate, organic carbon, black carbon, nitrate, and dust contribute to a net negative radiative forcing due to scattering and absorption of radiation (Solomon et al. 2007). Aerosols also indirectly contribute to cloud albedo forcing (Solomon et al. 2007), which is the reflection of solar radiation by a surface or object (IPCC 2007). It should be noted that the effects of aerosol radiative forcing on climate change are characterized by a comparatively lower level of scientific understanding as compared to greenhouse gases. However, understanding of "aerosol radiative forcing is now considerably better quantified than previously and represents a major advance in understanding since the time of the [IPCC's third assessment report in 2001]." (Solomon et al. 2007) Also, significant volcanic eruptions can contribute to episodic reductions in radiative forcing by emitting volcanic aerosols (e.g., sulfate) into the earth's stratosphere, although such changes are generally short-term (Solomon et al. 2007).

Changes in solar output have been noted since 1750 that contribute to changes in radiative forcing, although continuous observations of solar irradiance starting in 1979 indicate that long-term changes in solar output may be a result of sunspots, or localized depletions in solar radiation on the sun's surface (Solomon et al. 2007).

Changes in land-cover and the deposition of black carbon aerosols on snow cover have caused changes in the earth's surface albedo (Solomon et al. 2007). Additionally, changes in tropospheric ozone and changes in halocarbons (e.g.

chlorofluorocarbons, or CFCs) (Solomon et al. 2007), and to a lesser degree aviation contrails (Solomon et al. 2007) can also contribute to changes in radiative forcing.

2.3 Atmospheric-Oceanic General Circulation Models (AOGCMs)

Sun and Bleck (2001) explain that "the global climate to a large extent is a result of the interaction between ocean and atmosphere." Over the past decades, numerous models have been developed to better understand these interactions, and to make projections about future global climate. The predominant family of models, called coupled atmospheric-oceanic general circulation models (AOGCMs), combine aspects of atmospheric general circulation models (AGCMs) and oceanic general circulation models (OGCMs) into coupled models that account for interactions between the two systems, and have relatively coarse spatial resolution: 1° to 5° grids for atmospheric resolution, and 0.3° to 5° grids for oceanic resolution (Randall et al. 2007).

Atmospheric concentrations of GHGs, aerosols and other radiatively active species are used to force the AOGCMs to determine climate conditions (Meehl et al. 2007). This can be done with known historical concentrations to assess an AOGCM's recreation of historical climate conditions, or with projected concentrations (these are discussed in the next section) to project future climate.

To evaluate the limitations and capabilities of these global climate models, different types of model evaluations have been carried out. One of these is the intercomparison of climate models, which is predominantly orchestrated by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) located at Lawrence Livermore National Laboratory in the United States. The program's mission is "to provide insightful diagnostics of community simulations taken collectively, and not to make judgments on individual models." (AchutaRao et al. 2004) One of the activities of PCMDI is the Coupled Model Intercomparison Project – phase three (CMIP3), which Randall et al (2007) notes is "by far the most ambitious organised effort to collect and analyse Atmosphere-Ocean General Circulation Model (AOGCM) output from standardised experiments…" (p. 594) The CMIP3 also makes modeling outputs publically available through its Multi-Model Dataset (MMD) archive, to enable researchers from outside the major contributing modeling groups to "perform research of relevance to climate scientists preparing the Fourth Assessment Report (AR4)" (PCMDI 2013) and "scrutinise the models from a variety of perspectives." (Randall et al. 2007) The 25 AOGCMs included in CMIP3 are listed in Table 2.3. Note that the CSIRO-MK3.5 and INGV-SXG models were not listed in the IPCC's AR4, nor apparently used in its generation of climate projections.

Table 2.3 AOGCMs Participating in the MMD at PCMDI

Adapted from (Randall et al. 2007) **and** (PCMDI 2007)

Model Identifier	Year	Sponsor(s)	Country
BCC-CM1	2005	Beijing Climate Center	China
BCCR-BCM2.0	2005	Bjerknes Center for Climate Research	Norway
CCSM3	2005	National Center for Atmospheric Research	United States
CGCM3.1(T47)	2005	Canadian Center for Climate Modeling and Analysis	Canada
CGCM3.1(T63)	2005	Canadian Center for Climate Modeling and Analysis	Canada
CNRM-CM3	2004	Meteo-France/Centre National de Recherches Meteorologigues	France
CSIRO-MK3.0	2001	Commonwealth Scientific and Industrial Research Organization (CSIRO) Atmospheric Research	Australia
CSIRO-MK3.5	2006	Commonwealth Scientific and Industrial Research Organization (CSIRO) Atmospheric Research	Australia
ECHAM5/MPI-OM	2005	Max Planck Institute for Meteorology	Germany

Table 2.3 (Continued)

Model Identifier	Year	Sponsor(s)	Country
ECHO-G	1999	Meteorological Institute of the University of Bonn, Meteorological Research Institute of the Korea Meteorological Administration (KMA), and Model and Data Group	Germany/Korea
FGOALS-g1.0	2004	National Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG)/Institute of Atmospheric Physics	China
GFDL-CM2.0	2005	U.S. Department of Commerce/National Oceanic and Atmospheric Administration (NOAA)/Geophysical Fluid Dynamics Laboratory (GFDL)	United States
GFDL-CM2.1	2005	U.S. Department of Commerce/National Oceanic and Atmospheric Administration (NOAA)/Geophysical Fluid Dynamics Laboratory (GFDL)	United States
GISS-AOM	2004	National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS)	United States
GISS-EH	2004	National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS)	United States
GISS-ER	2004	National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS)	United States
INGV-SXG	2005	Instituto Nazionale di Geofisica e Vulcanologia	Italy
INM-CM3.0	2004	Institute for Numerical Mathematics	Russia
IPSL-CM4	2005	Institut Pierre Simon Laplace	France
MIROC3.2(hires)	2004	Center for Climate Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan
MIROC3.2(medres)	2004	Center for Climate Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan
MRI-CGCM2.3.2	2003	Meteorological Research Institute	Japan
PCM	1998	National Center for Atmospheric Research	United States
UKMO-HadCM3	1997	Hadley Center for Climate Prediction and Research/Met Office	United Kingdom
UKMO-HadGEM1	2004	Hadley Center for Climate Prediction and Research/Met Office	United Kingdom

The development of numerous AOGCMs enables an ensemble approach in understanding plausible future climate conditions. Ranges of plausible future climate conditions can be determined “by collecting results from a range of models from different modelling centres” (Randall et al. 2007) using the same forcing conditions (i.e., future scenarios of atmospheric concentrations of radiatively active species) for each model; these are called multi-model ensembles. Another ensemble modeling technique, perturbed physics ensembles, generates “multiple model versions within a particular model structure, by varying internal model parameters within plausible ranges.” (Randall et al. 2007) This latter technique is used primarily for exploring uncertainties within individual models, or projecting future changes in extreme weather and climate (Meehl et al. 2007).

It is noted that although AOGCMs are “the most comprehensive models available” (Randall et al. 2007), simpler models of the global climate system that are less computationally intensive are also used. These consist of two families of models: Simple Climate Models (SCMs), and Earth Models of Intermediate Complexity (EMICs). Randall et al. (2007) notes that SCMs are “useful mainly for examining global-scale questions” and impacts such as global mean surface temperature and global mean sea level rise. In contrast to AOGCMs, EMICs are not fully coupled models and are therefore less computationally costly to run (Terando et al. 2010). Randall et al. (2007) notes that “…it would not be sensible to apply an EMIC to studies that require high spatial and temporal resolution,” for example studying regional impacts. However, EMICs are a valuable mechanism in exploring the full probability density function of key parameters influencing the climate system (Terando et al. 2010). Given the need in this study for projections with greater spatial resolution and the prevalence of AOGCMs in efforts to downscale regional climate impacts, SCMs and EMICs are not discussed further, but it is understood that they are often used in conjunction with AOGCMs to assess climate, as in the PCMDI Multi-Model Dataset and AR4 climate projections (Solomon et al. 2007).

2.4 Emissions Scenarios: SRES and RCP

The previous section discussed the formulation of future climate projections using AOGCMs that are forced by scenarios of future concentrations of radiatively active species. Current climate change projection efforts predominantly use a series of future concentration scenarios that were defined in the IPCC's Special Report on Emission Scenarios (SRES) (Nakicenovic et al. 2000) . The SRES takes into account "driving forces such as demographic development, socio-economic development, and technological change." (Nakicenovic et al. 2000) The SRES presents a series of four "storylines" of plausible futures simplified as the intersection of two spectrums for the driving forces: globalization vs. regionalization, and economic focus vs. environmental focus (Nakicenovic et al. 2000). The four storylines are named: A1, A2, B1, and B2 (see Table 2.4). The A1 storyline contains three groups that project alternative energy technology development pathways: A1T (predominantly non-fossil fuel), A1B (balances fossil and non-fossil fuel usage), and A1FI (fossil fuel intensive) (Nakicenovic et al. 2000).

In practical application for AOGCM forcing, the SRES scenarios are commonly simplified on a spectrum from low to high emission levels. For example, Terando et al.

(2010) characterizes the emission scenarios A1FI, A2, A1B and B1 as “high,” “mid-high,” “mid,” and “lower” emissions, respectively. Stoner et al. (2012) offers a similar characterization of A1FI as higher emission and B1 as lower emission. A discussion correlating mean global temperature change and sea level rise with the SRES scenarios in the IPCC’s AR4 places the B2 and A1T scenarios between A1B and B1 in the “mid-low” range, both with somewhat similar resulting levels of global average impacts (Solomon et al. 2007).

Table 2.4 SRES Emission Storyline Descriptions

Adapted from (Nakicenovic et al. 2000)

	Economic Focus	Environmental Focus
Globalization	**A1** **(A1T, A1B, A1FI)** Rapid economic growth; low population growth; rapid introduction of new and more efficient technologies	**B1** low population growth; cleaner, efficient technologies; global economic, social, and environmental sustainability
Regionalization	**A2** Regionally focused economic development; high population growth; fragmented and slower technological change	**B2** moderate population growth; less rapid, more diverse technological change; local economic, social and environmental sustainability

At its 25th meeting in 2006, the IPCC decided to not to commission future sets of emissions, instead deciding to “[leave] new scenario development to the research community.” (Moss et al. 2010) Thus, in 2007 the research community formed the Integrated Assessment Modeling Consortium (IAMC) to develop the next generation of climate scenarios of new scenarios – representative concentration pathways (RCPs)

(Moss et al. 2008; Moss et al. 2010). The RCP scenarios offer several improvements over the SRES scenarios; for example, consideration of (1) the influence of climate policy and mitigation on future atmospheric GHG concentrations, and (2) a wider range of possible futures (Vuuren et al. 2011). However, given their recent introduction into climate modeling, the RCPs have not yet been widely used in generating future climate projections. Thus, the SRES scenarios still represent the current state-of-the-art in climate model forcing conditions, although a shift to the RCPs in the coming years should be expected.

2.5 Statistical & Dynamical Downscaling

Downscaling is a technique used to enhance the spatial resolution of large-scale climate model (e.g., AOGCM) outputs to a regional- or local-scale (e.g., 10-100km). It is noted that "downscaling can provide more precision in representing future climate conditions at a regional and local scale, [but] in its current form, in general, it does not provide more accuracy (Meyer et al. Forthcoming). The two classifications of methods commonly used to downscale climate projections are statistical/empirical downscaling and dynamical downscaling (IPCC 2007).

Dynamical downscaling generally utilizes a nested regional climate model (RCM) that simulates regional physical processes and forcings (e.g., orography, coastlines, lakes, land surface characteristics, snow, aerosols, etc.) (Giorgi et al. 2001; Murphy 1999), that is "driven by lateral boundary conditions provided by a coarse GCM." (Mearns et al. 1999) Effectively, the AOGCM is used to determine large-scale (i.e., low-resolution) global forcings, which are then used to drive boundary conditions for a higher-resolution

RCM. The RCM then, in effect, "acts…as a physically based interpolator of the GCM output," (Murphy 1999) describing climate variations and physical processes at a regional scale. In North America, the North American Regional Climate Change Assessment Program (NARCCAP) (an international program run by U.S. National Center for Atmospheric Research) maintains a set of six RCMs with boundary conditions defined by output from four AOGCMs (CCSM, CGCM3, GFDL, and HadCM3) (National Center for Atmospheric Research 2007).

Mearns et al. (1999) notes several advantages and disadvantages to dynamical downscaling. Advantages include: (1) RCMs based in physical science can respond to different external forcings, (2) the principle can be applied anywhere on Earth as it is independent of historical weather observation data availability, and (3) output resolution can be varied according to need. Conversely, disadvantages include: (1) RCMs are very computationally intensive, (2) control run simulations can still be inaccurate, (3) output is largely dependent on the quality of the GCM output used to define RCM boundary conditions, and (4) nested RCMs require extensive tuning and parameterization when applied to a new region. In the case of the third possible disadvantage, recall that downscaling generally increases precision of climate projections, but not accuracy; therefore, the accuracy of GCM output used to define the RCM boundary conditions is crucial.

Statistical downscaling is a comparatively less computationally costly method that "adopts statistical relationships between regional climate and carefully selected large-scale parameters" (Schmidli et al. 2007) from AOGCMs. That is, local observations of present-day weather ("predictands") are related to atmospheric circulation parameters (“predictors”) in GCM simulations, which are generally viewed as more “reliable than the distributions of climate elements such as [surface air temperature or precipitation].” (Murphy 1999) Relationships between AOGCM parameters and present day local weather observations are established using statistical models including regression, neural networks, and analogs (Giorgi et al. 2001; Mearns et al. 1999).

Statistical downscaling is dependent upon several simplifying assumptions. The first is that relationships between present-day observed local weather variables and large-scale circulation patterns are assumed to remain the same under greenhouse warming conditions (Mearns et al. 1999; Richards and Timmermann 2008). It also requires that sufficient observed data of large-scale circulation and local scale variables are available to establish a statistical relationship, and furthermore that any relationship is sufficiently strong (Mearns et al. 1999).

Because of the concerns associated with both downscaling techniques, and the relative advantages of some techniques in predicting various climatic phenomena, it is noted that some combination of downscaling methods may provide a more suitable projection of future climate than using either method in isolation (Giorgi et al. 2001; Richards and Timmermann 2008).

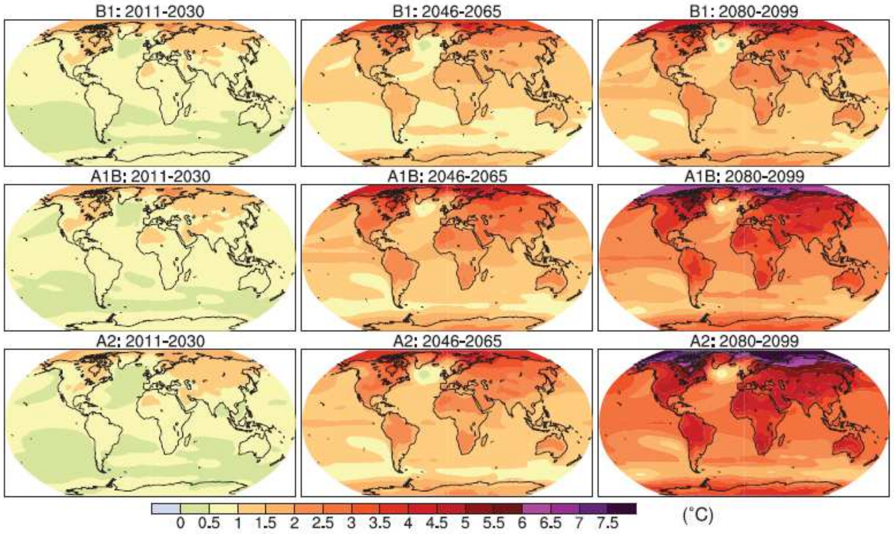
2.6 Climate Change Projections

This section summarizes global-scale changes in climate to establish a context for the extent and timeline of anticipated changes, and also summarizes regional climate change projections relevant to the United States. This latter discussion provides regional generalizations of anticipated changes to motivate the discussion of specific changes relevant to the regional case studies used to explore the framework developed in this dissertation research.

Projections of global climate change are dependent upon the forcing scenarios (i.e., SRES) and the AOGCMs used for evaluation. Generally speaking, higher emission scenarios project greater changes in average climate conditions than lower emission scenarios. For example, Figure 2.2 shows global spatial projections of mean surface temperature increases for three future time periods, and for three emission scenarios: A2 (mid-high), A1B (mid), and B1 (low). Note that for all emission scenarios some warming is exhibited, and that these figures represent the mean output of a multi-model ensemble.

Due to the coarse resolution of global-scale climate projections, numerous efforts have been undertaken to assess climate projections and impacts at a regional level. In the United States, some of these efforts include the North American Regional Climate Change Assessment Program (NARCCAP), the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction (NCEP), and the United States Global Change Research Program (USGCRP), to name a few. The latter of these efforts summarized key climate projections and impacts in the United States in its second national climate assessment (USGCRP 2009). Several of these findings are presented here to motivate this study's assessment of regional climate change impacts to transportation infrastructure.

Table 2.5 summarizes several major projected changes in climate, both globally and in the United States. Projected climate stressors are shown consistent with those listed in Table 2.1 and discussed in section 2.1. Several additional notes and comments specific to individual stressors are given in the following sub-sections (2.6.1 to 2.6.4).



Source: (Meehl et al. 2007)

Figure 2.2 Annual Mean Surface Temperature Increases by Time Period and Emission Scenario

Table 2.5 Projected Changes in Climate, Globally and in the United States

Climate Stressor	Global	United States
Temperature		
Average	• Variable with region and scenario • End of 21st century scenario ranges +1.6°C (B1) to +4.0°C (A1FI) [1] • Near-term warming +0.2°C per decade across all scenarios [1]	• 2°C-4°C warming by end of 21st century (A1B)[8]
Extreme	• Highly variable with region • Generally, more frequent heat waves of longer duration[2] • Some evidence that the intensity of heat-waves will increase, particularly in western-Europe, the Mediterranean, and the United States (west and south-west) [2] • Decrease in northern-hemisphere frost days[2]	• Increase in the frequency of maximum temperatures in summer months[5] • Decrease in frequency of extreme minimum temperatures during winter months[5] • 20-year event projected to have a 3-year return period by mid-21st century, and 2-year return period by end of 21st century (A1B)[9] • Increase in days over 90°F from 60 days to 150 days by end of 21st century (A1B)[4]

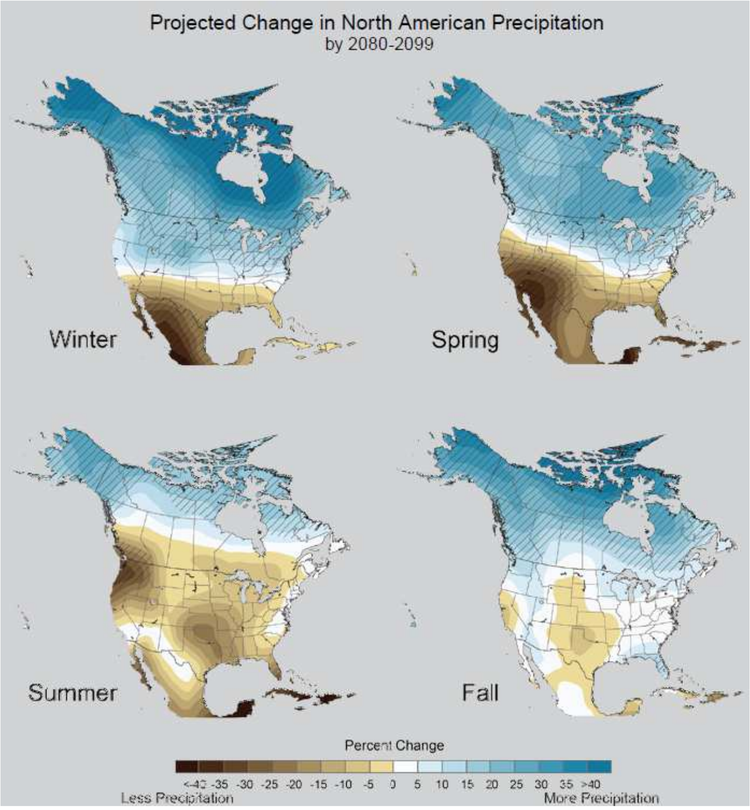
Table 2.5 (Continued)

Climate Stressor	Global	United States
Sea Level Rise	• Variable with region and scenario, ranges from +1.6°C (B1) to +4.0°C (A1FI) by end of 21st century[1]	• Regionally variable. Ranges from: o +1.5m in northeastern US by end of 21st century[6] o -4cm in Pacific Northwest by 2030[7]
Precipitation		
Average	• Regionally and seasonally variable • Generally increasing precipitation in northern latitudes[2] • Generally decreasing precipitation in subtropics and mid-latitudes[1]	• Highly regionally and seasonally variable • Increasing average precipitation by 20-25% for 2080-2099 compared to present[4]: Northern latitudes Winter months • Decrease in average precipitation during summer months[8], by 25-35% for 2080-2099 compared to present[4]
Extreme	• Highly variable with region • Generally, more intense events separated by longer dry periods[2] • Increases in intensity more pronounced in northern latitudes and tropical regions • Increases in extremes will regionally mirror increases in average precipitation[2]	• Precipitation intensity will increase over most regions at a rate greater than mean precipitation[5] • 20-year event return period projection (A1B): o 12-15 year return period by mid 21st century[9] o 6-8 year return period by end of 21st century[9] • 20-year event return period projected to be as low as 4-6 years in NE United States by end of 21st century[4]
Extreme Events		
Hurricanes/ Cyclones	• Increased intensity (wind speeds and precipitation)[2] • Some evidence that weaker storms could be fewer in number[1]	• Projections highly variable • 1-8% increase in intensity per 1°C increase in sea surface temperature[5] • 6-18% increase in precipitation rates per 1°C increase in sea surface temperature[5,10,11,12]
Winter & Sub-tropical storms	• Poleward shift in extratropical storm tracks, particularly in the northern hemisphere[1] • Regionally, increased intensity is possible[3]	• Not well understood at regional level • Global models suggest continued poleward shift in extratropical storm tracks, particularly in northern hemisphere [13]

1. Solomon et al. (2007)
2. Meehl et al. (2007)
3. Leckebusch and Ulbrich (2004)
4. USGCRP (2009)
5. Gutowski et al. (2008)
6. New York State Sea Level Rise Task Force (2010)
7. NRC (2012)
8. Christensen et al. (2007)
9. Kharin et al. (2007)
10. Chauvin et al. (2006)
11. Hasegawa and Emori (2005)
12. Yoshimura et al. (2006)
13. Meehl et al. (2007)

2.6.1 Precipitation Seasonality

Projections of average precipitation in the United States are highly variable, both spatially and seasonally. It is noted that northern latitudes will experience the greatest increase in average precipitation, particularly in the winter months (USGCRP 2009), whereas most AOGCMs project a decrease in precipitation in the summer months (Christensen et al. 2007). Figure 2.3 shows the seasonal and spatial variability in North American precipitation projections generated from a 15 model ensemble using the A2 SRES scenario; hatching represents higher confidence projections. It should also be noted that confidence in North American precipitation projections is generally higher for winter and summer months than for spring and fall months (USGCRP 2009).

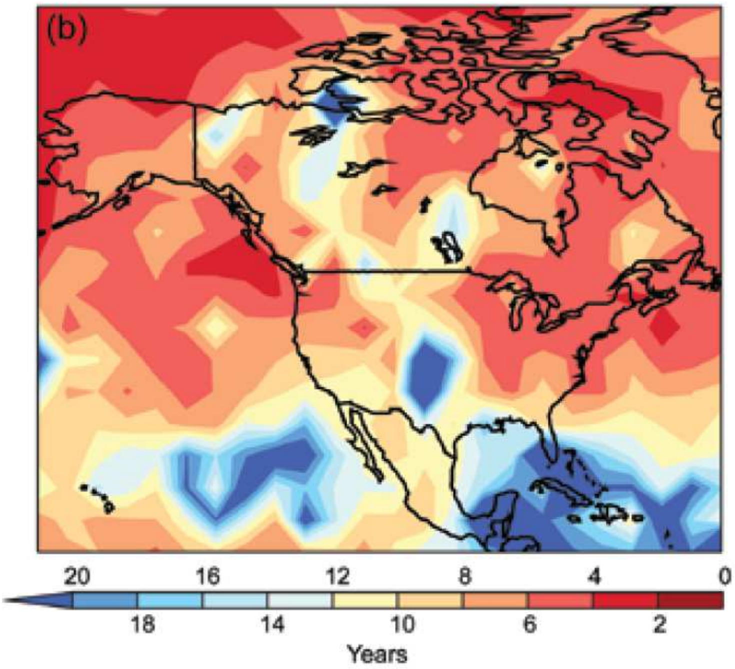


Source: (USGCRP 2009)

Figure 2.3 Projected Seasonal Average Change in Precipitation in North America

2.6.2 Precipitation Intensity

Changes in precipitation intensity exhibit high regional variability, however it is generally noted that some increase is projected over most regions, and increases in precipitation intensity will occur at a greater rate than changes in mean precipitation (Gutowski et al. 2008). Furthermore, it is projected that the greatest increases will occur in the wettest regions (USGCRP 2009). For example, in a case study of California, Bell et al. (2004) found that changes in the 95th percentile precipitation events "followed changes in mean precipitation, with decreases in heavy precipitation in most areas." (Christensen et al. 2007) Figure 2.4 shows the spatial distribution of projected changes in extreme precipitation in North America represented as reductions in the 20-year event return period (SRES A1B scenario, 2090 to 2099).



Adapted from: (Gutowski et al. 2008)

Figure 2.4 Projected Changes in 20-year Daily Precipitation Extreme Return Period

2.6.3 Tropical Cyclone Intensity, Precipitation, and Frequency

In projecting tropical cyclone activity, changes in intensity and frequency are perhaps the best understood characteristics, although it is noted that projected changes in intensity are clearer than changes in frequency (Kunkel et al. 2008). Due to the range of modeling uncertainties, some projections show a decrease or no change to intensity (Chauvin et al. 2006), whereas others suggest an increase in intensity between 10% and 20% (Henderson-Sellers et al. 1998) and 14% globally, and 20% in the northern Atlantic given a 2.5°C increase in sea surface temperature (Oouchi et al. 2006).

With respect to tropical cyclone precipitation, Gutowski et al. (2008), summarizing several studies (Chauvin et al. 2006; Hasegawa and Emori 2005; Yoshimura et al. 2006) to suggest that storm core precipitation rates will increase globally between 6% and 18% per 1°C increase in tropical sea surface temperature.

There is generally insufficient information and consensus to project how the frequency of tropical cyclones in the Atlantic and North Pacific will change as compared to historical observations (Gutowski et al. 2008). Although, some studies have suggested that the frequency of high intensity storms will increase despite a general reduction in the global frequency of tropical cyclones [(Oouchi et al. 2006) in (Gutowski et al. 2008)].

2.6.4 Sea Level Rise

Global projections of mean sea level indicate increases under all SRES emission scenarios (Solomon et al. 2007), however regional changes are highly variable. For example, regional studies of the Pacific coastline (NRC 2012), the Gulf Coast region (Keim et al. 2012), Florida (Technical Ad hoc Work Group 2011) and New York (New

York State Sea Level Rise Task Force 2010) project changes ranging from -4cm by 2030 in the Pacific Northwest to significant end-of-century increases in excess of 1.5 meters in the northeastern United States.

It is also noted that the increases in global mean sea level can exacerbate the effects of storm surges (Gesch et al. 2009), such as those posed by tropical cyclones, which suggests a projected increase in the possibility of coastal flooding (Gutowski et al. 2008).

2.7 Uncertainty in Climate Change Projections

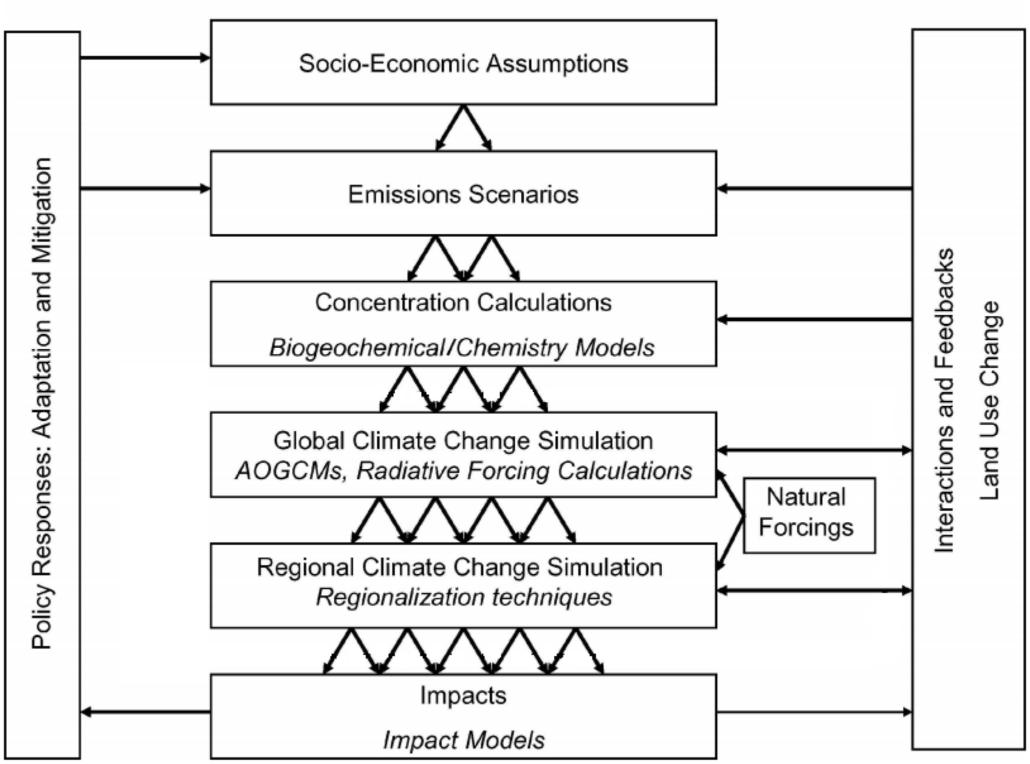
While the observed changes in climate and scientific projections of climate generated by multi-model ensembles strongly suggest that the climate is changing, the extent and timing of such changes are characterized by some degree of uncertainty. There are many definitions of uncertainty, but perhaps the simplest is "any departure from the unachievable ideal of complete determinism." (Walker et al. 2003) In engineering literature, uncertainty is classified frequently, and broadly, as *aleatory* (stemming from natural variability within a system) and *epistemic* (stemming from lack of knowledge) (Abrahamson 2006; Apel et al. 2004; Der Kiureghian and Ditlevsen 2009; Oberkampf et al. 2004; Ross et al. 2009; Sun et al. 2012).

In climate change prediction, Willows and Connell (2003) discuss four general classifications of uncertainty that expand upon the distinction between aleatory and epistemic uncertainty:

1. **Environmental Uncertainty/Natural Variability –** Both in natural systems (e.g., weather) and in societal systems (e.g., global economies) which may have an impact, directly or indirectly, on global climate.
2. **Data Uncertainty –** This includes insufficient or incomplete data, measurement error, and extrapolation.
3. **Knowledge Uncertainty –** Particularly uncertainty about future conditions or technological advancements that may affect, for example, future emission scenarios.
4. **Model Uncertainty –** This includes model choice and structure, input values, parameters, output variables and values, sensitivities.

While the sources of these uncertainties are numerous and affect climate prediction at various stages in the process, they also can compound one another in what Mearns et al. (2001) terms "the cascade of uncertainty." Figure 2.5 shows the several steps of generating a climate prediction across which uncertainty can propagate, or "cascade." For example, knowledge-based uncertainties concerning future energy technologies, global economies and trade, and land-use patterns are inherent to the first step, "Socio-Economic Assumptions," which are used to inform the generation of emission scenarios (e.g., SRES scenarios). Additionally, data uncertainty and model uncertainty affect AOGCM structure, parameterization, and output.

To address these uncertainties in projecting climate, it has been suggested that ranges of scenarios be examined (Mearns et al. 2001). The wide use of ensemble modeling efforts undertaken by CMIP3 and others in generating climate projections reflects this suggestion. Mearns et al. (2001) offer additional suggestions in addressing climate projection uncertainty, particularly in the response to impacts; for example, the use of climate scenario generators, risk assessment frameworks, and expert judgment. Methods of handling uncertainty in response to projected impacts are discussed further in Chapter 3.



Adapted from (Giorgi 2005)

Figure 2.5 Cascading Uncertainty in Climate Prediction

CHAPTER 3

CLIMATE CHANGE ADAPTATION AND RISK-BASED ADAPTATION IN THE TRANSPORTATION SECTOR

Transportation systems and infrastructure are engineered and built according to design standards that account for known environmental conditions. Meyer (2008) notes that “it is a basic tenet of civil engineering that the design of structures cannot be divorced from the environment within which they are built.” However, given the climate change projections discussed in Chapter 2, we must now consider that future environmental conditions may differ from those that were anticipated when existing infrastructure systems were designed, and that some adverse impacts may result.

There are two general responses to climate change that have been identified by the United Nations Framework Convention on Climate Change (UNFCCC): mitigation and adaptation (Klein et al. 2007). Mitigation refers to the “anthropogenic intervention to reduce the anthropogenic forcings of the climate system; it includes strategies to reduce greenhouse gas sources and emissions and enhancing greenhouse gas sinks.” (IPCC 2007) That is, mitigation encompasses actions taken to moderate the systems believed to be contributing to anthropogenic climate change.

The second response, adaptation, is defined by the IPCC as “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.” (IPCC 2007) Three sub-classifications of adaptation are also defined (IPCC 2007):

1. **Anticipatory adaptation –** Also called “proactive adaptation,” refers to actions taken before impacts are observed.
2. **Autonomous adaptation –** Actions that “do not constitute a conscious response,” but rather that are triggered in naturally occurring systems, or by market or welfare changes in human systems.
3. **Planned adaptation –** Actions taken to “return, maintain, or achieve a desired state” given awareness to observed or imminent changes in climate condition.

This chapter first introduces adaptation and climate change uncertainty, as well as several general methods that are used to address uncertainty in the planning process – particularly risk-management. This is followed by a general discussion of risk and risk management practices, and then by a discussion of adaptation strategies in the transportation. Finally, this chapter synthesizes current adaptation planning frameworks from the global transportation and infrastructure community, arriving at a generalized approach to climate change adaptation risk management.

3.1 Adaptation and Uncertainty

In recent years, there has been heightened awareness of the need for general climate change adaptation planning in the United States (National Research Council 2010; USGCRP 2009), as well as adaptation planning specific to the transportation sector (TRB 2008). Under a traditional engineering approach, adaptation to potential climate change impacts requires that engineers, planners, and policymakers have an understanding of, and ability to anticipate, future conditions with some degree of certainty. However, the significant and cascading uncertainties associated with projecting future climatic conditions complicates adaptation planning, and requires some innovative approaches.

Uncertainty, as a general concept in transportation planning and policy, is familiar to transportation engineers and professionals – for example, changes in land use, new technologies, and infrastructure financing. Marchau, Walker, and van Wee (2010) note that "uncertainty has attracted a great deal of interest in transport policy and planning since the 1990s." In response to the uncertainties inherent in many transportation activities, numerous approaches to account for uncertainty have emerged over the past decades. Several of these methods may be useful in climate change adaptation planning in the transportation sector, particularly when used in combination. Although risk-management practices have emerged as a predominant method for accounting for uncertainty and enabling adaptation planning in the transportation sector (this is discussed in the next section), several of the methods introduced below are frequently used in combination with one another, or may be useful as adaptation practices evolve in the future. They are presented here to provide additional context for uncertainty planning as may be applicable to climate change adaptation.

3.1.1 Scenario Analysis

Scenario analysis (also called scenario planning) is widely used in policymaking and planning to examine plausible futures, and to aid in selecting a policy that performs satisfactorily across these futures. Such a solution is called a *robust* solution (Walker 2000). Scenario analysis is widely applied in the transportation sector to plan for future uncertainties (Redd et al. 2012; Sanderson 2012; Schwetz et al. 2012; van de Riet et al. 2008; Walker 2000), and has been suggested for use in general climate change adaptation by numerous organizations (IPCC 1994; Mearns and Hulme 2001; National Research Council 2010; Willows and Connell 2003), as well as for dealing with climate change uncertainties specifically in transportation (Dewar and Wachs 2008). However, the IPCC has more recently acknowledged that "the certainty that some climate change will occur…is driving adaptation assessment beyond the limits of what scenario-driven methods can provide." (Carter et al. 2007) This is because the GHG emission mitigation and reduction efforts, which directly affect the scenarios used in adaptation planning, remain largely uncertain. In response, the IPCC suggests moving towards a risk-management approach (Carter et al. 2007); however, scenario analysis is still widely used in conjunction with risk management and other approaches.

3.1.2 Risk Management

Risk management identifies, assesses, and then responds to risks. It has been widely used to address uncertainty in transportation planning (Mehndiratta et al. 2000) and in climate change adaptation (Carter et al. 2007; Willows and Connell 2003). For example, risk appraisal and risk management is central to the United Kingdom Highways Agency's *Climate Change Adaptation Strategy and Framework* (Parsons-Brinkerhoff 2009).

A key challenge in a risk-based adaptation approach is determining the likelihood of system impacts under uncertainty. Traditionally, when data are known, a probability distribution is used to describe uncertainty or likelihood (Mehndiratta et al. 2000; Morgan

2003), and risk becomes a function of an event’s likelihood and its consequences or impacts. However, it is noted that downscaled, high-resolution climate change projections of regional significance are largely unavailable to transportation professionals (TRB 2008). Thus, subjective probability distributions are often used to describe likelihood (Willows and Connell 2003), and “probability distributions become statements of ‘degree of belief’” (Morgan 2003), which are inexact, and thus may be problematic.

Risk management, and the use of risk-based practices in current transportation adaptation planning activities are discussed in greater detail in Section 3.3. As is discussed later, a more appropriate use of risk-based practices in climate change adaptation planning may require a modification in the definition of risk from its traditional form.

3.1.3 Expert Opinion

Expert opinion can be used in conjunction with risk management to determine the subjective distributions that describe the likelihood of a future event or outcome (Morgan 2003; Willows and Connell 2003); to rank and prioritize adaptation options (de Bruin et al. 2009); or, more broadly, to assess the timeline of local climate impacts, the general uncertainty of climate change, and the possible impacts to a system (Parsons-Brinkerhoff 2008). With climate change, however, the subjectivity associated with expert opinion may problematic, as experts can have widely differing opinions that can be influenced by geographical location, field of study, or other specific interests. In one case study it was also noted that judging climate impacts and infrastructure criticality based on expert opinion may not be “politically acceptable,” (Nguyen et al. 2011) given the subjectivity of that method.

3.1.4 Cyclic or Iterative Analysis

Cyclic or iterative approaches to adaptation have also been used to address uncertainty in climate change and infrastructure adaptation planning. In the United Kingdom (Parsons-Brinkerhoff 2008; Parsons-Brinkerhoff 2009; Willows and Connell 2003), New Zealand (Gardiner et al. 2008), Canada (NRCAN 2011), and the United States (Department of Homeland Security 2009; Major and O'Grady 2010), to name a few, frameworks have been developed wherein risks are periodically identified, assessed, and responded to in a cyclic or iterative approach over time. These frameworks address uncertainty by assuming that future outcomes will be better understood, or that uncertainty will diminish, over time. It should be noted that new information can either diminish or increase uncertainty (Walker et al. 2003), particularly when uncertainty is epistemic. Also, these approaches often utilize iterated scenario analysis to predict or update a set of future risks, which may or may not come true, and which may or may not require the previous response set to be changed. Thus, aside from the question of efficiency in periodically reassessing and responding to risks in a system, the efficacy of relying on this temporal approach to decrease uncertainty remains unclear.

3.1.5 Emerging and Innovative Approaches

In recent years, numerous planning approaches have emerged that respond to a number of the shortcomings in the methods discussed above to account for uncertainty in the planning and policymaking process. Generally speaking, these new approaches either seek to build flexibility into the basic structure of the ongoing policymaking or planning process, and therefore the plans and policies themselves, or make use of computers to clarify uncertainty through large ensemble scenario analysis.

3.1.5.1 Dynamic Strategic Planning (DSP)

Dynamic Strategic Planning is a systems analysis method that incorporates elements of decision analysis and real options (de Neufville 2000). Decision analysis is used to assist in decision making under uncertainty, using decision trees and/or influence diagrams to predict the likelihood and consequences of decision outcomes (Dewar and Wachs 2008). Real options (de Neufville 2003) responds to the risks identified in the decision analysis by building flexibility into the "design of technological projects and systems" (de Neufville 2000), such as infrastructure, to dynamically adapt to future conditions.

3.1.5.2 Computer-Based Exploratory Analysis

Computer-based exploratory analysis is a term applied here to generalize a family of policy analysis methods that employ computer modeling or simulation to consider large ensembles of scenarios, thus enabling decision makers to consider a much wider range of futures, as well as additional uncertainties (e.g., those associated with model structure, input, and parameters). These include:

- *Exploratory Modeling,* which treats uncertainty by "conducting a large number of computer simulation experiments on many plausible formulations of the problem, rather than using computer resources to increase the resolution of a single best-estimate model" (Lempert et al. 1996), thus enabling policymakers to make decisions that are robust across large numbers of *plausible* futures, not just a small number of *probable* or expected futures;

- *Computer Assisted Reasoning* (CAR), in which software that facilitates the use of Exploratory Modeling by evaluating assumptions and hypotheses to create "landscapes of plausible futures" (Lempert 2002), or visualizations that represent the outcomes of ensembles of scenarios that can be evaluated to identify "robust regions" that help policymakers "identify key strategies that perform relatively well compared with the alternatives over a wide range of scenarios" (Lempert 2002);
- *Robust Adaptive Planning* (Lempert et al. 2002) and Robust Decision Making (Dewar and Wachs 2008), which are both computer implementations of Exploratory Modeling in decision analysis frameworks designed to identify policies that are robust across wide ranges of plausible futures.

3.1.5.3 Assumption Based Planning

Assumption Based Planning (ABP) was developed at the RAND Corporation to improve the robustness of an existing plan by identifying its underlying assumptions that are vulnerable to plausible events, and taking actions to increase the plan's robustness to these events (Dewar 2002; Dewar et al. 1993). ABP consists of five steps (Dewar and Wachs 2008): (1) identify all assumptions that form the basis for the plan; (2) identify the "load bearing" assumptions critical to the success of the plan and those that are vulnerable to plausible future events (Exploratory Modeling can be used for this); (3) produce signposts to monitor vulnerable assumptions and serve as a warning sign of impending surprises; (4) design and implement shaping actions to influence the outcomes of uncertain events in ways favorable to the plan's success; and (5) design and implement hedging actions to mitigate the impacts should an assumption fail to occur as expected.

3.1.5.4 Dynamic Adaptive Planning

Dynamic adaptive planning (DAP) is an evolution of adaptive management, which originated in the environmental management field (Holling 1978; McLain and Lee 1996; Walters and Hilborn 1978). Adaptive management can be broadly defined as a "structured process of learning by doing, and adapting based on what's learned." (Williams 2011) This learning process is facilitated by what Holling (1978) discusses as *monitoring* of specific system performance *indicators* over the implementation of a management plan. More specifically, the National Research Council (2004) defines adaptive management as:

> "...flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process."

Adaptive approaches have been noted as an important concept in managing climate change risks (National Research Council 2010).

DAP is a framework that outlines an adaptive management-type approach that is generalized for broader applications to deal with uncertainty in different fields (Walker 2000; Walker 2000; Walker et al. 2001), and expands upon some of ABP's core concepts. In brief, DAP involves developing a basic plan, identifying the vulnerabilities of the plan (i.e., how it might fail), developing a series of actions to guard against these vulnerabilities, and establishing a series of signposts, similar to ABP, to monitor the uncertain vulnerabilities. During implementation, if the monitoring program indicates that signposts reach predetermined critical levels, a series of predetermined adaptive actions are taken to ensure that the basic plan stays on track to meet its goals and objectives. The basic plan, monitoring program, and planned adaptations remain in place unless monitoring indicates that the intended outcomes can no longer be achieved, or if the goals and objectives of the basic plan change. In these instances, the adaptive plan is then reassessed. The elements of flexibility, adaptability, and learning enable DAP to adjust to new information as it becomes available, and therefore to deal with deep uncertainty (Marchau et al. 2010).

Numerous studies have applied DAP in transportation planning (Kwakkel et al. 2010; Kwakkel et al. 2010; Marchau and Walker 2003; Marchau et al. 2009; Marchau et al. 2010). It has also been suggested as a response to climate change in infrastructure and transportation applications (Dewar and Wachs 2008; Rahman et al. 2008).

3.2 The Evolution of Climate Change Impact Assessment and Adaptation

Much of the early guidance on impact assessment and adaptation comes from the Working Group II (WG2) of the IPCC. When it was established in 1988, the goal of WG2 was, and continues to be, to "assess the scientific, technical and socio-economic information relevant for the understanding of human induced climate change, its potential impacts and options for mitigation and adaptation." (IPCC 2010) Working Group II's contribution to the IPCC's First Assessment Report (AR1) (IPCC 1990) primarily focused on impact assessment. This assessment method was largely a scenario-based exercise to provide an overview of impacts and vulnerabilities in specific sectors (e.g., agriculture, natural ecosystems, transport and industry, etc.). In AR1, the focus was on impact assessment, rather than adaptation options evaluation.

In their 1992 Supplementary Report, WG2 established an "analytical outline" (IPCC 1992) for impact assessment; it was designed to enable flexibility in analytical methods, recognizing the different needs of different sectors. They note, however that "there is little experience with evaluating the social and economic impacts of climate change," and that "it is desirable that future versions address these topics in more detail." (IPCC 1992) The seven steps of the proposed impact assessment were:

1. Definition of the problem
2. Selection of the method
3. Testing of the method
4. Selection of scenarios
5. Assessment of impacts
6. Evaluation of adjustments

7. Consideration of policy options

Within this impact assessment framework, discussions of adaptation are restricted to the final step, ‘consideration of policy options.’ In that step, however, only “adaptive policies” are briefly discussed, such as the “lifting of government subsidies on some food crops” as a means of “offsetting overproduction due to a more favourable climate.” (IPCC 1992) No discussions of deeper adaptation actions or strategies were provided.

In 1994 the IPCC released the *IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptation* (IPCC 1994). This report expanded the scope from an impact analysis and evaluation, to include an examination of “the possible adaptive responses for reducing adverse effects or exploiting new opportunities,” thereby allowing “policy makers and decision makers to choose among a set of adaptation options.” (IPCC 1994) The term “impact assessment” was also expanded to include the consideration of adaptation responses, resulting in a revised framework for generalized, non-sector specific impact and adaptation analysis (IPCC 1994):

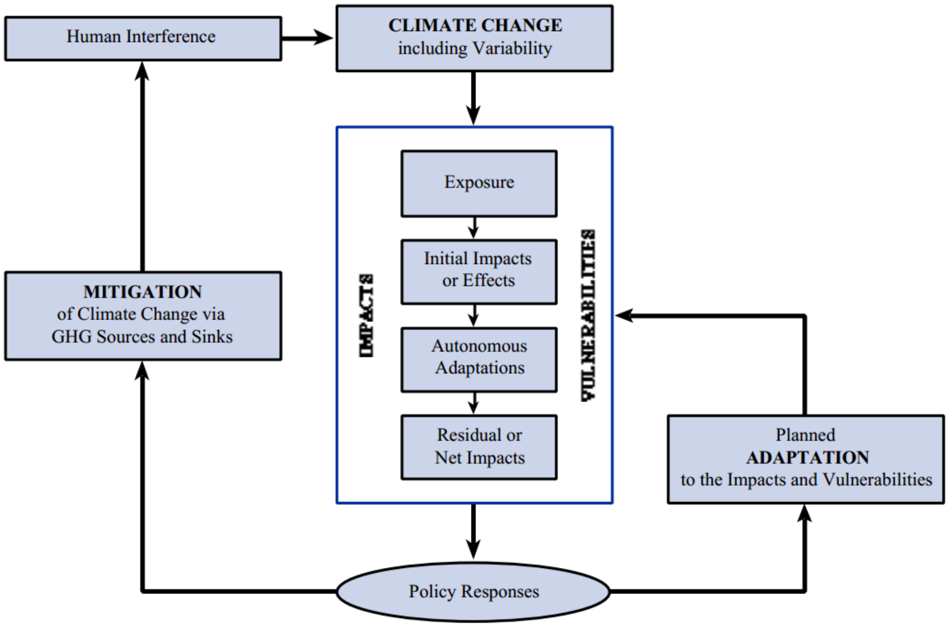
1. Define problem
2. Select method
3. Test method/sensitivity
4. Select scenarios
5. Assess biophysical impacts, and socio economic impacts
6. Assess autonomous adjustments
7. Evaluate adaptation strategies

The final step, ‘evaluate adaptation strategies,’ was further broken down into a series of progressive steps, as outlined by the IPCC adaptation evaluation framework include (IPCC 1994; IPCC 1995):

1. Defining goals and objectives
2. Specifying important climate impacts
3. Identifying adaptation options
4. Examine constraints of identified options
5. Quantify measures and formulate alternative strategies
6. Weight objectives and evaluate trade-offs
7. Recommend adaptation measures

In their Third Assessment Report (TAR), the IPCC (Adejuwon et al. 2001) presents a more formalized framework developed by Smit et al., (1999) to evaluate the vulnerabilities of systems (i.e., not specifically transportation systems) to climate change impacts, and develop adaptive policy responses (Figure 3.1). Note that in addition to illustrating a cyclic or iterative approach to adaptation (see section 3.1.4), this framework also shows the interrelationship of adaptation and mitigation as discussed briefly at the beginning of this chapter.

In discussing this framework, the IPCC defines the vulnerability of a system to climate impacts as lying on a spectrum between vulnerability and resilience. Vulnerability is defined as “the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes,” (IPCC 2007) and is characterized as a function of that system’s: (1) sensitivity to climate impacts, (2) adaptive capacity, and (3) exposure to climate impacts (Adejuwon et al. 2001). Adaptive capacity is defined as “ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.” (IPCC 2007)



Source: (Adejuwon et al. 2001)

Figure 3.1 IPCC TAR Vulnerability and Adaptation Framework

In the TAR, the IPCC also introduces the concept of risk management in impact assessment and adaptation (concepts of risk and risk management are discussed further in the next section). Prior reports (IPCC 1992; IPCC 1994; IPCC 1995) had only provided cursory discussions of risk, or risk analysis as part of the impact analyses. The TAR mentions three studies (Hisschemoller and Olsthoorn 1999; Nguyen et al. 1998; Perez et al. 1999) in discussing the potential to modify existing risk management programs for climate change impact adaptation, but does not provide any specific guidance on how to merge risk management principles with climate change impact assessment or adaptation strategies beyond the use of risk analysis for general impact assessment.

The IPCC's fourth Assessment Report (AR4) broadens guidance for risk management in what it terms "climate change impact, adaptation and vulnerability (CCIAV) assessment." (Carter et al. 2007) CCIAV carries forward practices from previous Assessment Reports (namely, impact assessment, adaptation assessment, vulnerability assessment, and integrated assessment), but introduces risk management as a tool "in mainstream policy-making." (Carter et al. 2007)

The AR4 notes "the certainty that some climate change will occur [which] is driving adaptation assessment beyond the limits of what scenario-driven methods can provide." (Carter et al. 2007) Therefore, risk management's further development in the AR4 is motivated by its ability to address these limits, which include (Carter et al. 2007):

- Assessing current adaptations to climate variability and extremes before assessing adaptive responses to further climate
- Assessing limits of adaptation
- Linking adaptation to sustainable development
- Engaging stakeholders
- Decision-making under uncertainty

The AR4 proposes a series of general steps for risk management in adaptation and impact evaluation frameworks: (1) a scoping exercise; (2) risk identification; (3) risk analysis; (4) risk evaluation; and (5) risk treatment (Carter et al. 2007). These risk management steps are generally consistent with international standards; for example, *AS/NZ 4360:2004 – Australian and New Zealand Standard on Risk Management*, (Standards Australia and Standards New Zealand 2004), and *ISO 31000:2009 – Risk Management Principles and Guidelines* (International Organization for Standardization 2009). Risk, risk management, risk standards, and risk based adaptation frameworks are discussed further in the next section.

Risk management, as an approach to adaptation, has gained significant traction in recent years and has been broadly identified and endorsed by the global adaptation community (Carter et al. 2007; Meyer et al. Forthcoming; National Research Council 2010; TRB 2008; USGCRP 2009; Willows and Connell 2003). In their review and synthesis of adaptation strategies and frameworks from the global transportation community, Wall and Meyer (2013) note that "much of the transportation and infrastructure sector's approach to climate change impact analysis and adaptation planning is based on risk management practices." Section 3.4 provides a more detailed review of the current state-of-the-art in adaptation planning frameworks (which are primarily based on risk and vulnerability) from the global transportation community.

3.3 Risk and Risk Management Principles

The concept of risk has several definitions. An early distinction by Knight (1921) is that risk refers to random adverse events with probabilities of occurrence that can be statistically calculated; uncertainty, however refers to random events that cannot be predicted by statistical probability (Lofstedt and Boholm 2009). This definition suggests that risk and uncertainty are parallel and mutually exclusively concepts. More recent definitions of uncertainty suggest otherwise. Walker et al. (2003) define uncertainty as "any departure from the unachievable ideal of complete determinism." This definition suggests that uncertainty is the characteristic of randomness in events (aleatory uncertainty) or limited knowledge (epistemic uncertainty), and that risk may be a subset of uncertainty that can be quantified by statistical probability. Additionally, the International Organization for Standardization (2009) offers the broad definition of risk as the "effect of uncertainty on objectives."

The early definitions of risk have evolved into a more practical definition, which states that risk is "a measure of the probability and severity of adverse effects" from some event (Lowrance 1976) in (Haimes 2004). That is, risk is a function of (1) the likelihood (i.e., probability) of an event's occurrence, and (2) the consequences of that event. Although the early definition by Knight (1921) notes that risk refers to "adverse occurrences," (Lofstedt and Boholm 2009), it is noted that the consequences of an uncertain event can be positive, as well as negative (International Organization for Standardization 2009). Furthermore, it is noted that the likelihood of an event's occurrence can be determined or measured either qualitatively (e.g., through expert opinion) or quantitatively (e.g., mathematically) (International Organization for Standardization 2009).

Risk analysis and risk management have evolved to respond to the presence of uncertainty in decision-making. Haimes (2004) states that risk assessment attempts to "identify, measure, quantify and evaluate risks and their consequences and impacts." Risk management refers to "coordinated activities to direct and control an organization with regard to risk." (International Organization for Standardization 2009)

The discrete processes of risk assessment and risk management have likewise evolved. Haimes (1981) outlines five steps for risk assessment and risk management:

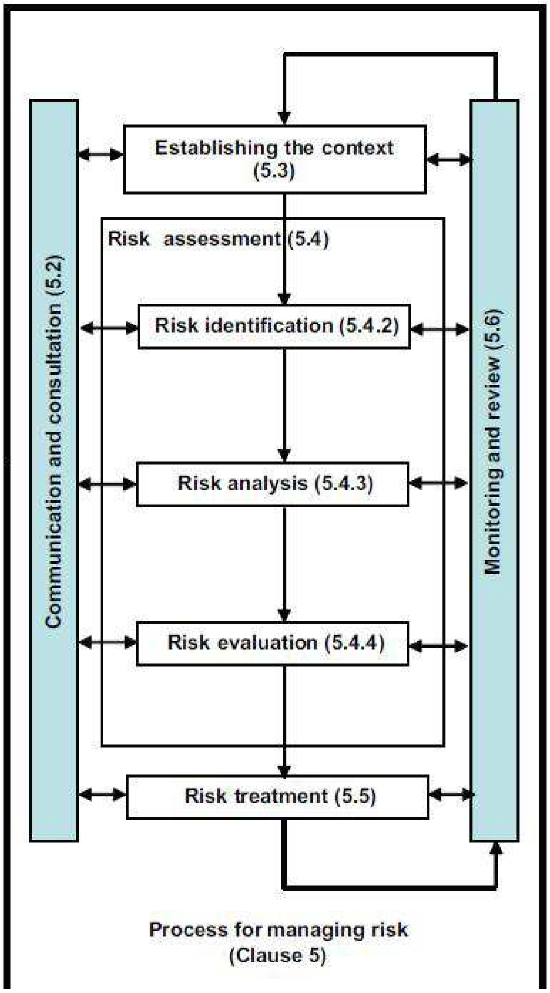
Risk Assessment

1. Risk identification
2. Risk modeling, quantification, and measurement
3. Risk evaluation

Risk Management

4. Risk acceptance and avoidance
5. Risk management

Later frameworks, however, place risk assessment as a component of larger risk management frameworks. For example, the Australia/New Zealand standard, *AS/NZS 4360:2004 - Risk Management* (Standards Australia and Standards New Zealand 2004), and the international standard, *ISO 31000:2009 – Risk management – Principles and Guidelines* (International Organization for Standardization 2009), indicate that risk assessment is one part of the risk management process, and consists of three components: (1) risk identification, (2) risk analysis, and (3) risk evaluation (Figure 3.2)



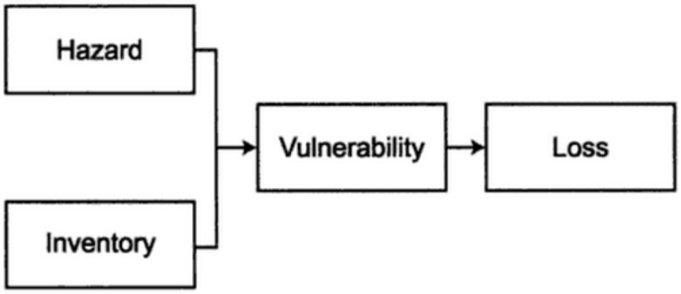
Source: (International Organization for Standardization 2009)

Figure 3.2 ISO 31000:2009 Risk Management Process

3.4 Adaptation in the Transportation and Infrastructure Sector

Over the past two decades, governments and agencies in charge of managing transportation and infrastructure systems have developed numerous adaptation strategies to address the impacts of climate change on their systems. These adaptation strategies seem to have initially drawn upon the concepts of impact and vulnerability analyses (e.g., CCIAV) to identify systems and areas that will be exposed to and affected by projected climate changes. In more recent years, frameworks have evolved to incorporate risk-based practices to identifying, assessing, and responding to climate change impacts strategically.

It should be noted that vulnerability-based analyses and risk-based analyses are not mutually exclusive. Rather, as discussed later in this section, vulnerability analyses are an important component of a risk-based analysis framework, where risk is employed to enable prioritization of adaptation needs. For example, see the catastrophe model shown in Figure 3.3 (Grossi and Kunreuther 2005; Kunreuther and Michel-Kerjan 2007), which explicitly discusses vulnerability in the assessment of the risks associated with catastrophic events. Botzen and Van Den Bergh (2009) discuss the use of catastrophe models in the context of climate change to assess risks associated with "increases [in the] frequency or severity of extreme weather." This type of model is also discussed in the context of climate change assessment by Moss et al. (2013), and Peterson et al. (2008), where it is referred to as "a typical risk model used by the insurance industry."



Source: Grossi and Kunreuther (2005)

Figure 3.3 Catastrophe Model

The catastrophe model consists of four components: (1) a hazard analysis, (2) an inventory analysis, (3) a vulnerability analysis, and (4) a loss analysis. In the context of risk management frameworks (e.g., Figure 3.2), this four-component risk model could be viewed as the risk assessment component of risk management. It is also consistent with the earlier conceptual discussion of risk as the combination of likelihood of an event, and the adverse consequences of that event. In Figure 3.3, the event's probability is determined in the hazard component; the event's consequences are determined in the vulnerability component (i.e., how structures and systems are impacted by the hazard), and quantified as costs in the loss component.

This section first synthesizes 28 climate change adaptation frameworks from the global transportation and infrastructure community. The synthesis was carried out specifically to examine: (1) commonalities in adaptation framework development and structure, (2) commonalities in the types of climate impacts assessed, and (3) common barriers to adaptation experienced by the developing agencies. This synthesis then generalizes the risk-based climate change adaptation framework approaches to serve as a foundation for the development of the risk assessment methodology developed later in this study.

3.4.1 Frameworks from the Global Transportation Community[1]

Numerous adaptation frameworks were reviewed from the global transportation and infrastructure community to gain an understanding of the current state-of-the-art practices. All of the adaptation frameworks reviewed incorporate some element of risk-based practices into their analysis and management of climate change impacts. Table 3.1

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[1] Substantial portions of this section synthesizing risk-based adaptation strategies in transportation sector were previously presented in Wall and Meyer (2013).

provides a summary of those frameworks that were reviewed, the countries of origin, and the originating agency or organization.

Two general categories of risk-based adaptation frameworks were examined for this study. The first category of frameworks (shown in the first section of Table 3.1) addresses general infrastructure system concerns, but address transportation infrastructure as part of the broader examination. These frameworks were generally developed by agencies or governments at the municipal and regional level, national engineering societies, or were incorporated into frameworks from intersecting fields (e.g., flood risk management).

The second category of adaptation frameworks specifically address transportation infrastructure and management activities, and were generally developed by government transportation agencies, and by independent and private-sector transportation organizations (e.g., airport, port, and rail operators). While additional risk-based adaptation frameworks exist in the global transportation sector, those selected provide a broad sampling upon which conclusions about the current state of practice in the transportation community can be formed.

Table 3.1 Global Adaptation Frameworks for Transportation and Infrastructure

Framework - General Infrastructure	Country of Origin	Agency/Organization
Climate Change Risks to Australia's Coast - A First Pass National Assessment	Australia	Department of Climate Change (2009)
Climate Change Risks for Coastal buildings and Infrastructure - Supplement to the First Pass National Assessment	Australia	Department of Climate Change and Energy Efficiency (2011)
Infrastructure and Climate Change Risk Assessment for Victoria	Australia	Victorian Government; CSIRO (2007)

Table 3.1 (Continued)

Adapting To Climate Change - Canada's First National Engineering Vulnerability Assessment of Public Infrastructure	Canada	Engineers Canada – Public Infrastructure Engineering Vulnerability Committee (PIEVC) (2008)
PIEVC Engineering Protocol for Climate Change Infrastructure Vulnerability Assessment	Canada	Engineers Canada – Public Infrastructure Engineering Vulnerability Committee (PIEVC) (2009)
Adapting to Climate Change - A Risk-based guide for Ontario Municipalities	Canada	Ontario Ministry of Municipal Affairs and Housing (Bruce et al. 2006)
Adapting to Climate Change - A Risk-based guide for Local Governments	Canada	National Resources Canada (Black et al. 2010)
Ahead of the Storm - Preparing Toronto for Climate Change	Canada	Department of Climate Change Adaptation Strategy (2008)
Climate Change Risk Management Strategy for Halifax Regional Municipality	Canada	Halifax Regional Municipality (Dillon Consulting and de Romilly & de Romily LTD. 2007)
The National Flood Risk Assessment	Scotland	Scottish Environmental Protection Agency (SEPA) (2011)
Flood Risk Management Strategies and Local Flood Risk Management Plans	Scotland	Scottish Environmental Protection Agency (2011)
Climate Change Adaptation in New York City - Building a Risk Management Response	United States	New York City Panel on Climate Change (Major and O'Grady 2010)
Preparing for Climate Change - A Guidebook for Local, Regional, and State Governments	United States	King County (WA) Executive (Sonover et al. 2007)

Framework - Transportation Infrastructure	**Country of Origin**	**Agency/Organization**
Impact of Climate Change on Road Infrastructure	Australia	Austroads (Norwell 2004)
Risk Management for Roads in a Changing Climate - A Guidebook to the RIMAROCC Method	European Union	ERA-NET (Bies et al. 2010)
Climate Change Uncertainty and the State Highway Network: A Moving Target	New Zealand	Transit New Zealand (Kinsella and McGuire 2005)
Climate Change Effects on the Land Transport Network Volume One - Literature Review and Gap Analysis	New Zealand	NZ Transport Agency (Gardiner et al. 2008)
Climate Change Effects on the Land Transport Network Volume Two - Approach to Risk Management	New Zealand	NZ Transport Agency (Gardiner et al. 2009)
Scottish Road Network Climate Change Study	Scotland	Scottish Executive (Galbraith et al. 2005)

Table 3.1 (Continued)

Scottish Road Network Climate Change Study - Progress on Recommendations	Scotland	Transport Scotland (Galbraith et al. 2008)
Scottish Road Network Landslides Study	Scotland	Scottish Executive (Winter et al. 2005)
Adaptation Reporting Powers, reports received*	United Kingdom	Department of Environment, Food & Rural Affairs (DEFRA 2012)
Climate Change Adaptation Strategy	United Kingdom	UK Highways Agency (2008)
Climate Change Adaptation Strategy and Framework	United Kingdom	UK Highways Agency (2009)
Climate Change Risk Assessment	United Kingdom	UK Highways Agency (2011)
Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Pilot of the Conceptual Model**	United States	Federal Highway Administration (Federal Highway Administration 2012)
Climate Change & Extreme Weather Vulnerability Assessment Framework	United States	Federal Highway Administration (Federal Highway Administration 2012)
Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska	United States	Oregon Transportation Research and Education Consortium (OTREC) (MacArthur et al. 2012)
Climate Change, Extreme Weather Events and the Highway System: A Practitioner’s Guide	United States	Transportation Research Board – National Cooperative Highway Research Program (NCHRP), (Meyer et al. Forthcoming)

* Twenty-three agency reports were reviewed under the DEFRA reporting powers requirement. A full agency list can be found at: <http://www.defra.gov.uk/environment/climate/sectors/reporting-authorities/reporting-authorities-reports/>

** This includes five pilot-program case study reports, some of which revised the framework: MTC (Nguyen et al. 2011), NJTPA (2011), Oahu MPO (SSFM International 2011), Virginia DOT (2011), Washington DOT (Maurer et al. 2011)

3.4.1.1 Risk Standards and the Basis for Framework Structures

Transportation agencies and organizations generally drew from existing risk management practices to inform their adaptation frameworks. Independent and private-sector transportation organizations (i.e., port authorities, airports), reported that enterprise risk management practices were already a part of their existing business management activities, and that climate change adaptation planning could be incorporated into these practices. Some noted specific standards as having been used in developing their enterprise risk management practices. For example, the Port of Dover (2011) and NATS (2011) noted that the international standard, *ISO 31000:2009 – Risk Management – Principles and Guidelines*, (International Organization for Standardization 2009) was used to develop their risk management programs.

In Canada, the Ontario Ministry of Municipal Affairs & Housing (Bruce et al. 2006) and National Resources Canada (NRCAN 2011) both reported that the Canadian standard, *CAN/CSA-Q850-01 – Risk Management: Guidelines for Decision-Makers*, was used to develop their frameworks; the Halifax Regional Municipality (Dillon Consulting and de Romilly & de Romily LTD. 2007) used an earlier edition of that standard, as well as *CAN/CSA-Q634-M91 – Risk Analysis Requirements and Guidelines*.

Frameworks in Australia and New Zealand (Gardiner et al. 2009; Gardiner et al. 2008; Victorian Government et al. 2007) were predominantly informed by the standard *AS/NZS 4360:2004 – Risk Management*, and the superseding standard *AS/NZS 31000:2009 – Risk management Principles and Guidelines*. This latter standard is also specified by the International Organization for Standardization as *ISO 31000:2009 – Risk Management Principles and Guidelines*, which was used in the development of the RIMAROCC framework in the European Union (Bies et al. 2010).

3.4.1.2 Focus of Adaptation Frameworks

The frameworks reviewed focused on three types of adaptation: (1) physical infrastructure and assets; (2) operations and maintenance; and to a lesser degree (3) organizational management.

Adaptation of physical infrastructure and assets was a primary focus of the frameworks reviewed. Generally speaking, this type of adaptation seeks to evaluate the impacts and vulnerabilities of existing physical infrastructure and assets, and then identify and implement actions that seek to minimize or mitigate climate change vulnerabilities. This is consistent with the general definition of adaptation offered in the NCHRP framework by Meyer et al. (Forthcoming) as "actions taken to reduce the vulnerability of natural and human systems or increase system resiliency in light of expected climate change." Many adaptation planning frameworks examine infrastructure at the system and corridor levels; however some frameworks – for example, the FHWA Conceptual Framework (Federal Highway Administration 2012) and related pilot studies (Maurer et al. 2011; Nguyen et al. 2011) – evaluated infrastructure at the individual asset level. Additionally, the RIMAROCC framework (Bies et al. 2010) from the European Union was designed to enable adaptation analysis and planning at the system, corridor, and individual asset levels.

Adaptation of operations and maintenance practices was also a primary focus of the adaptation frameworks reviewed. This type of adaptation seeks to evaluate the impacts of future climate conditions on operations and maintenance practices, and identify and implement strategies to mitigate the impacts of future climate conditions. An example would be an airport operator purchasing more snow clearing equipment to ensure that increases in winter storm events do not significantly disrupt airport operations. Particularly in the United Kingdom, several of the DEFRA reporting power agency frameworks (DEFRA 2012) explicitly considered climate change impacts on operations and maintenance. For example, every UK airport operator that submitted an adaptation report to DEFRA identified significant impacts of climate induced changes in weather on airport operations and maintenance – ranging from an increasing number of extreme weather periods (impacting operations), to longer growing seasons for vegetation (impacting maintenance).

A limited number of frameworks evaluated the broader impacts of climate change on organizational management. The prime example is the UK Highways Agency (Highways Agency 2011), which considered that increases in mean temperature would affect the amount of energy consumed to heat and cool their offices, control centers, and outstations.

3.4.1.3 Barriers and Limitations of Current Adaptation Frameworks

In discussing the development of their frameworks, many agencies reported the limitations of their risk-based adaptation frameworks, as well as barriers – both internal and external – that could inhibit the framework's implementation. Common barriers and limitations can be characterized by five categories. These categories can be divided into two classifications: those that have a high frequency of occurrence, and those that have a lesser, or moderate frequency of occurrence. Categories 1-3 constitute high-frequency; categories 4 & 5 constitute moderate-frequency limitations and barriers:

1. Data limitations

2. Treatment of risk
3. Availability of sufficient resources
4. Legal, political, regulatory barriers
5. Uncertain future system demand

Data Limitations: Of the barriers and limitations noted, limited data was the most prevalent, and applies to two types of data: (1) infrastructure system and asset data, and (2) climate data. Primarily three types of limitations apply to infrastructure asset and system data:

- **Unavailable –** No inventory or database exists for certain types of assets (e.g., culverts)
- **Incomplete/inconsistent –** Data does not contain all necessary or relevant fields (e.g., asset condition), or contains information for some assets but not others
- **Not easily accessed –** Necessary or relevant data may be available, but is spread across multiple departments within an agency and must be coalesced.

The predominant limitation noted for climate data was that the projections available to agencies for planning purposes are not downscaled to a level of detail sufficient for decision making at the local or regional level. Some agencies also noted that some types of climate impacts are better characterized in projections than others. For example, port authorities in the United Kingdom noted that changes in wind and fog conditions could significantly impact their operations, yet their projections contain significantly more uncertainty than other projected impacts (Gardiner et al. 2011; Harwich Haven Authority 2011).

Treatment of Risk: The way in which risk is perceived and characterized was the second most commonly listed limitation or barrier. Most significantly, numerous agencies noted that it is difficult to define acceptable levels or risk, relevant types of risks, and the critical thresholds of risk. Furthermore, in the decision-making process difficulty was noted in linking the immediate need for action with risks that are perceived to be of long-term or distant consequence.

The difficulty in linking risk levels to the decision-making process is further compounded by what many agencies discussed as the qualitative treatment of risk. As noted in the previous section, risk analysis and prioritization is primarily conducted using expert opinion and risk matrices. This qualitative approach, although necessitated by data limitations and uncertainty, was found to be “politically unacceptable” in determining priorities and infrastructure asset criticality (Nguyen et al. 2011).

Availability of Sufficient Resources: The third most commonly discussed barrier inhibiting framework development and implementation was insufficient financial and staffing resources. With respect to financial barriers, agencies noted that sufficient financial resources were not available to implement adaptation planning as specified in the frameworks developed. In addition, several agencies noted that sufficient financial resources were not available to develop further or refine the adaptation planning frameworks themselves.

Agencies also noted that they, themselves, often do not have sufficient staff available to undertake adaptation planning in addition to their other planning efforts.

This is closely related to insufficient financial resources, as additional funding would likely enable additional staff to be hired.

Interdependency & Regulatory Barriers: When conducting climate change risk assessments, it was difficult for agencies to completely characterize their own risk without some knowledge of the climate risks faced by interdependent agencies. For example, Mersey Docks (UK) noted that the operations of their facilities are dependent upon the supply of utilities (e.g., water, gas, electricity), the surrounding highway infrastructure, and adjacent properties leased from third parties (Gardiner et al. 2011). However, as climate risks are not fully characterized within these three interdependent sectors, Mersey Docks noted that this will have to be "further addressed over time through engagement with those organizations with which there are interdependencies" (Gardiner et al. 2011) to understand fully the climate-related risks that they face.

Regulatory barriers also pose a significant challenge to private and independent transportation organizations, such as airport operators and port authorities, whose funding and investment programs must be approved by their regulating agencies. For example, London Gatwick Airport noted that any plans to "develop, improve and grow the airport" must be agreed upon by the United Kingdom Civil Aviation Authority (CAA) and the airlines for each 5-year investment cycle (Gatwick Airport Limited 2011). However, they also noted that this short investment approval cycle is difficult to reconcile with long-term climate projections that predict environmental conditions well beyond the timeframe of the 5-year cycle. This temporal discrepancy makes it difficult to justify investment in projects whose benefits are uncertain and may occur well after the current investment cycle.

Future Demand: The uncertainty associated with future transportation demand was noted as a difficulty in determining the need for adaptive actions, and forced many agencies to make assumptions as to future demand circumstances. For example, the Associated British Ports predicts throughput and cargo flows up to the year 2030 in their master planning process, but noted that “it is difficult to accurately predict the way that world trade and hence international cargo flows will change.” (Associated British Ports 2011) Therefore, the uncertainty associated with climate change-related adaptation needs is compounded by the uncertainty associated with future demand-related needs. Some agencies, for example the New Zealand Transport Agency, did not consider the impacts of climate change on travel demand and land use changes to simplify their analysis and thus enabled the focus of their analysis to be directed towards physical impacts on infrastructure and assets (Gardiner et al. 2008).

3.4.2 Generalizations of the Risk-Based Adaptation Frameworks[2]

The common approaches of the frameworks listed in Table 3.1 for evaluating climate change adaptation needs were generally consistent with practices outlined in the generic risk standard, *ISO 31000:2009 – Risk Management Principles and Guidelines* standard shown (Figure 3.2). Several of the steps were commonly altered or expanded to tailor the generic approach to the unique aspects of climate change planning (e.g., need for qualitative likelihood).

Step 1 – Establishing Context: This step generally consisted of defining goals and objectives, collecting infrastructure inventory and projected climate data, and assembling

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[2] Substantial portions of this section synthesizing risk-based adaptation strategies in the transportation sector were previously presented in Wall and Meyer (2013).

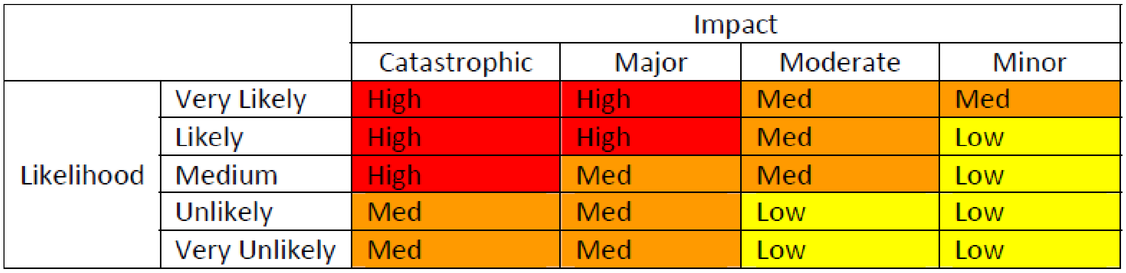
expert panels. The use of expert panels, or expert workshops, in the risk assessment activities (Steps 2 through 4) was nearly universal across the frameworks reviewed. This is a widely accepted method to account for climate change uncertainties in the planning process (see earlier discussion, Section 3.1.3).

Step 2 – Risk Identification: This step commonly consisted of identifying relevant climate change hazards/impacts, identifying vulnerabilities within the infrastructure system or agency's activities, and identifying likely consequences of climate impacts. This could also include identification of regional focus areas or priorities (e.g., focus only on coastal sea-level rise, specific regions, etc.), and critical infrastructure systems. Agencies often developed matrices to aid in this effort across multiple infrastructure types, agency activities, and impact types (Bies et al. 2010; Highways Agency and Parsons-Brinkerhoff 2009; MacArthur et al. 2012; PIEVC and Engineers Canada 2008; Victorian Government et al. 2007).

Step 3 – Risk Analysis: This step consisted of assigning qualitative (e.g., low/medium/high) or semi-quantitative (e.g., 1 through 5) scores to the aspects of the climate impact. Typically this was simply the risk's likelihood and consequences. In some cases, the analysis examined at other elements. For example, the UK Highways Agency framework (Highways Agency and Parsons-Brinkerhoff 2009) asked experts to rank (low/medium/high) four specific risk criteria: (1) uncertainty, (2) rate of climate change (i.e., time horizon associated with predicted changes), (3) extent of disruption (i.e., number of locations, extent of network), and (4) severity of disruption (i.e., recovery time or disruption time). Another example, the Washington State DOT (Maurer et al.

2011), examined two elements: (1) impact severity (e.g., reduced capacity, temporary failure, complete failure) and (2) asset criticality.

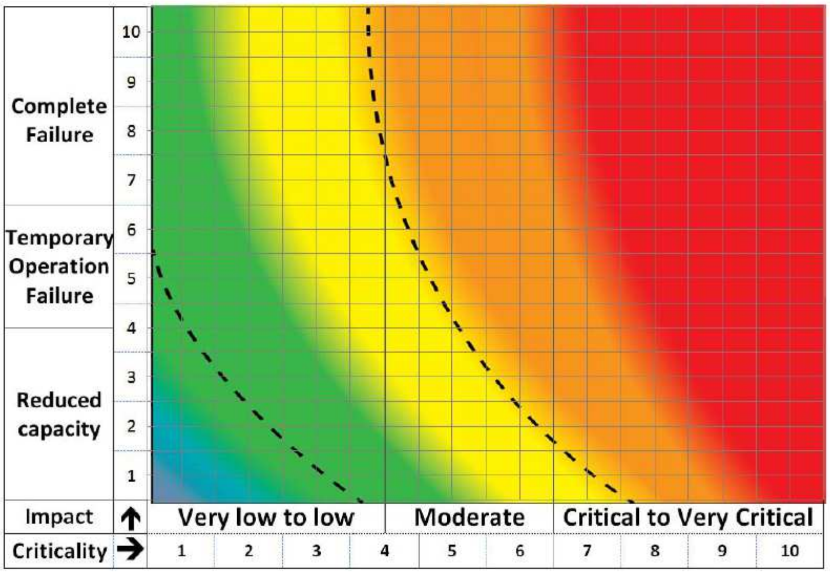
Step 4 – Risk Evaluation: Generally speaking the evaluation of risks involves some type of ranking of the risk analysis results to identify priorities for adaptation. Most commonly this consisted of inputting the scores from Step 3 into a risk matrix to evaluate and prioritize risks. Risk matrices position the variables (e.g., likelihood and consequence, criticality and impact, etc) associated with a climate change impact on the x- and y-axis of a Cartesian coordinate system; those events in opposite corners receive higher and lower risk prioritization scores, respectively. Matrices range from simple matrices with discrete low/medium/high regions (Figure 3.4) to much more complex matrices with less discrete heat map regions (Figure 3.5), or multi-dimensional matrices that incorporate additional criteria (Figure 3.6).



		Impact			
		Catastrophic	Major	Moderate	Minor
Likelihood	Very Likely	High	High	Med	Med
	Likely	High	High	Med	Low
	Medium	High	Med	Med	Low
	Unlikely	Med	Med	Low	Low
	Very Unlikely	Med	Med	Low	Low

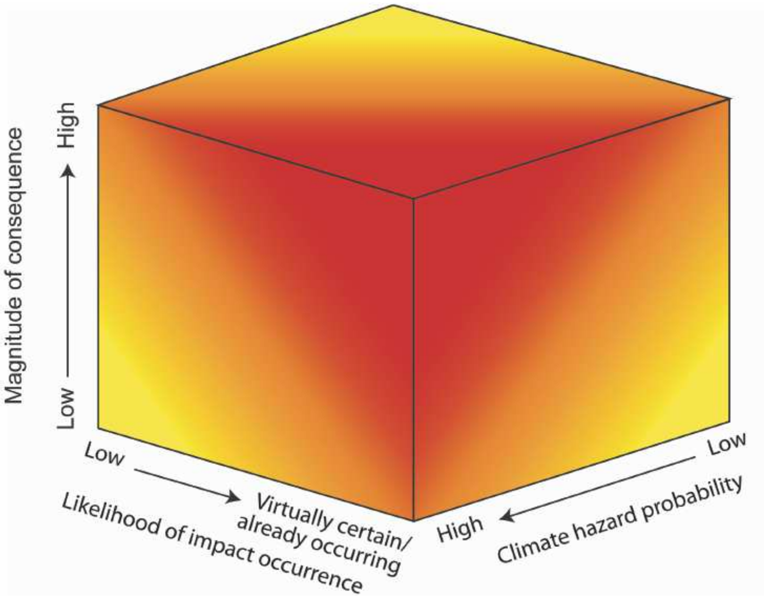
Source: (MacArthur et al. 2012)

Figure 3.4 Simple Risk Prioritization Matrix



Source: (Maurer et al. 2011)

Figure 3.5 Complex Risk Prioritization Matrix



Source: (Major and O'Grady 2010)

Figure 3.6 Multi-Dimensional Prioritization Matrix

Another common approach to risk evaluation consisted of quantitatively determining risk scores, or priority rankings. One motivation for this approach is that it enables the examination of additional criteria, which is beyond the capacity of a two- or three-dimensional risk matrix. The risk score is generally computed using a simple equation of the relevant criteria. For example, the UK Highways Agency (Highways Agency and Parsons-Brinkerhoff 2009) assigns low, medium, and high criteria ratings scores of 1, 2 and 3, respectively. These are then input into the following equation to arrive at an "indicator score":

$$\frac{[Rate\ of\ climate\ change]\ x\ [Extent\ of\ disruption]\ x\ [Severity\ of\ disruption]\ x\ (\ 4\ -\ [Uncertainty]\ )}{81}$$

More complicated evaluations of risk did exist, for example the Virginia DOT pilot study of the FHWA Conceptual Model (Virginia Department of Transportation 2011) computed scores by incorporating climate, economic, deterioration, ecological, and traffic demand criteria into a multicriteria decision analysis (MCDA) model to evaluate risks under multiple climate scenarios.

Steps 3 and 4 were frequently combined into a single step, called a "risk appraisal" (Highways Agency and Parsons-Brinkerhoff 2009), or a "risk assessment" (PIEVC 2009).

<u>Step 5 – Risk Treatment</u> The treatment of risk concerns the development, selection, and implementation of an adaptation action. This step was commonly broken into two discrete steps: (1) identification, evaluation, and selection of adaptive action options, and (2) implementation of the selected option.

The identification, evaluation, and selection of an adaptation action generally consisted of a multi-step options analysis. To identify viable adaptation options, some frameworks contained tables with generic classes of adaptation options (Bies et al. 2010;

Highways Agency and Parsons-Brinkerhoff 2009), others offered examples for certain types of infrastructure and suggested a site analysis for the affected assets (Meyer et al. Forthcoming).

The United Kingdom Climate Impacts Programme (Willows and Connell 2003), – which presents a non-transportation specific risk-based adaptation framework, classifies adaptation option evaluation techniques in three tiers: (1) systematic qualitative analyses; (2) “alternative methods” (i.e., semi-quantitative); and (3) quantitative and economics-based methods. They present 26 separate evaluation methods that might be used to evaluate adaptation options (Table 3.2). The synthesis of adaptation strategies in Table 3.1, however, revealed that the evaluation of adaptation options and the selection of a preferred option most frequently involved a benefit-cost analysis (Bies et al. 2010; Highways Agency and Parsons-Brinkerhoff 2009; Meyer et al. Forthcoming). However, other selection methodologies included multi-attribute analysis (Gardiner et al. 2009), ad-hoc multi-attribute evaluation matrices (Black et al. 2010; Major and O'Grady 2010), or general recommendations to consider “effectiveness, cost, residual risks and stakeholder acceptance.” (Bruce et al. 2006) In some cases – for example, New York City Panel on Climate Change (Major and O'Grady 2010) – the Risk Evaluation step was further broken down to identify synergies with other agency activities. For example, the FHWA framework (Federal Highway Administration 2012) identifies synergies with several practices: (1) asset management, (2) emergency and risk management, (3) hazard mitigation plans, (4) transportation planning project selection criteria, and (5) environmental review.

Table 3.2 General Adaptation Option Evaluation Methods

Adapted from: **(Willows and Connell 2003)**

Tool/technique	**Qualitative methods**	**Alternative methods**	**Quantitative and/or economics based methods**
Consultation Exercises	x		
Focus Groups	x		
Ranking/Dominance Analysis	x		
Screening		x	
Scenario Analysis	x	x	x
Cross-Impact Analysis	x		
Pairwise Comparison	x		
Sieve Mapping	x		
Maximax, Maximin, Minimax, Regret			x
Expected Value			x
Cost-Effectiveness Analysis			x
Cost-Benefit Analysis			x
Decision Analysis			x
Bayesian Methods			x
Decision Conferencing			x
Discounting			x
Environmental Impact Assessment/Strategic Environmental Assessment		x	
Multi-Criteria Analysis (Scoring and Weighting)		x	
Risk-Risk Analysis		x	
Contingent Valuation			
• Revealed performance			x
• Stated performance		x	x
Fixed Rule-based Fuzzy Logic	x	x	x
Financial Analysis			x
Partial Cost-benefit Analysis	x		x
Preference Scales	x		
Free-form Gaming	x		
Policy Exercise	x		

The second component of *Step 5 – Risk Treatment*, is to implement the selected adaptation option(s). In some cases, the implementation plan and delivery were discretized into specific steps and responsibilities (Black et al. 2010; Bruce et al. 2006; Highways Agency and Parsons-Brinkerhoff 2009).

Implementation frequently included the development of a monitoring framework to periodically collect data on climate, asset performance, and agency activities. It was frequently noted in the frameworks reviewed (Bies et al. 2010; Federal Highway Administration 2012; Gardiner et al. 2009; Gardiner et al. 2008; Kinsella and McGuire 2005; Maurer et al. 2011; Meyer et al. Forthcoming; Virginia Department of Transportation 2011; Winter et al. 2005), and elsewhere (Meyer et al. 2010; O'Har 2013; Woolston Undated) the importance of linking climate change adaptation planning with transportation asset management (TAM) programs due to the data-driven nature of those programs, which could be synergistic with adaptation monitoring.

3.5 Conclusions and Observations for Development of an Assessment Framework

As discussed in Chapter 1, the purpose of this research study is to develop a risk-based assessment framework to prioritize at a network-level the risks of highway culvert assets to climate change impacts, as may be relevant to infrastructure management practices (e.g., TAM, strategic planning). This section provides some observations and conclusions from the preceding synthesis to inform the development of the risk-based assessment framework in this study. Observations and conclusion are in two general categories: (1) a characterization of the typical steps for climate change adaptation assessment, and (2) reasonable paths to progress the current state-of-the-art in climate change adaptation frameworks.

3.5.1 Risk Assessment Framework Structure

In the ISO 31000:2009 general risk management framework discussed in Section 3.3 (also, see Figure 3.2), risk assessment encompasses three steps: (1) risk identification, (2) risk analysis, and (3) risk evaluation. These steps were discussed in the context of climate change adaptation in Section 3.4.2. In most instances, the frameworks developed were implemented for programming- or network-level planning activities. There were notable exceptions where asset-level analyses were conducted (Bies et al. 2010; Maurer et al. 2011; Nguyen et al. 2011), however it appears that most of these broadly-applicable frameworks were developed and implemented with a focus towards network-level programming activities for multiple infrastructure asset types.

The ISO risk management model is generalized for applications to myriad situations beyond physical impacts to facilities (for example, enterprise goals, future funding sources, etc). In contrast, the catastrophe model shown in Figure 3.3 is intended for assessing loss to physical facilities due to catastrophic events. Given the primary focus of current adaptation planning activities on assessing and responding to potential physical impacts to transportation systems, the catastrophe model may offer an assessment structure that is suited to the network-level assessment of individual asset types and facilities. Additionally, utilization of the catastrophe model would not necessitate significant divergence from the ISO model’s structure, which, as noted above, has been more widely adopted within the transportation sector for climate change adaptation assessments. Figure 3.7 offers one way in which the ISO standard’s risk assessment process and the catastrophe model could be combined and reformulated to assess climate vulnerabilities at an asset-level. Note that in this reformulation, the step

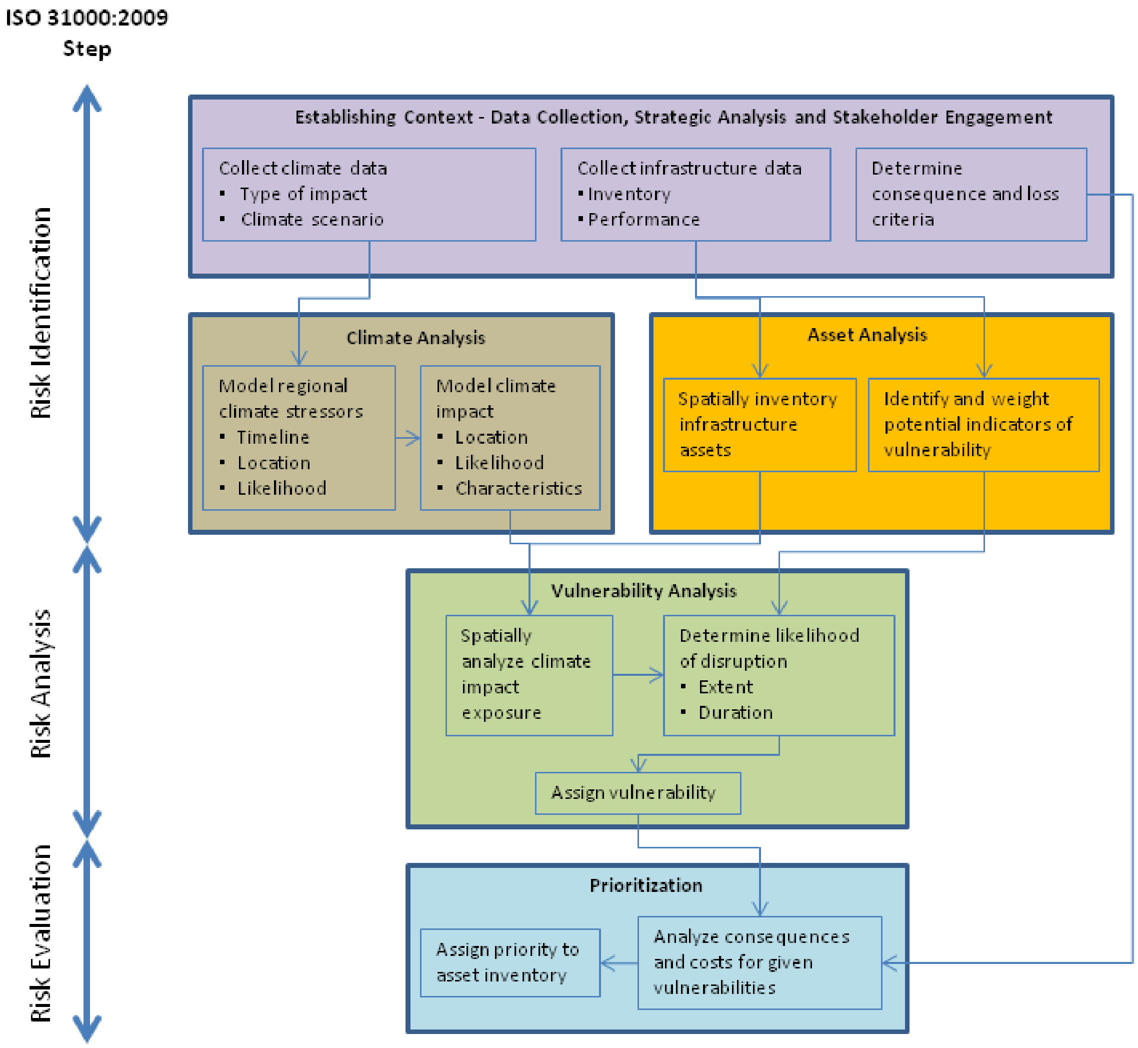


Figure 3.7 Reformulated Infrastructure Asset Conceptual Risk Assessment Model

"Establishing Context," is added. In the ISO standard, this step occurs prior to the risk assessment as part of the larger risk management framework. Within the catastrophe model, data collection is implicit within the various steps of the process. However, given the data acquisition and availability difficulties noted in the synthesis of existing climate change assessment frameworks (Section 3.4.1.3), inserting an explicit step to collect and coalesce climate and infrastructure data for use in the analyses is reasonable.

3.5.2 Risk Assessment Framework Progress Areas

Numerous similarities among approaches to climate change risk assessment were noted in Section 3.4.2. Building upon the established approaches of the adaptation frameworks reviewed in the synthesis, this section provides several suggestions to improve aspects of the framework analysis methods, synergize with other agency activities, and progress the state-of-the-art in climate change and infrastructure adaptation planning.

Section 3.4.2 noted that several frameworks discussed the identification of synergies with other agency activities and priorities to make climate change adaptation planning more effective and efficient. Transportation asset management (TAM) was widely noted as a possible area for synergy relevant to ongoing infrastructure monitoring. However, the large volumes of asset inventory and attribute data that are collected as part of normal TAM programs could enable a more consistent and complete assessment of asset risks and vulnerability to climate change impacts. For example, Khelifa et al. (Forthcoming) demonstrate how bridge inventory and performance data collected as part of the National Bridge Inventory (NBI) can be incorporated into the FHWA’s HYRISK model to predict scour vulnerability, failure risk, and costs associated with climate change induced changes in riverine flow.

It has been noted that bridge management systems (BMS), pavement management systems (PMS) and safety management systems (SMS) are common elements of TAM programs at US state DOTs, but that increasingly, state DOTs are moving to also include ancillary assets (e.g., culverts, earth retention structures, traffic signals) into their TAM practices (Akofio-Sowah 2011; Akofio-Sowah et al. 2012). The data collected as part of ancillary asset management (AAM), in addition to BMS, PMS, and SMS data could provide a common point of departure for a more broadly applicable adaptation assessment, as well as offer data collection costs savings through synergy.

Within the adaptation frameworks reviewed above, the projection of future climate and assessment of impacts largely relies on expert opinion. When used in case studies to supplement expert opinion, climate modeling predominantly examined the impacts of sea-level rise and coastal storm surge (Berry et al. 2012; Nguyen et al. 2011; NJTPA 2011; SSFM International 2011; Technical Ad hoc Work Group 2011; Virginia Department of Transportation 2011), although the FHWA's Gulf Coast 2 Study (Choate et al. 2012), modeled some additional impacts, albeit in a coastal location.

The literature detailing frameworks that examine inland climate change impacts is sparse. There are some examples that examine flooding impacts to transportation and infrastructure (Chang et al. 2011; Stack et al. 2007; Stack et al. 2010), however none that present a broadly applicable assessment framework that could be used in assessing asset-level impacts, or for incorporation into network-level decision making and management programs (e.g., TAM).

As noted above in Section 3.4.2, much of the risk evaluation step involves the prioritization of climate impact risks. As stated in that section, and illustrated in Figure 3.6, prioritization was predominantly conducted using expert opinion with the aid or risk matrices of varying complexity (e.g., 2-dimensional or 3-dimensional) and resolution (e.g., high/medium/low, scale from 1 to 10). Although Nguyen et al. (2011) noted that the subjective nature of expert opinion may pose a challenge for public decision making, the subjective nature does enable decision makers to weigh competing risk criteria and consequential costs of impacts that may be difficult to quantify in monetary terms (e.g., environmental impacts, or impacts to wildlife due to a culvert failure).

In contrast to the practice of using expert opinion and risk matrices to evaluate risks, the Virginia DOT (Virginia Department of Transportation 2011) case study of the FHWA Conceptual Model (Federal Highway Administration 2012) used a multicriteria decision analysis (MCDA) framework to evaluate and prioritize infrastructure assets and projects according to various criteria. This type of approach enables a more quantitative, objective evaluation of risks while preserving the ability to evaluate criteria that are not easily quantified monetarily. In addition, as the VDOT case study showed, MCDA can also be used to assess the sensitivity of climate change adaptation priorities to multiple climate scenarios.

These types of considerations are important to recognize in the development of a risk-based climate change adaptation assessment framework. The assessment framework developed in this dissertation research, which is discussed from a methodological perspective in Chapter 5, seeks to incorporate many of the observations discussed above into its structure and composition.

CHAPTER 4

CULVERT MANAGEMENT DATA AND PERFORMANCE ASSESSMENT RATING FRAMEWORKS

Culverts can be defined simply as structures that “convey surface water across or from the [roadway] right of way,” (AASHTO 1999) although they can also serve other functions (e.g., utilities, livestock and wildlife passage, land access). Structurally, culverts differ from bridges in that culverts are “usually covered with embankment and are composed of structural material around the entire perimeter.” (FHWA 2012) Hydraulically, culvers also differ from bridges in that they “are usually designed to operate at peak flows with a submerged inlet to improve hydraulic efficiency.” (FHWA 2012) This intentional constriction of waterway flow has several implications for maintenance and performance. First, it can increase the potential for waterway blockage and scour (FHWA 2012). Additionally, the intentional flooding of culvert end structures and embankments (i.e., upstream ponding) exerts a hydraulic head pressure on the culvert and embankment. These factors can contribute to an increased risk of adverse impacts (e.g., excess flooding, roadway disruption, embankment failure). As discussed in Chapter 1, the repair and replacement costs associated with culvert damage and failure can be substantial.

Given the potential for increases in extreme precipitation events associated with climate change (and thus the potential for increased stream flows), there is some cause for concern that adverse impacts to culvert assets may result. Furthermore, the potential for such adverse impacts will likely be amplified among those individual culvert assets with functional performance deficiencies. Therefore, an important aspect of adapting culvert assets to the impacts of climate change is an understanding of the condition and functional performance of existing roadway culverts to better characterize and prioritize vulnerabilities.

This chapter first provides an overview of culvert management practices in the United States (Section 4.1). This begins with a general discussion of Federal culvert inspection procedures and then discusses the current state of culvert management in the United States. Section 4.2 then presents several frameworks that have been developed to assess the condition and performance of culverts. These are based upon the inspection standards presented in Section 4.1, as well as additional data items proposed within the frameworks. The condition and performance assessment frameworks are then briefly discussed with respect to their possible use in climate change impact vulnerability assessment applications, specifically the assessment framework developed in Chapter 5 of this dissertation research. This chapter concludes with a discussion of culvert failure modes and potential indicators of vulnerability that may contribute to such failures.

4.1 Culvert Inspection Data & Management Systems

This section provides a discussion of culvert inspection procedures and culvert management systems in the United States. It begins with a discussion of the *National Bridge Inspection Standards – Culvert Inspection Manual* (Arnoult 1986), which provides a baseline for culvert inspection procedures and influences widely the culvert performance rating systems discussed in Section 4.2. Culvert management practices are then discussed in the context of transportation asset management, which is briefly introduced, and the state of culvert management practice in the United States is discussed.

4.1.1 National Culvert Inspection Procedures

The National Bridge Inspection Program, established in 1971, created a uniform inspection system and database for the "structural and functional safety" of bridge assets (Arnoult 1986). Inspection procedures for this program and additional guidance were provided in the *Bridge Inspector's Training Manual 70* (FHWA 2012). Manual 70 distinguishes culverts as structures with spans less than 20-ft. (as measured along the centerline of the roadway) and bridges as structures with spans greater than 20-ft. However, the recognition over time that some structures with spans greater than 20-ft. can have the hydraulic and structural design characteristics of culverts necessitated supplemental inspection standards. Thus, the Federal Highway Administration (FHWA) issued the *Culvert Inspection Manual* (CIM) (Arnoult 1986) to provide guidance for the inspection and rating of structures that have the design characteristics of culverts (discussed above), but spans greater than the 20-ft. standard. The CIM notes that the guidelines outlined therein "should also be generally applicable to culverts with openings which are less than 20 feet long." (Arnoult 1986) The FHWA *Bridge Inspector's Reference Manual* (BIRM) (FHWA 2012) also provides a useful supplemental discussion of the inspection procedures outlined in the CIM.

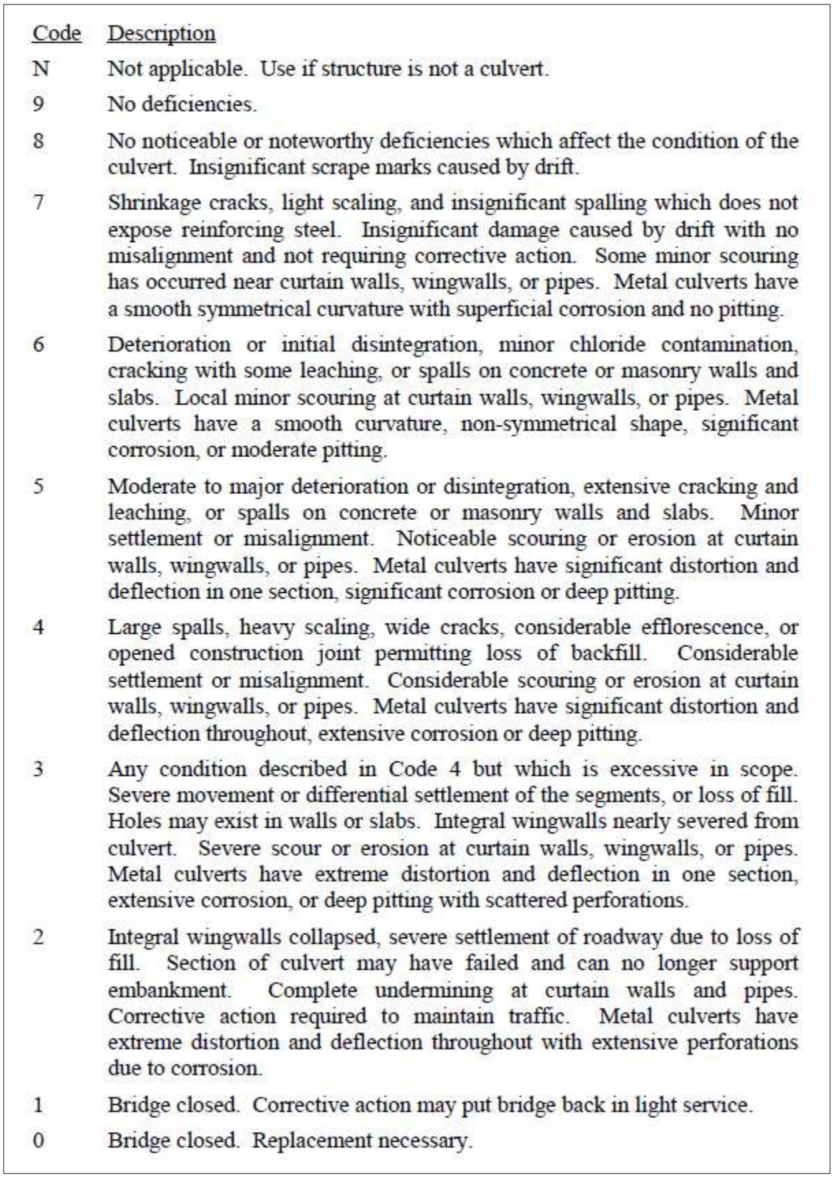
The National Bridge Inventory (NBI) component condition rating guidelines only provide one item to assess overall culvert condition: Item 62 – Culvert and Retaining

Walls. However, the CIM does note that additional condition and appraisal items are applicable to culverts, and may be useful in evaluating culverts:

1. Item 61 – Channel and channel protection
2. Item 63 – Estimated remaining life
3. Item 64 – Operating rating (maximum permissible loads)
4. Item 65 – Approach roadway alignment
5. Item 66 – Inventory rating
6. Item 67 – Structural condition (i.e., with respect to current standards)
7. Item 68 – Deck geometry
8. Item 70 – Safe load capacity
9. Item 71 – Waterway adequacy
10. Item 72 – Approach roadway alignment

With the exception of Items 63, 64, and 66, all of the above condition and appraisal rating items use a numerical scale from 0 to 9, where 9 is the best score possible. Although these items do not directly assess the structural and hydraulic condition of the culvert, nor will they necessarily be available for all culverts spanning less than 20-ft, they may be a useful component of more in-depth, project-level condition and performance assessments.

NBI Item 62, used to assess a culvert's overall condition, evaluates "the alignment, settlement, joints, structural condition, scour, and other items," (FHWA 2012) such as end treatments and the embankment (Arnoult 1986). As discussed, culvert condition is ranked using a 0 to 9 point scale, where 9 is the best score. This rating scale and accompanying descriptions are shown in Figure 4.1. However, additional evaluation guidance is provided in the CIM and BIRM to assist inspectors in assigning the overall condition rating. Specific guidance is provided to evaluate culvert barrels, which are generally classified according to structural system: rigid and flexible (sometimes called, non-rigid) designs. Guidance is also provided for waterways and appurtenances.



Code	Description
N	Not applicable. Use if structure is not a culvert.
9	No deficiencies.
8	No noticeable or noteworthy deficiencies which affect the condition of the culvert. Insignificant scrape marks caused by drift.
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.
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.
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.
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.
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.
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.
1	Bridge closed. Corrective action may put bridge back in light service.
0	Bridge closed. Replacement necessary.

Source: (FHWA 2012)

Figure 4.1 NBI Component Condition Rating Guidelines for Culverts

Rigid culverts are those whose structure provides the primary load-bearing capacity, rather than the surrounding embankment soil. These generally consist of concrete, masonry, and timber culverts. Separate rating scales are given in the CIM for the following types of rigid culverts (Appendix A contains the individual CIM rating scales for each type listed):

1. Concrete culverts
    a. Precast concrete pipe culvert barrels
    b. Cast-in-place concrete culvert barrels
2. Masonry culverts

Flexible culverts provide little bending resistance and therefore rely on proper interaction with surrounding soils to support loads. These generally consist of corrugated pipes (steel or aluminum), structural metal plate, and plastic pipe culverts. Separate guidance is given in the CIM for the following types of flexible culverts (Appendix A contains the individual CIM rating scales for each type listed):

1. Corrugated metal culverts
    a. Round or vertical elongated corrugated metal pipe barrels
    b. Corrugated metal pipe-arch barrel
    c. Structural plate arch barrels
    d. Corrugated metal box culvert barrel
2. Corrugated metal long-span culverts
    a. Low-profile arch long-span culvert barrel
    b. High-profile arch long-span culvert barrel

c. Pear shaped long-span culvert barrel

d. Horizontal ellipse long-span culvert barrel

In addition to culvert barrel inspection guidance, the CIM also provides guidance for inspecting culvert end and stream bed features, including:

1. The approach roadway (e.g., depressions, cracks)
2. Waterways (e.g., channel alignment and scour, waterway adequacy)
3. End treatments (e.g., headwalls, wingwalls)
4. Appurtenances (e.g., energy dissipaters, aprons)

Appendix A contains the individual CIM rating scales pertaining to waterways (Channel and Channel Protection; Waterway Adequacy); the CIM does not provide rating scales for the other culvert end and stream bed items listed.

Both the CIM and the BIRM note that the overall rating of culvert condition should not be taken as a simple average of the constituent component ratings. They note that a very low rating of one critical component may control the overall rating (Arnoult 1986). Instead, both documents specify that inspectors should consider the functionality, safety, and need for repairs or rehabilitation or each culvert when assigning an overall condition rating consistent with the rating scale shown in Figure 4.1.

4.1.2 Transportation Asset Management

Transportation asset management (TAM) is a strategic approach to managing infrastructure assets and investments of resources. The American Association of State

Highway and Transportation Officials (AASHTO) currently offers the following definition for TAM:

> "Transportation Asset Management is a strategic and systematic process of operating, maintaining, upgrading, and expanding physical assets effectively throughout their lifecycle. It focuses on business and engineering practices for resource allocation and utilization, with the objective of better decision making based upon quality information and well defined objectives." (AASHTO 2011)

The infrastructure management investments mentioned in this definition of TAM can be characterized as falling into one of three general categories, defined as (Cambridge Systematics 2006):

1. **System Preservation:** Investments in capital projects and maintenance actions that extend the life of existing facilities and repairs damage to facilities that impedes mobility or safety of system users.
2. **System Management and Operation:** Investments in capital, maintenance, and operational projects that promote operational efficiency and user safety within the system.
3. **Capacity Expansion:** Investments that add additional capacity to existing facilities, or that expand capacity through the acquisition or construction of new facilities.

As mentioned, these three categories of investment are approached strategically and systematically through the use of performance measurement and monitoring to inform decision making and analysis. This performance based approach to decision making is reflected in the "core principles" of TAM offered in National Cooperative Highway Research Program (NCHRP) Report 551 (Cambridge Systematics 2006):

1. **Policy-driven:** Resource allocation decisions are based on a well-defined set of policy goals and objectives
2. **Performance-Based:** Policy objectives are translated into system performance measures that are used for both day-to-day and strategic management
3. **Analysis of Options and Tradeoffs:** Decisions on how to allocate funds within and across different types of investments are based on an analysis of how different allocations will impact achievement of relevant policy objectives and the best options to consider.
4. **Decisions Based on Quality Information:** The merits of different options with respect to an agency's policy goals are evaluated using credible and current data.
5. **Monitoring Provides Clear Accountability and Feedback:** Performance results are monitored and reported for both impacts and effectiveness.

Historically, TAM in the United States has focused predominantly on managing structures (i.e., bridges) and roads (i.e., pavement), although the need for its application to other asset categories has been noted (e.g., safety features, facilities) (Cambridge Systematics 2009). More recently, Akofio-Sowah (2011) has noted that, in fact, many transportation asset management programs have already begun to apply TAM practices to so-called ancillary assets (e.g., lighting, guardrails, culverts), although such applications are not yet universal among agencies.

4.1.3 Culvert Management Systems

Since the introduction of the *Culvert Inspection Manual* (Arnoult 1986) supplement to the National Bridge Inspection Standards, interest in culvert management systems appears to have been growing incrementally. In 1989, McNichol (1989) developed a computer-based culvert management system. In 2001, the FHWA released a computerized Culvert Management System (CMS) that was developed as part of its Local Technical Assistance Program (LTAP) (FHWA 2007). However, a 2007 survey of state DOTs showed that none were using the FHWA CMS, although 29 state DOTs reported having some sort of culvert management system (FHWA 2007). Roughly half of these were developed in-house, while several others reported using the bridge management software PONTIS (FHWA 2007).

Results from several syntheses and survey efforts (Akofio-Sowah 2011; Najafi et al. 2008; Wyant et al. 2002) suggest that the primary task of culvert management systems, consistent with the earlier discussion of TAM, is *preservation* management. However, practices and culvert management system development vary widely among DOTs. For example, Najafi et al. (2008) note that 40% of state DOTs surveyed did not include a condition assessment process, 78% did not have a model to predict service life, and 83% did not have a decision support system (DSS) to aid in managing maintenance and repair needs. These findings suggest that in the context of the TAM maturity scale (AASHTO 2011), culvert management practices range from *Initial* or *Awakening* in most states, to *Structured* in only a handful of state DOTs (e.g., Maryland, Minnesota).

The developing maturity level of culvert management practices in the United States poses several challenges to studies, such as this, that seek broadly applicable solutions in infrastructure management. One significant challenge is the wide variability in culvert data collection, inspection standards, and management practice among state DOTs and other transportation agencies. With respect to inspection guidance and data collection, the Culvert Inspection Manual (Arnoult 1986) provides baseline guidance for large culvert structures (i.e., spans > 20-ft.). However, a 2002 survey of transportation agencies noted that the CIM practices were also used as guidance by several agencies for smaller culverts (Wyant et al. 2002). The most common range of small culverts (i.e., smaller than 20-ft span) was found to be from 12-in. to 12-ft. spans (Wyant et al. 2002), but some agencies reported inspecting up to the 20-ft. span distinguished in the NBIS (Najafi et al. 2008). With respect to national standards for culvert *management*, the only identifiable framework that seeks to nationally standardized culvert management practices for smaller culverts (i.e., < 20-ft. span) is the FHWA CMS, although as noted earlier, no states currently employ the CMS, and its application has only been demonstrated by a small number of agencies in an FHWA case study (FHWA 2007).

The lack of any recent synthesis studies of culvert management practices among state DOTs (the most recent synthesis study quoted above is 5 years out of date) makes it difficult to assess the current state of practice in this rapidly developing field. For this reason, the case study element of this research project is particularly important to aid in developing a framework that is broadly applicable to the current, albeit widely ranging, states of practice among DOTs. Culvert management for the case study DOTs is discussed in greater detail in the Chapter 5.

4.2 Culvert Condition and Performance Assessment and Rating

Given the generally nascent state and implementation of culvert management systems in the United States, it is not surprising that relatively few broadly applicable frameworks exist that assess the structural condition and hydraulic performance of roadway and highway culverts, and that analyze such data to rank or index culverts for network-level programming and management activities. Kurt and McNichol (1991) developed an early computer-based ranking system that was based on user and agency cost models. These models calculated the economic costs of deficient conditions by comparing current culvert conditions to agency "goal conditions." Cost factors examined included: (1) the vehicle load-bearing capacity of the culvert (as related to detours due to vehicle loads in excess of capacity); (2) the hydraulic capacity of the culvert (as related to flood detouring and damage); (3) deficiency in culvert width (as related to safety, collision hazard, and damage liability), and (4) maintenance costs and priorities. One shortcoming of this ranking system is the exclusive use of culvert inventory information (i.e., no condition of functional performance information is incorporated). Although the exclusion of performance information likely reflects the state of culvert management practices at the time, it creates difficulty in assessing maintenance needs, replacement needs, or likelihood of failure.

The Federal Highway Administration manual, *Hydraulic Design of Culverts, 3rd Ed.* (Schall et al. 2012) discusses the assessment of existing culvert conditions in its chapter on culvert repair and rehabilitation. In that chapter, it references three documents that provide support for culvert assessment:

1. FHWA *Bridge Inspector's Manual* (Ryan et al. 2006); recently updated in (FHWA 2012)
2. FHWA *Culvert Inspection Manual – Supplement to the Bridge Inspector's Training Manual* (Arnoult 1986)
3. FHWA Federal Lands Highway (FLH) *Culvert Assessment and Decision-Making Procedures Manual* (Hunt et al. 2010)

Of the three documents listed above, all provide guidance on the inspection and assessment of culvert structures. However, the FLH report provides additional specific guidance on the analysis of collected structural conditions and hydraulic performance data in a decision-making framework to determine corrective actions (e.g., repair, replacement, further investigation). In the design manual, *Hydraulic Design of Culverts*, the FHWA appears to adopt and apply the principles from the FLH report. Because of its analysis component, the FLH framework is applicable to this research study, and is therefore discussed in greater detail later in Section 4.2.1. Additional literature searches revealed several additional culvert condition and performance assessment frameworks, which are discussed in greater detail in Sections 4.2.2 through 4.2.6

4.2.1 FLH Culvert Assessment and Decision-Making Procedures Manual

The *Culvert Assessment and Decision-Making Procedures Manual* (Hunt et al. 2010) was developed by the Federal Highway Administration's Office of Federal Lands Highway (FLH) to provide "guidelines for assessing the condition and performance of existing roadway culverts," and also presents a decision-making framework for "selecting corrective actions for deficiencies found" during inspection (Hunt et al. 2010). The manual states that the procedures outlined therein are specifically intended for “project-level rather than programmatic or inventory level use.” However, it also recognizes that “the manual and its component tools do easily lend themselves to programmatic applications.” (Hunt et al. 2010)

The FLH manual consists of two primary components: (1) the culvert assessment tool, and (2) the culvert decision-making tool. Culvert assessments are conducted at two levels: Level 1 and Level 2. A Level 1 assessment “is intended for rapid assessment of a culvert’s condition and performance.” (Hunt et al. 2010) The outcomes of the Level 1 assessment include the following:

1. **No further action –** condition and performance are acceptable
2. **Level 1 maintenance –** clearing or cleaning to restore observed performance deficiencies, or to enable further Level 1 assessment
3. **Level 1 repair or replacemen**t **–** repair of deficient condition of culvert and/or appurtenances
4. **Level 2 assessment –** Indicators in the Level 1 assessment may identify the need for a more in-depth assessment of the culvert

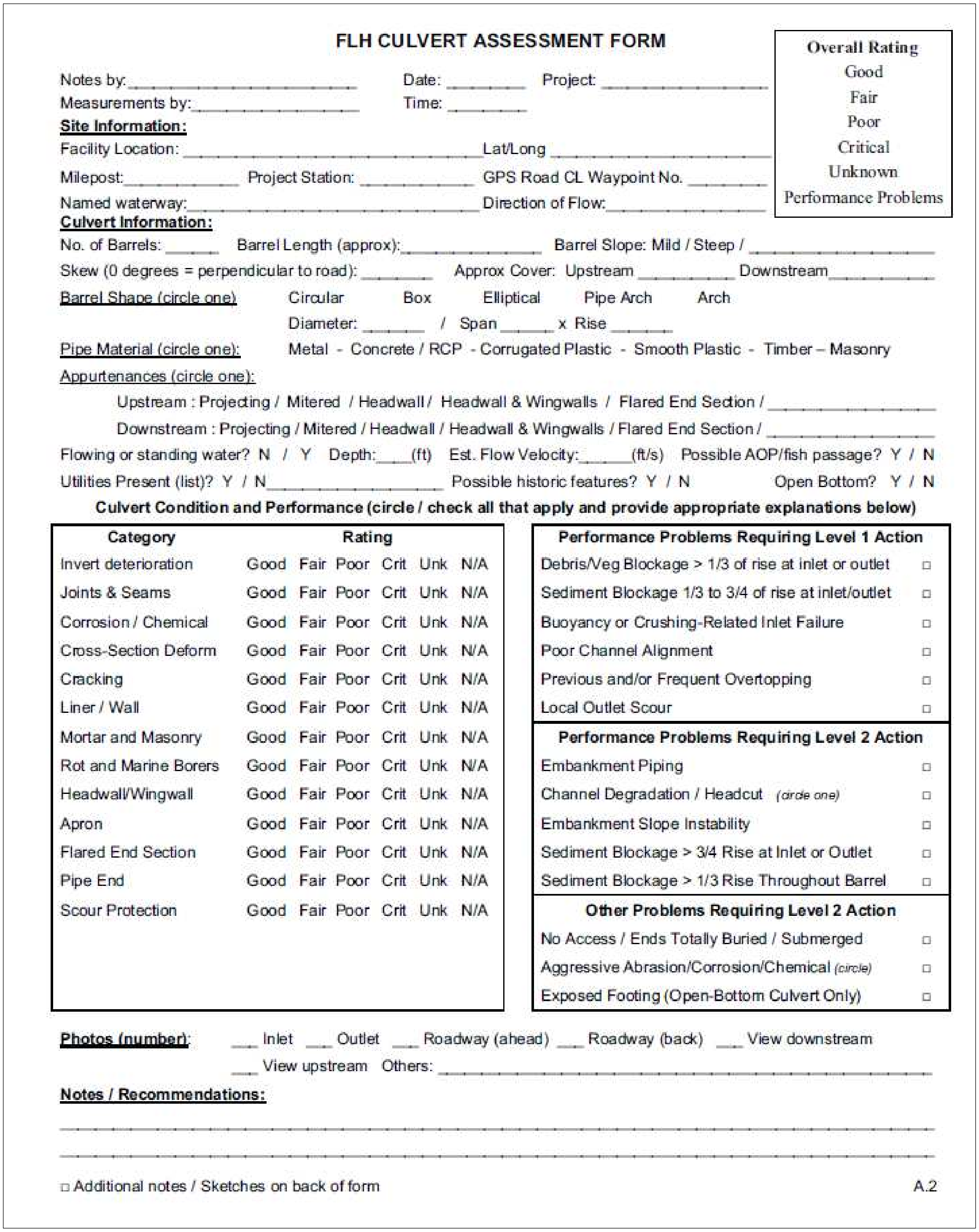
The Level 2 assessment is a site-specific, discipline-specific investigation of culvert condition and performance, which is triggered by a prescribed set of inspection indicators (these are discussed later). The FLH manual’s “Culvert Assessment Tool” provides guidance for Level 1 assessments (this is discussed in greater detail in the next sub-section). However, given the site-specific, in-depth nature of Level 2 assessments, the FLH manual only provides guidance as to the appropriate disciplines (e.g., geotechnical, hydraulic, structural, materials, etc.) that should be consulted to conduct Level 2 assessments.

4.2.1.1 Culvert Assessment Tool

The culvert assessment tool facilitates a rapid assessment of culvert and appurtenance condition and performance. The assessment tool consists primarily of a culvert assessment form (Figure 4.2) and a related culvert assessment guide. The manual’s appendices contain a supplementary photographic guide that illustrates various levels of condition and deficiency of real-world culverts to assist inspectors in their assessments.

The culvert assessment tool examines multiple criteria related to culvert condition and performance. Condition criteria are shown in the bottom left table in the inspection form (Figure 4.1). Condition criteria are assigned rating codes using the scale shown in Table 4.1.

The tool also provides specific guidance and criteria according to culvert barrel material type: (1) concrete & reinforced concrete pipe; (2) corrugated metal pipe; (3) plastic pipe; (4) timber; (5) masonry; and (6) appurtenances (e.g., headwall/wingwall, apron, scour protection). Note that not all condition criteria shown in Figure 4.2 are applicable to every material type (e.g., “mortar and masonry” is only applicable to that material type). The material-specific rating code guidance tables are given in Appendix B. Note that while the ratings in these tables are generally qualitative in nature, quantitative criteria are given in a limited number of instances; for example, percentage areas of culvert aprons affected by cracking.



FLH CULVERT ASSESSMENT FORM

Overall Rating
Good
Fair
Poor
Critical
Unknown
Performance Problems

Notes by: ____________________ Date: ________ Project: ________________
Measurements by: ________________ Time: ________

Site Information:
Facility Location: ________________________ Lat/Long ____________________
Milepost: __________ Project Station: __________ GPS Road CL Waypoint No. ________
Named waterway: ________________________ Direction of Flow: ______________

Culvert Information:
No. of Barrels: _____ Barrel Length (approx): ____________ Barrel Slope: Mild / Steep / ________________
Skew (0 degrees = perpendicular to road): _______ Approx Cover: Upstream _________ Downstream __________
Barrel Shape (circle one) Circular Box Elliptical Pipe Arch Arch
Diameter: ______ / Span _____ x Rise ______
Pipe Material (circle one): Metal - Concrete / RCP - Corrugated Plastic - Smooth Plastic - Timber – Masonry
Appurtenances (circle one):
Upstream : Projecting / Mitered / Headwall / Headwall & Wingwalls / Flared End Section / _______________
Downstream : Projecting / Mitered / Headwall / Headwall & Wingwalls / Flared End Section / _______________
Flowing or standing water? N / Y Depth: ____(ft) Est. Flow Velocity: ______(ft/s) Possible AOP/fish passage? Y / N
Utilities Present (list)? Y / N________________ Possible historic features? Y / N Open Bottom? Y / N

Culvert Condition and Performance (circle / check all that apply and provide appropriate explanations below)

Category	Rating					
Invert deterioration	Good	Fair	Poor	Crit	Unk	N/A
Joints & Seams	Good	Fair	Poor	Crit	Unk	N/A
Corrosion / Chemical	Good	Fair	Poor	Crit	Unk	N/A
Cross-Section Deform	Good	Fair	Poor	Crit	Unk	N/A
Cracking	Good	Fair	Poor	Crit	Unk	N/A
Liner / Wall	Good	Fair	Poor	Crit	Unk	N/A
Mortar and Masonry	Good	Fair	Poor	Crit	Unk	N/A
Rot and Marine Borers	Good	Fair	Poor	Crit	Unk	N/A
Headwall/Wingwall	Good	Fair	Poor	Crit	Unk	N/A
Apron	Good	Fair	Poor	Crit	Unk	N/A
Flared End Section	Good	Fair	Poor	Crit	Unk	N/A
Pipe End	Good	Fair	Poor	Crit	Unk	N/A
Scour Protection	Good	Fair	Poor	Crit	Unk	N/A

Performance Problems Requiring Level 1 Action	
Debris/Veg Blockage > 1/3 of rise at inlet or outlet	☐
Sediment Blockage 1/3 to 3/4 of rise at inlet/outlet	☐
Buoyancy or Crushing-Related Inlet Failure	☐
Poor Channel Alignment	☐
Previous and/or Frequent Overtopping	☐
Local Outlet Scour	☐
Performance Problems Requiring Level 2 Action	
Embankment Piping	☐
Channel Degradation / Headcut *(circle one)*	☐
Embankment Slope Instability	☐
Sediment Blockage > 3/4 Rise at Inlet or Outlet	☐
Sediment Blockage > 1/3 Rise Throughout Barrel	☐
Other Problems Requiring Level 2 Action	
No Access / Ends Totally Buried / Submerged	☐
Aggressive Abrasion/Corrosion/Chemical *(circle)*	☐
Exposed Footing (Open-Bottom Culvert Only)	☐

Photos (number): ___ Inlet ___ Outlet ___ Roadway (ahead) ___ Roadway (back) ___ View downstream
___ View upstream Others: ____________________________________

Notes / Recommendations:

____

____

☐ Additional notes / Sketches on back of form

A.2

Source: (Hunt et al. 2010)

Figure 4.2 FLH Culvert Assessment Form

Table 4.1 FLH Culvert Condition Assessment General Rating Codes

Adapted from **(Hunt et al. 2010)**

Condition Assessment Rating Codes	
Good	Like new, with little or no deterioration, structurally sound and functionally adequate
Fair	Some deterioration, but structurally sound and functionally adequate
Poor	Significant deterioration and/or functional inadequacy, requiring repair action that should, if possible, be incorporated into the planned roadway project
Critical	Very poor conditions that indicate possible imminent failure that could threaten public safety, requiring immediate repair action
Unknown	All or part of the culvert is inaccessible for assessment or a rating cannot be assigned

Specific indicators within the culvert condition criteria can trigger a Level 2 inspection, which necessitates in-depth, site-specific assessment (i.e., project-level) of culvert conditions. For example, if the side of a footing is exposed in an open-bottomed corrugated metal pipe culvert, this condition automatically triggers the need for a Level 2 assessment. For a complete list of all culvert condition criteria indicators necessitating a Level 2 assessment, see the “Notes” sections in the condition rating code tables in Appendix B.

In addition to assessing culvert condition, the FLH culvert assessment tool also assesses culvert and channel performance. This is done using a binary rating scale (i.e., the situation exists, or it does not). Two classes of culvert and channel performance criteria are assessed: (1) performance problems requiring Level 1 action; and (2) performance problems requiring Level 2 action. These criteria are listed in Table 4.2 (Level 1 action) and Table 4.3 (Level 2 action). In addition to performance criteria, some non-performance based criteria can instigate a Level 2 action; these additional criteria are listed in Table 4.4.

Table 4.2 Performance Problems Leading to a Level 1 Action

Adapted from: **(Hunt et al. 2010)**

Problem	Field Indicator(s)
Debris/Vegetation Blockage	Debris/Vegetation blocks 1/3 or more of inlet opening
Sediment Blockage at Inlet or Outlet	Sediment Blocks 1/3 to 3/4 of rise, localized at the inlet or outlet only
Buoyancy-Related Inlet Failure	Inlet barrel raised above streambed
Poor Channel Alignment	Barrel skewed > 45-degrees to upstream channel with associated damage to embankment or end treatment
Previous and/or Frequent Overtopping	Drift on guardrail
	Erosion of downstream side of embankment
	Loss of pavement structure
	Maintenance history/testimony
Local Scour at Outlet	Undermined culvert, end treatment, or embankment slope

An overall rating is assigned to culverts based on the condition and performance inspection ratings. Ratings are assigned as: (1) Good, (2) Fair, (3) Poor, (4) Critical, (5) Unknown, or (6) Performance Problems (see Figure 4.2). In the FLH manual, Hunt et al. (2010) note that generally, “the lowest elemental rating for the culvert determines the overall rating.” However, it is also noted that in cases where culvert conditions are determined to be “Good” or “Fair,” the presence of certain performance deficiencies could trigger a Level 1 or Level 2 action. See Hunt et al. (2010) for a more detailed discussion.

Table 4.3 Performance Problems Leading to a Level 2 Action

Adapted from: **(Hunt et al. 2010)**

Problem	Field Indicator(s)
Embankment Piping	Settlement or holes in roadway with no significant joint problems identified in culvert
	Holes in embankment outside of culvert with no significant joint problems identified in culvert
Channel Degradation	Perched inlet and/or outlet with adjacent channel banks vertical or unstable (sloughing)
Headcut	Unstable channel drop of 2 feet or more within sight of culvert
Embankment Slope Instability	Failure of upstream embankment with channel approach angle less than 45-degrees to barrel
	Failure of downstream embankment beyond that caused by local outlet scour
Sediment Blockage and Channel Aggradation	Full barrel length blocked 1/3 or more of rise with sediment and culvert not an AOP design
	Blockage 3/4 or more of rise local to the inlet or outlet only
Aggressive Abrasion, Corrosion and/or Chemical Environment	Poor or Critical condition reached in 5 years or less
Exposed Footing (Open-Bottom Culvert)	Side of any footing exposed

Table 4.4 Other (Non-Performance) Problems Leading to a Level 2 Action

Adapted from: **(Hunt et al. 2010)**

Problem	Field Indicator(s)
No Access	Condition cannot be adequately assessed by an end-only inspection
	Access precluded by factors not remedied by routine maintenance (e.g., total submergence in water)
Aquatic Organism Passage (AOP) Culvert	Any performance problem
Historical Culvert or Headwalls	Any performance problem or condition rating of Poor or Critical
Open-Bottom Culvert	Any condition rating of Poor or Critical

4.2.1.2 Culvert Decision-Making Tool

The Culvert Decision-Making Tool provides “project-level decision-making guidance for post-assessment actions to be taken for existing roadway culverts” (Hunt et al. 2010) based upon the outcomes of the culvert assessment described above. The decision-making tool consists of a series of very detailed flow charts that guide users through the decision-making process. The first series of flow charts guides users to one of five paths: (1) no further action required; (2) Level 1 maintenance; (3) Level 2 in-depth investigation; (4) replacement; or, (5) repair. The second series of flow charts then guide users towards specific actions, and in many cases refers finally to a series of options matrices that include unit-cost based metrics and considerations. For example, the flowcharts may lead users inspecting a masonry culvert to the specific action, “repair with lining,” and then refers users to a liner-type selection matrix that includes type-characteristics, unit-cost information, limitations, and other considerations.

The Culvert Assessment Tool component of the FLH manual is of primary relevance to this research study as it may be applicable for network-level condition and functional performance assessments. As the Culvert Decision-Making tool is concerned primarily with project-level assessments, no further discussion of that tool is given. For further documentation of the Culvert Decision-Making Tool, see Hunt et al. (2010).

4.2.2 WTI Rating System for Rural Culvert Crossing Repair and Maintenance

The *Rating System for Rural Culvert Crossing Repair and Maintenance* (Baker 2001) was developed jointly by the Montana Department of Transportation (MDT) and the Western Transportation Institute (WTI) at Montana State University (MSU) as “a formalized rating system that proactively addresses the repair and maintenance needs of culverts." (Baker et al. 2001) There are two primary components in the WTI rating system: (1) a Culvert Data Collection Guide (Baker et al. 2001), and (2) a Microsoft Excel-based scoring template.

In general, the WTI rating system assesses specific culvert and site characteristics, which are then entered into an algorithm that specifies an overall condition index for the site. The condition index ranges from 1 (Poor) to 5 (Excellent). Although condition indexes are determined using site-specific assessment data, the generalized nature of the condition index output lends itself to network-level planning and management activities.

4.2.2.1 WTI Culvert Data Collection Guide

The WTI Culvert Data Collection Guide offers guidance for culvert and site condition assessments, as well as an assessment data-collection form (this form is given in Appendix C) for concrete, metal, and plastic pipe culverts.   Masonry, wood, and stone culverts, are excluded from the assessment. In addition to general site and culvert inventory data (e.g., dimensions, material, etc; see form in Appendix C), nine condition/performance criteria are assessed and assigned ratings. Three types of rating scales are used: (1) Yes/No; (2) scale from 0 to 2; and (3) percentage-based. The nine criteria and associated rating scales are shown in Table 4.5.

To assist inspectors in appropriately assigning condition ratings, the data collection guide provides some descriptive and photographic examples of field conditions associated with specific rating levels. For a complete discussion of WTI culvert condition ratings and descriptions, see Baker et al. (2001) and Baker (2001).

Table 4.5 WTI Culvert and Site Condition Data Items and Rating Scales

Inspection Item	Rating Value
Culvert Age	0 - 100 years
Degree of Scour at Outlet	0 - No indication of outlet scouring
	1 - Moderate scour
	2 - Major scour
Evidence of Major Failure	0 - No evidence of failure
	1 - Visual evidence of failure
Degree of Corrosion (inside or outside)	0 - No indication of corrosion
	1 - Minor corrosion
	2 - Major corrosion
Invert Worn Away	0 - No damage to the culvert lining
	1 - Minor damage to the culvert lining
	2 - Major damage to the culvert lining
Sedimentation of Cross Section	0 - 100% blockage
Physical Blockage	0 - 100% blockage
Joint Separation	0 - No joint separation observed
	1 - Joint separation observed
Physical Damage	0 - No physical damage
	1 - Minor physical damage, not inhibiting flow
	2 - Major physical damage, inhibiting flow

4.2.2.2 WTI Culvert Condition Index Scoring Template

The WTI Culvert Condition Index Scoring Template is a Microsoft Excel-based implementation of an indexing algorithm that uses the nine data items specified in Table 4.5 to calculate a culvert condition index. The condition index, or condition rating, is a scaled, whole-number value from 1 (poor) to 5 (excellent).

The indexing algorithm was developed by comparing an estimated ordered probit model of multiple condition indicators with field data gathered and assessed by MDT personnel (i.e., expert judgment). First, 33 potential predictors (i.e., condition indicators) were collected for 460 culverts across 11 MDT maintenance regions. A probit model was then estimated using the 33 potential predictors, and compared to field inspection ratings for overall condition (i.e., expert judgment condition ratings from 1 to 5) using a *t*-test to eliminate predictors that were not found to be significant at the 95% confidence level. An initial condition indexing algorithm was then constructed using the remaining nine predictors (Table 4.5) and corresponding regression coefficients:

$$y^* = 4.65 + \sum_{i=0}^{9} x_i \beta_i$$

Where:

y^* = the model output variable

x_i = the culvert predictor rating value

β_i = the model coefficients

The culvert predictor input values, x_i, and corresponding model coefficients, b_i, are given in Table 4.6. The resulting model variable output values, y^*, are then associated with five ranges of values, each corresponding to a discrete culvert condition rating values. The thresholds of these ranges are shown in Table 4.7. Average Daily Traffic (ADT) and detour-length information was then used as a relative indicator of facility importance to adjust the output of the initial condition indexing algorithm. For example, the index value for culverts with greater ADT or detour-lengths are adjusted down (i.e., poorer condition ratings) to indicate greater importance, and vice-versa. The algorithm development process is discussed in greater detail in Cahoon et al. (2002).

Table 4.6 Statistical Model Parameter Input Values and Coefficients

Adapted from Adapted from: **(Cahoon et al. 2002)**

Parameter	Input (x_i)	Coefficient (b_i)
Intercept	n/a	4.65
Culvert Age	Integer Years	-0.0149
Degree of Scour at Outlet	0, 1, or 2	-0.513
Evidence of Major Failure	0 or 1	-0.897
Degree of Corrosion	0, 1, or 2	-0.481
Invert Worn Away	0, 1, or 2	-0.49
Sedimentation of Cross Section	0 to 100%	-0.0207
Physical Blockage	0 to 100%	-0.0155
Joint Separation	0 or 1	-0.472
Physical Damage	0, 1, or 2	-0.406

Table 4.7 Condition Ratings and Associated Model Output Ranges

Adapted from **(Cahoon et al. 2002)**

Condition Rating (y_i)	Model Output Ranges
1	$y^* \leq 0$
2	$0 < y^* \leq 1.16$
3	$1.16 < y^* \leq 2.26$
4	$2.26 < y^* \leq 3.98$
5	$y^* > 3.98$

The WTI rating system developers note that in some situations where only one deficiency exists, even when that deficiency would render the culvert inoperable, the condition rating may provide an unrealistic rating for the culvert (Cahoon et al. 2002). The example given is that a culvert with 100% sedimentation (i.e., a significant functional performance deficiency), but no other conditional deficiencies, would receive a condition rating of 4 (Good).

4.2.3 Ohio DOT Culvert Management Manual & ORITE Risk Assessment and Update of Inspection Procedures for Culverts

The report, *Ohio Risk Assessment and Update of Inspection Procedures for Culverts*, (Mitchell et al. 2005) is the product of an Ohio DOT-sponsored research project conducted by the Ohio Research Institute for Transportation and the Environment (ORITE) at Ohio University. The primary research objective was "to reduce the risk of structural failure of short-span [i.e. < 10-ft.] culverts serving major highways in Ohio." (Mitchell et al. 2005) In practice, the project serves as an update to the culvert inspection and assessment methodology developed in the ODOT *Culvert Management Manual* (CMM) (ODOT 2003). It also suggests additional culvert assessment items and develops a risk/vulnerability assessment with these items. The culvert assessment methodology from the ODOT CCM is first discussed, followed by a discussion of the ORITE risk methodology. The July 2013 update to the ODOT CCM (ODOT 2013) is used for this discussion (as opposed to the 2003 edition used in the ORITE study). Primary differences between the two are minor (e.g., incorporating known errata, etc).

4.2.3.1 ODOT Culvert Management Manual

The ODOT Culvert Management Manual (ODOT 2013) provides guidance for the collection of culvert inventory data and the assessment of culvert condition and performance for structures with that span less than a 10-ft. Of particular interest are the condition rating guidelines, which assess 16 items pertaining to culvert, channel, and roadway approach performance. Each item is scored according to an item-specific ten point scale (0-9) similar to that in the FHWA Culvert Inspection Manual (Arnoult 1986).

Illustrative descriptions of conditions for each item are included in the CCM. The specific items assessed are shown in Table 4.8. Several items have multiple rating scales specific to various material types.

Table 4.8 Ohio DOT CMM Culvert Condition Rating Items

Item Number	Inspection Category	Category Notes, Sub-Items
Culvert		
1	General	Separate scales for: Metal; Concrete; Masonry; Plastic
		• Deterioration to barrel material or footing
		• Cracks
		• Dents and Localized Damage
2	Culvert Alignment	Separate scales for: Masonry; all other material types
3	Culvert Shape	Flexible Culverts Only
		Separate scales for: Corrugated Metal; Plastic
4	Seams or Joints	Separate scales: Corrugated Metal Multi-plate structures; Corrugated Metal, Concrete, Plastic Pipe & Masonry
5	Slab	Slab-top culverts only (excluding precast structures)
6	Abutment	Slab-top culverts only (excluding precast structures)
		Separate Scales: Slab-top; Masonry
7	Headwalls	Includes: headwalls, endwalls, and wingwalls
		Specifies: projections, mitered ends, pipe end sections
		Pipe End Sections
8	End Structure	Includes: catch basins, inlets, manholes, junction chambers, other structures associated with storm sewer
Channel		
9	Channel Alignment	
10	Channel Protection	
11	Culvert Waterway Blockage	Percentage of culvert cross-sectional area blockage
12	Scour	Based on depth of scour holes, footing exposure.
Approaches		
13	Pavement	Cracking, spalling, potholes, settlement, pavement or embankment failure
14	Guardrail	Sagging, rotation, misalignment
15	Embankment	Rutting, erosion encroachment, failure
16	Level of Inspection	Non-entry, manned entry, video inspection

Culverts are then assigned an overall “General Appraisal Rating” and an “Operational Status.” The General Appraisal Rating is based on the lowest rating from Items 1-7 or 12 (Items 7 and 12 are only considered if inspectors judge a culvert to be scour-critical). The Operational Status is associated with any restrictions necessitated by a culvert’s conditional deficiency (e.g., load-carrying capacity restriction).

4.2.3.2 ORITE Risk Assessment and Update of Inspection Procedures for Culverts

The Ohio Research Institute for Transportation and the Environment (ORITE) Risk Assessment framework (Mitchell et al. 2005) builds upon the ODOT CMM condition assessment framework and introduces a risk-assessment component. It should be noted that the ORITE risk-assessment component differs from the definition of risk discussed earlier in Chapter 3; it does not introduce a consequence component. For the purposes of this study, the ORITE method may be more appropriately discussed as an assessment of *vulnerability*, rather than risk.

The ORITE study evaluates and builds upon the ODOT CCM framework in several ways. First, it proposes additional culvert performance items for culvert condition or risk (i.e., vulnerability) assessments. Second, it conducts statistical analyses of inventory and performance data items to: (1) verify the validity of the ODOT CCM framework items, and (2) to identify relevant items from the proposed ORITE framework items. Third, it develops a series of equations that assign culverts overall average rating (OAR) scores. OAR scores are determined from both the ODOT CCM inspection framework items and from the ORITE proposed framework items. These OAR scores are then adjusted given additional, region-specific factors identified as significant in the statistical analysis to produce the ORITE adjusted overall rating (AOR) scores associated with the risk assessment. The data items collected in the ORITE study, and proposed rating scales, can be found in Appendix D. For details of the statistical analyses, see Mitchell et al. (2005).

Two series of OAR equations were developed in the ORITE study: (1) those based on the ODOT inspection items, and (2) those based on the ORITE inspection items. Within each series, separate equations were developed according to culvert material type. Equations 4.1 to 4.4 calculate the OAR scores based on the ODOT inspection items:

$OAR = (GR + CA + SJ + CS)/4$ Metal Culverts Eq. 4.1

$OAR = (GR + CA + J)/3$ Concrete Pipe & Elliptical Culverts Eq. 4.2

$OAR = (GR + CA + S + A)/4$ Concrete Slab on Top & Box Culverts Eq. 4.3

$OAR = (GR + CA + CS + J)/4$ Thermoplastic Pipe Culverts Eq. 4.4

Where: GR = General Rating; CA = Culvert Alignment; SJ = Seams and Joints; CS = Culvert Shape; J = Joints; and A = Abutment. As discussed earlier, the ODOT CMM (ODOT 2003; ODOT 2013), bases its General Appraisal Rating on the lowest score of inspection items 1-7, and 12 (Table 4.8). However, in the equations above, note that the OAR is calculated as an average of select inspection items. Therefore, the OAR and General Appraisal Rating are not equivalent ratings.

Equations 4.5 to 4.8 calculate the OAR scores based on the ORITE proposed inspections items:

$OAR = (MP + HA + SJ + CS + SS + CD)/6$ Metal Culverts Eq. 4.5

$OAR = (CM + HA + SS + J)/4$ Concrete Pipe & Elliptical Culverts Eq. 4.6

$OAR = (CM + SS + HA)/3$ Concrete Slab on Top & Box Culverts Eq. 4.7

$OAR = (CB + HA + SJO + SJC + DE + DI + SS)/7$ Plastic Pipe Culverts Eq. 4.8

Where: MP = Metal Plate; HA = Horizontal Alignment; SJ = Seams and Joints; CS = Culvert Shape; SS = Slope and Settlement; CD = Culvert Deflection; CM = Culvert Material; J = Joints; CB = Cracking and Buckling; SJO = Seams and Joints Opening; SJC = Seams and Joints Cracking; DE = Shape Observation Deflection; and DI = Shape Observation Distortion.

The OAR scores are then adjusted into AOR scores, which account for regional variability in factors such as drainage flow abrasiveness and water pH. The AOR modifier equations are:

$AOR = AOR = M_1 * M_2 * M_3 * M_4 * (OAR)$ Metal & Concrete Culverts Eq. 4.9

$AOR = M_4 * (OAR)$ Plastic Pipe Culverts Eq. 4.10

Where: M_1 = culvert age modifier; M_2 = water pH modifier; M_3 = drainage flow abrasiveness modifier; and M_4 = modifier based on the Height/Rise ratio. Modifier values are given in Table 4.9. Height to rise (H/R) ratios are associated with driver-safety; lower ratios are associated with increased risk to motorists (Mitchell et al. 2005).

The ORITE study calculated and compared OAR and AOR scores for a sample of 60 culverts of various materials and configurations. In most cases, the AOR scores were found to be lower than the OAR scores (i.e., indicating poorer conditions in the adjusted scores). A comparison of AOR scores based on the ODOT inspection items with those based on the ORITE inspection items found strong similarities in the calculated AORs between the two inspection systems. Scores were typically the same, or deviated by 1 point (on a 0-9 point scale). There was no apparently trend in over- or under-prediction of AORs between the ODOT and ORITE-based inspection systems.

Table 4.9 Adjusted Overall Rating (AOR) Equation Modifier Values

Adapted from **(Mitchell et al. 2005)**

Age Modifier		
Culvert Age	**Concrete Modifier Value**	**Metal Modifier Value**
< 20 years	1.0	1.0
20 - 40 years	0.95	0.9
40 - 60 years	0.9	0.85
> 60 years	0.85	0.8
pH Modifier		
pH	**Modifier Value**	
> 7.0	1.0	
5.0-7.0	0.95	
< 5.0	0.9	
Abrasiveness Modifier		
Condition	**Abrasiveness Modifier Value**	
Abrasive	0.9	
Non-Abrasive	1.0	
Height/Rise Ratio Modifier		
H/R Ratio	**H/R Ratio Modifier Value**	
> 5	1.0	
2.5 - 5	0.9	
< 2.5	0.85	

4.2.4 Utah DOT Condition and Performance Assessment

The Utah DOT research report, *Condition Assessment of Highway Culverts and Determination of Performance Measures* (McGrath and Beaver 2004), developed a "system of qualitative and quantitative measures to assess both short- and long-term in situ performance of highway culverts and storm drains." The study focused on culverts with spans from 2-ft. to 5-ft. (approximately half of the culverts in Utah fall within this range). Short-term performance is primarily concerned with performance measures during construction, and immediately after construction. Long-term performance is then concerned primarily with performance measures of existing culverts, which is of greater significance to this research study. Culvert performance is assessed using two general performance categories: waterway performance, and barrel performance. Waterway and barrel performance are rated using a ten point scale (0-9) similar to that in the FHWA CIM (Arnoult 1986). Separate barrel performance scales are provided according to barrel material type. Illustrative descriptions of general conditions are provided for each rating level in Appendix E.

Overall waterway performance ratings are based on three categories: (1) alignment, (2) scour, and (3) obstructions/roadway/structure. However, guidance for considering additional factors is provided; this includes (1) roadway and side slope condition, (2) channel and channel protection, (3) end treatments and appurtenances, and (4) soil and groundwater.

Culvert barrel performance ratings are based on multiple factors that are specific to the culvert barrel material. Separate rating scales are provided for (1) round/vertical elongated corrugated metal pipe barrels, (2) concrete pipe barrels, and (3) plastic pipe barrels. In addition to the primary factors used to assess barrel performance, guidance is also provided for considering additional factors relevant to each primary factor. Table 4.10 shows the primary culvert barrel rating factors, as well as the additional consideration factors, organized by culvert barrel material type.

Table 4.10 Utah DOT Culvert Barrel Performance Rating Criteria

Culvert Barrel Material	Primary Rating Criteria	Additional Rating Criteria
Metal	• Shape; • Seams and Joints; • Metal	Deflection
		Seam Defects in Fabricated Pipe
		Longitudinal Seam Defects in Structural Plate Culverts
		Dents and Localized Damage
		Misalignment
		Joint Defects
		Durability (wall deterioration)
Concrete	• Alignment; • Joints; • Concrete (condition)	Misalignment
		Joint Defects
		Longitudinal Cracks
		Circumferential Cracks
		Spalls
		Radial Tension Failure
		Diagonal Tension Failure
		Durability
Plastic	• Shape and Alignment; • Joints	Deflection
		Local Buckling
		Cracks
		Seam Defects
		Misalignment
		Joint Defects
		Durability

The overall culvert performance rating is taken as the lower of the two performance category ratings. This overall culverts performance rating is then modified using a multiplicative "Importance Modifier." Three modifiers are used, one each for culvert size, roadway importance, and waterway type. The Importance Modifiers are shown in Table 4.11. Note that modifiers less than 1.0 adjust ratings to indicate greater importance (lower overall ratings are associated with greater performance deficiency).

Table 4.11 Utah DOT Culvert Rating Importance Modifiers

Roadway Class Modifier		
UCD Roadway Class Function	Description	Importance Modifier
1	Rural Interstate System	0.91
2	Rural Other Principal Arterials	0.91
6	Rural Minor Arterial System	1
7	Rural Major Collector	1.1
8	Rural Minor Collector	1.1
9	Rural Local System	0.91
11	Urban Interstate System	0.91
12	Urban Other Freeways & Expressways	0.91
14	Urban Other Principal Arterials	0.91
16	Urban Minor Arterial System	1
17	Urban Collector System	1
19	Urban Local System	1.1
Culvert Purpose Modifier		
UDC Drain Type	Description	Importance Modifier
Main	Under the roadway	0.91
Edge	Runs parallel to roadway, may be under shoulder lane, supports embankment	1
Lateral	Drains land adjacent to roadway, typically not under roadway	1.1
Slope	Drains a slope adjacent to the roadway, typically not under roadway	1.1
Barrel Span and Rise		
Minimum Span or Rise	Maximum Span or Rise	Importance Modifier
0 ft.	2 ft.	1.1
2 ft.	4 ft.	1
4 ft.	10 ft.	0.9

Once an adjusted rating is determined using the Importance Modifiers, the Utah DOT framework then assigns Maintenance Ratings. Maintenance ratings are associated with batched ranges of the culvert performance ratings, and are similar to the Low/Medium/High rating systems discussed in the context of risk analysis in Chapter 4. Culvert adjusted performance ratings from 9 to 6 (i.e., better condition) constitute low priority ratings; 5 to 3 constitute medium priority ratings; and 2 to 0 constitute high priority ratings. Complete maintenance rating descriptions, general courses of action, and descriptors of immediacy are provided in Appendix E.

4.2.5 Engineering Forensics Research Institute Large Culvert Sufficiency Rating

The Large Culvert Sufficiency Rating (LCSR) was developed by the Engineering Forensics Research Institute at the Rose-Hulman Institute of Technology as part of a research experience for undergraduates (REU) summer program (Billingsley et al. 2004; Wissink et al. 2005). The LCSR framework utilizes the current culvert inspection procedures of the Indiana DOT, which first rates 21 inspection items on a scale from 0 to 9, similar to the FHWA CIM (Arnoult 1986). A series of weighting factors are then applied to adjust the culvert inspection items and produce an overall culvert sufficiency rating. The weighting factors were developed to apply greater weighting to items that may be indicators of six primary causes of culvert failure identified in the study: corrosion, erosion, blockage, shape loss, deterioration, and other. Weighting factors are applied using equation 4.11 (Wissink et al. 2005):

$$R = \frac{\sum w_i r_i}{\sum w_i} + C \qquad \text{Eq. 4.11}$$

Where, R = the overall culvert sufficiency rating; w_i = weighting for each factor, i; r_i = rating for each factor; and C = calibration constant. The culvert inspection items and corresponding weighting factors, w_i, are shown in Table 4.12. Note that weighting factors are not evenly apportioned. That is, the lower three factors are 1 (Not Important),

Table 4.12 LCSR Inspection Items and Weighting Factor Codes

Inspection Area	Inspection Item	Weighting Factor, w_i
Roadway	Road Alignment	1
	Pavement/Wearing Surface	2
	Shoulders	2
	Embankment/Side Ditches	6
	Guardrail/Concrete Barrier	1
Type 1 - Culverts & Pipes	Barrel/Box	25
	Headwalls/Anchors	6
	Wingwalls	6
	Settlement	3
Type 2 - Structures (Superstructure)	Concrete Slab	25
	Beams/Girders	25
	Coping/Headwalls	6
Type 2 - Structures (Substructure)	Caps	3
	Abutments	25
	Wingwalls	6
	Footings	6
	Pilings	3
Channel	Channel Alignment	1
	Bank Erosion	6
	Channel Scour	6
	Drift/Sediment	6

2 (Low Importance), and 3 (Marginal Importance); the higher factors are 6 (Very Important) and 25 (Crucial).

The LCSR recognizes the need for “inspectors [to] incorporate their own judgment into the final overall rating” (Wissink et al. 2005), particularly when the calculated rating may not accurately reflect the failure risk of a culvert. The example given is when an individual critical factor is significantly deficient (e.g., a Barrel/Box rating = 2), indicating a structurally poor condition, but the remaining factors are within acceptable ranges. For this reason, a series of rating factors were developed for use at the inspectors discretion when individual items are assigned ratings from 0 to 3. These rating factors are shown in Table 4.13

Table 4.13 LCSR Critical Item Alternate Weighting Factors

Inspection Rating	Critical Weighting, w_i	Extremely Critical Weighting, w_i
0	1350	2700
1	450	900
2	150	300
3	50	100

The general approach of the LCSR may prove useful as it develops a rating procedure that utilizes data collected by existing culvert inspection procedures. However, the LCSR lacks sufficient justification for how weighting factors were selected. Additionally, only a basic comparison of existing Indiana DOT rating procedures and the LCSR were conducted. This comparison indicated that the LCSR rated lower those culverts with high (i.e., good) ratings, rated higher those culverts with middle ratings (e.g., 4 or 5), and rated roughly equal those culverts with lower (i.e., poor) ratings (Wissink et al. 2005). However, whether or not the LCSR offers an improvement over the existing Indiana DOT culvert rating system is unclear.

4.2.6 Midwest Regional University Transportation Center Basic Condition Assessment (BCA) for Culverts

The Midwest Regional University Transportation Center (MRUTC) developed a condition assessment protocol for culverts and drainage structures to evaluate their overall condition and to “provide a base for culvert renewal decision-making process.”

(Najafi et al. 2008) The condition assessment protocol consists of two condition assessment models: a Basic Condition Assessment (BCA) and an Advanced Condition Assessment (ACA). The BCA is intended for general culvert inspection to determine a performance score that classifies culvert performance as (1) critical, (2) monitored (i.e., middle-rating), or (3) satisfactory. The ACA is intended for project-level inspection of culverts found to be "critical" during the BCA to determine what immediate actions should be taken. Given the ACA's project-level focus, it is not discussed further in this dissertation.

The BCA consists of a series of 6 "Modules." The first three modules collect general information, site information, and culvert identification information, respectively. These data types are listed in Table 4.14. Module four collects and rates condition assessment data. Condition is assessed for six individual culvert components using a scale from 1 (Failure/Critical) to 5 (Excellent). The culvert components assessed include (complete descriptions of each condition assessment item are provided in Appendix F):

1. Invert condition
2. End protection condition (headwall, wingwall)
3. Roadway condition
4. Embankment condition
5. Culvert footing condition
6. Overall culvert condition

Modules five and six weight the six condition components and calculate an overall culvert performance score. Weighting values were calculated using analytic

Table 4.14 MRUTC Basic Condition Assessment (BCA) Inventory Data

Adapted from **(Najafi et al. 2008)**

Inspection Module	Data Item
Module 1 - General Information	State code
	County Code
	Place Code
	Culvert Identification Number
	Year Built
	Date of Inspection
	Inspector's Name
	Maintenance Responsibility
Module 2 - Site Information	Inspection Season
	Climate
	Type of Inspection
	Type of Stream
	Water Level
	pH of Water
	Soil Resistivity
	Vegetation
	Natural Hazards
Module 3 - Culvert Identification Information	Shape
	Material
	Number of Cells
	Type of End Treatment
	Geometric Dimensions

hierarchical process (AHP), which involves a pair-wise comparison of the individual condition components to one another in a matrix format. The comparison matrix is populated with values from 1 (of equal importance) to 5 (of extremely greater importance) for each component, and these values are then normalized. The normalized values for an individual component are then averaged to produce that component's weight. Weighting factors are calculated for individual culvert, or sets of culverts. The final weighting factors calculated for the culvert case study set in the MRUTC project are shown Table 4.15 to give a general sense of their magnitude. See Najafi et al. (2008) for more details on the AHP calculation of weighting factors. The component condition ratings are then combined with the relative component weights (Table 4.15) to calculate culvert performance scores using equation 4.12. Performance scores above 3.5 are classified as "Satisfactory (Safe);" scores from 3.5-2.5 are classified as "Monitored (Intermediate)," and scores below 2.5 are classified as "Critical (Danger)." Those culverts found to be rated as "Critical" by the BCA are then examined at the project-level using the Advanced Condition Assessment (ACA), see (Najafi et al. 2008).

Table 4.15 BCA Component Weighting Factors

Source: **(Najafi et al. 2008)**

Component Type	Relative Component Weight
Condition of Inverts	0.3888
Condition of End Treatments	0.2196
Condition of Footings	0.1404
Condition of Roadway	0.1299
Condition of Embankment	0.0583
Overall Culvert Condition	0.063

$$Culvert\ Performance\ Score = \sum(Condition\ Rating \times\ Relative\ Weight) \qquad \text{Eq 4.12}$$

4.3 Culvert Data and Condition Assessment Discussion

The culvert condition and performance assessment frameworks reviewed in the previous section constitute the current state-of-the-art for network-level culvert assessment in the United States. Despite the significant variability among data collection and assessment methodologies, some relevant conclusions can be synthesized. These are discussed below.

4.3.1 Inspection Data Ratings

All inspection and assessment frameworks utilize some form of subjective numerical rating scale to evaluate various condition and performance indicators. In some cases, these scaled ratings are supplemented with percentage-based ratings (e.g., sedimentation as a percentage of cross-sectional area). The 0 to 9 rating scale established in the FHWA Culvert Inspection Manual (Arnoult 1986) is widely used [ODOT CMM & ORITE (Section 4.2.3), Utah DOT (Section 4.2.4), and LCSR (Section 4.2.6)], although truncated rating scales (e.g., 1 to 5, or shorter) are also used [FLH (Section 4.2.1),WTI (Section 4.2.2), and MRUTC (Section 4.2.6)]. The FHWA CIM rating scale may serve as a reasonable baseline for culvert performance indicator inspection ratings. However, it is also possible that the higher resolution of that scale (10 points, as opposed to fewer) may suggest a level of detailed condition knowledge that belies the uncertainty inherent in subject inspections of surface conditions. It is possible that less detailed scales (e.g.,3 or 5 points scales) will suffice for network-level assessments.

4.3.2 Condition and Performance Criteria

There is much similarity among the condition and performance criteria included in the frameworks reviewed. Much of this is likely due to the influence of the FHWA CIM and the guidance it provides for data collection and assessment. Some of the frameworks discussed apply statistical analyses to determine relevant performance criteria and weighting factors [e.g., WTI (Section 4.2.2) and ORITE (Section 4.2.3)], whereas others apply engineering and expert judgment [e.g., FLH (Section 4.2.1), MRUTC (Section 4.2.6)]. In the case of the EFRI Large Culvert Sufficiency Rating (Section 4.2.5), it is unclear how the weighting factors were chosen.

There is value in criteria selection based both on expert judgment and statistical analyses. In fact, the statistical analyses were frequently used to validate the significance of the myriad condition criteria ratings given subjective overall ratings assigned by inspectors. Particularly given the somewhat subjective nature of the performance and condition rating scales, it seems likely that the use of criteria derived from both statistical and expert judgment methods would be advisable in assessing culvert vulnerability.

4.3.3 Culvert Size and Material Focuses

The FHWA Culvert Inspection Manual states that it officially provides guidance for culverts that span greater than 20-ft., however the rating systems therein may be useful for assessing shorter-span culverts (Arnoult 1986). In contrast, the ODOT CCM and ORITE frameworks (Section 4.2.3) were primarily developed to assess culverts spanning 10-ft. or less, and the Utah DOT framework (Section 4.2.4) was primarily developed to assess culverts spanning 2-ft. to 5-ft. It is possible that these frameworks developed for smaller culverts may be useful in assessing general vulnerability of all sub-20-ft. culverts, but the efficacy of this will require further consideration.

Several of the assessment frameworks also provided separate rating scales and assessment criteria based on culvert material types and configurations. In considering this level of specificity during the development of a climate change risk assessment framework, it will be important to strike a balance between network-level assessment and project-level assessment, the latter of which may be the more appropriate level for material-specific considerations.

4.3.4 Assessment Outcomes

In all of the condition and performance assessment frameworks reviewed, the final outcome is some overall culvert condition rating that reflects its level of deficiency or vulnerability. However, in several cases [e.g., FLH (Section 4.2.1) and Utah DOT (Section 4.2.4)] these outcomes are intended also to indicate maintenance needs. In the case of the Utah DOT framework, the indication of maintenance needs is an additional analysis step beyond overall condition rating. However, in the case of the FLH framework, the maintenance need is determined in lieu of an overall condition rating. Whether or not maintenance need ratings can reasonably be used as surrogate indicators of overall condition or vulnerability requires further consideration. However, it is possible that culvert maintenance ratings, or the inspection criteria upon which they are based, could be useful information for assessing vulnerability in a risk prioritization framework.

4.4 Culvert Failure and Potential Indicators of Failure

The culvert condition assessment frameworks presented in Section 4.2 and discussed in Section 4.3 are intended to assess the condition and functional performance of culvert assets for infrastructure management purposes. However, these assessments may or may not provide reasonable indications of culvert vulnerability to increased flow conditions, or potential for failure. In discussing structural inspection and repair, the

FHWA's *Hydraulic Design of Highway Culverts* manual (Schall et al. 2012) notes that "what appears to be significant physical deterioration may not necessarily translate to performance issues, and may not even warrant repair." Therefore, it is necessary to better understand the nature, common modes, and common causes of culvert failure to better identify those inspection criteria that may provide a better indication of vulnerability or failure potential. For the purposes of this discussion, failure may be defined simply as any adverse impact to a culvert or embankment that disrupts travel on the roadway traversed or drained by a culvert. This ranges from overtopping to embankment failure and washout.

This section first reviews the relatively sparse literature on culvert failure to discusses and synthesize common culvert failure modes and causes. It then considers the culvert failure literature in the context of the culvert assessment frameworks reviewed above (Section 4.2) to select several criteria that may be useful as indicators of vulnerability to increased flows or failure potential.

By definition, culverts are structures that are "usually covered with embankment and are composed of structural material around the entire perimeter." (FHWA 2012) As will be seen, culvert failure often stems from problems associated with the interaction of the culvert structure and the surrounding fill material, particularly flexible culverts which rely on interaction with the surrounding soils for structural support. Many of the failure causes discussed below result from what Tenbusch et al. (2009) discuss as the "failure of the soil/pipe structure."

4.4.1 Piping and Seepage

Piping is defined as the “removal of soil material through subsurface flow of seepage water that develops channels or ‘pipes’ within the soil bank,” (Schall et al. 2012) and is widely recognized as a contributor to the failure of culvert structural support (Stuhff 2007; Thompson and Kilgore 2006; Van Kampen 2011; WisDOT 2004). This transport of material away from the culvert barrel creates a loss in structural support that can lead to bending, deformation, or collapse of the culvert structure.

In addition to water seepage along the exterior of the culvert barrel, piping can also be caused by water infiltrating from voids in the culvert barrel itself. Separation of culvert barrel joints allows water to enter the surrounding fill material and can lead to piping by removing or washing out of the supporting fill material (WisDOT 2004). Voids can also develop in culvert barrel material through other mechanisms. Corrosion, the “chemical or electro-chemical reaction between the soil and/or water and the culvert,” (Schall et al. 2012) can cause holes in the culvert barrel (predominantly metal culverts). This removes “the soil protection provided by the pipe material for the structural fill,” and can consequently remove the fill itself (Tenbusch et al. 2009). Abrasion, the “removal of material due to entrained sediment, ice, or debris rubbing against the [culvert barrel]” (Schall et al. 2012) can also cause holes to develop in the culvert barrel. Significant cracking (~1/4”) in concrete culverts may also allow significant infiltration or exfiltration and voids,” (Schall et al. 2012) lead to piping and removal of fill materials.

4.4.2 Scour and Embankment Erosion

Scour is the "erosion of streambed or bank material due to flowing water," and can be caused by constricted flow or other conditions such as flow around a bend (Schall et al. 2012). With respect to culverts, scour is most common at outlets where "increased water velocity can cause streambed scour and bank erosion," (Schall et al. 2012) or "undermining" (Van Kampen 2011) of the culvert outlet. It is noted that this scour-induced erosion of the embankment can, in extreme cases, eventually "remove the entire embankment and culvert." (Tenbusch et al. 2009) In more minor instances, the loss of structural fill due to scour and embankment erosion, and therefore loss of structural support, can contribute to joint separation and structural cracking of the culvert barrel. These factors, as discussed in Section 4.4.1, can contribute to piping and infiltration or removal of structural fill in the embankment.

Scour can also occur at culvert inlets (Schall et al. 2012). Poor alignment of a culvert's longitudinal axis with the flow channel can contribute to inlet erosion and scour, particularly scour of headwall/wingwall structure footings (Thompson and Kilgore 2006). Significant upstream or inlet ponding can, in the case of flexible culverts, lead to buoyancy issues (Stuhff 2007) wherein a submerged culvert inlet is lifted due to buoyant forces associated with air trapped inside the culvert. Buoyancy can contribute to barrel seepage along the barrel exterior (Van Kampen 2011), and therefore degradation of the embankment fill material.

Overtopping of culvert embankments due to stream flows in excess of a culvert's capacity can also contribute to embankment erosion (Schall et al. 2012). Other adverse impacts associated with overtopping conditions are discussed in the next section.

4.4.3 Blockage and Hydrostatic Pressure

Blockage of culvert barrels constricts the flow of water and can cause a culvert to "fail to perform as designed" by decreasing its flow capacity (Schall et al. 2012). A culvert barrel can become blocked due to the accumulation of debris (e.g., wood, vegetation, trash), sedimentation, or significant barrel distortion (cross-sectional deformation).

The FHWA notes that debris accumulation "may result in erosion at culvert entrances, overtopping and failure of roadway embankments" (Bradley et al. 2005) due to blockage and increased scour. As discussed in the previous section, embankment overtopping due to blockage or constricted flow can contribute to embankment erosion. Additionally, debris accumulation and constricted flow can exacerbate scour around structural elements (Bradley et al. 2005), and cause buoyant uplift of the culvert inlet (Schall et al. 2012). For this reason, it is important that debris is removed during maintenance activities, or that debris control structures are in place to mitigate debris accumulation.

Sedimentation is the deposition and buildup of sediments along a culvert barrel that are moved by the stream as a natural part of fluvial geomorphology. When sedimentation blockage is relatively low (< 1/3 of the culvert rise), "sufficient invert slope and periodic high flows...will likely clear out the blockage as a self-cleaning mechanism." (Schall et al. 2012) The FHWA notes, however, that skewed culvert barrels and multiple-barreled culverts can increase sedimentation, and also that storm events can accelerate erosion and sedimentation when stream depths and velocities are increased

(Schall et al. 2012). Flanagan (2004) also observes that “larger streams trigger a greater proportion of sediment-related failures.”

In addition to the issues of overtopping-related embankment erosion associated with blockage, Tenbusch et al. (2009) notes that blockage can also contribute to surcharge hydrostatic pressure. That is, unanticipated upstream ponding (due to blockage or stream flows in excess of the culvert’s capacity) can apply additional hydrostatic and hydrodynamic loads to the structure, structural fill and the embankment. In the case of deteriorated embankments (i.e., due to piping, scour, etc.) these increased loads may contribute to the failure or removal of the embankment.

4.4.4 Synthesis of Failure Modes and Potential Indicators

Given the discussion of culvert failure literature in Sections 4.4.1 to 4.4.3, several criteria emerge as potential indicators of culvert vulnerability to increased flows and potential failure. Examining the various indicators discussed in the literature, it appears that they can be categorized generally as: (1) embankment-related indicators, and (2) blockage-related indicators. The indicators and categorizations are shown in Table 4.16.

Within the embankment-related indicators, Item 1 through Item 3 (shown in bold) provide direct, observable indications of embankment condition. These are termed here as “explicit indicators.” Item 4 through Item 11, however, indicate conditions that may lead to embankment deterioration, but do not directly indicate that deterioration is occurring. These are termed here as “implicit indicators.” For example, joint separation may allow water to enter the embankment and remove structural fill material, but does not necessarily provide a direct indication that piping is occurring.

The same is true for blockage-related indicators in Table 4.16. Item 12 and Item 13 (shown in bold) are explicit indicators that blockage is occurring in the culvert barrel. Item 14 (deformation), however, does not necessarily indicate that flow capacity is reduced, which may only occur in extreme cases of deformation such as partial collapse of the barrel; it is thus classified as an implicit indicator.

Table 4.16 Potential Indicators of Culvert Vulnerability or Failure Potential

Embankment-Related Indicator	
1.	**Piping**
2.	**Embankment erosion**
3.	**Inlet or outlet scour**
4.	Joint separation
5.	Substantial barrel cracking
6.	Substantial barrel corrosion
7.	Substantial barrel abrasion
8.	Seepage
9.	Poor channel alignment
10.	Evidence of buoyant uplift
11.	Previous overtopping
Blockage-Related Indicator	
12.	**Sedimentation blockage**
13.	**Debris blockage**
14.	Barrel deformation

Several of the indicators shown in Table 4.16 align closely with the performance and condition criteria from the culvert assessment frameworks discussed in Sections 4.2 and 4.3. For example, all of the Level 1 Maintenance Criteria (Table 4.2) in the FLH *Culvert Assessment and Decision-Making Procedures Manual* (Section 4.2.1), are reflected in Table 4.16. Similarly, the WTI *Rating System for Rural Culvert Crossing Repair and Maintenance* (Section 4.2.2) criteria (Table 4.5) is strongly aligned with those in Table 4.16 (only culvert age is not considered here).

One possible challenge in using the vulnerability indicators listed in Table 4.16 to broadly assess culvert vulnerabilities is that the culvert performance and condition items collected by state DOTs are likely non-uniform from state to state, or incomplete within each state's records. This may create difficulty in developing an assessment framework that is broadly applicable among states and jurisdictions (some additional thoughts on this are discussed in Chapters 6 and 7). In the case study portion of this dissertation research, it may be necessary to limit culvert vulnerability analysis only to those state-collected criteria that overlap with the indicators in Table 4.16. While this may create a non-uniform analysis from state to state, it will nonetheless aid in identifying culverts that are vulnerable to increased flows, or that have a greater potential for failure.

4.5 Studies of Climate Change Impacts to Culvert Assets

Highway culvert assets have received relatively little attention from the transportation infrastructure adaptation community. Despite the mention of culverts in numerous studies as infrastructure assets vulnerable to the impacts of climate change (Arisz and Burrell 2006; City of Keane 2007; Kinsella and McGuire 2005; Maurer et al. 2011; Meyer 2008; Noehammer and Capano 2011; Schwartz et al. 2013; Shen and Peng 2011), only a very limited number of studies have focused specifically on culvert climate vulnerability and adaptation [for some examples, see Dickson (2011); Stack et al. (2007); Stack et al. (2010)].

Among the studies that do specifically address potential climate change impacts to culvert assets, the primary approach has been to conduct project-level case studies of a small number of culverts within a single watershed (Stack et al. 2007; Stack et al. 2010) or municipality (Dickson 2011). Stack et al. (2007) and Stack et al. (2010) applied similar analytical frameworks to examine sample sets of culverts in two separate watersheds in New Hampshire. The framework in these studies compared culverts' design flow capacities with those that would be required for mid-century (i.e., 2046-2075) precipitation projections (25-year, 24-hour precipitation events). Projections were determined for two climate scenarios (A1b, and A1Fi), using output from one GCM (the Geophysical Fluid Dynamics Laboratory, or GFDL model).

Dickson (2011) applied the general infrastructure climate vulnerability assessment protocol developed by Engineers Canada (PIEVC 2009) to evaluate a sample-set of three culverts in Toronto, Canada. This study examined multiple projected mid-century (i.e., 2040-2049) climate impacts (e.g., extreme temperatures, heavy precipitation, drought, etc.) on multiple aspects of culvert condition and management (e.g., roadway, utilities operation/maintenance, surrounding area, drainage, stream corridor, natural features). General risks associated with each impact type were first assessed for the three culverts using expert panel input. More in-depth engineering studies of each culvert were then conducted for the higher-risk climate impacts.

In each of these three culvert-specific climate vulnerability studies, the primary focus is project-level assessment, as evidenced by the culvert-specific engineering-design focus of the studies. In all instances, in-depth site visits were conducted to obtain relevant data, yet apparently the culvert condition information was neither systematically collected, nor explicitly considered in the analyses. Instead, the primary metric for vulnerability was deficient hydraulic design given projected climatic conditions. In some instances, restricted flow conditions and structural deficiencies were noted, but not systematically factored into the analysis.

Focused, design-based studies that examine culvert vulnerabilities to the impacts of climate change have significant value, however they do not readily interface with network-level infrastructure management, or culvert asset management programs. This research study seeks to address the currently narrow focus of culvert climate change studies by developing an assessment framework methodology (see Chapter 5) that enables the network-level assessment of culvert climate change risks. Such a framework will enable a network-level prioritization of climate risks among culvert assets, and may serve as somewhat of a screening process to motivate deeper project-level assessment of high-risk assets.

CHAPTER 5

ASSESSMENT FRAMEWORK DEVELOPMENT AND METHODOLOGY

The objective of this dissertation research is to develop a risk-based assessment framework to prioritize at a network-level the adaptation needs of roadway culvert assets as a result of the climate change-related impacts of extreme precipitation. This chapter discusses the development and structure of the assessment framework. This consists of a detailed discussion of the individual components of the assessment framework, data and data sources, and analysis methods. It also discusses the case-study implementation of the framework developed to evaluate its efficacy as a climate change assessment tool.

The assessment framework (hereafter referred to as the, culvert climate adaptation assessment framework, or CCAAF) seeks to complement the project-level, engineering design-based culvert adaptation assessments discussed in Section 4.4 and enhance the existing toolkit for culvert assessment. Specifically, it is intended to provide a network-level assessment that could be used to assist decision-makers in prioritizing programming or management activities. This has the potential to also better inform infrastructure managers in deciding where to best target project-level, or engineering design-based adaptation studies (such as those discussed in Section 4.4) to those culverts that have been identified as higher-risk through network-level assessments.

Two core principles underlying the development of the CCAAF are replicability and flexibility. Seeking to increase the replicability of the framework will enable transportation professionals and practitioners in different regions to conduct similar assessments. This, in turn, may enable greater comparison among regions and also facilitate knowledge-sharing related to implementation or further development. Also, should federal funding become available for climate change adaptation activities in the future, a broadly replicable assessment framework may enable a more equitable competition for such funding among agencies from different regions. To facilitate replicability in the framework, national datasets that are freely available to practitioners are used. This includes climate change projection datasets and other transportation infrastructure datasets.

Seeking to increase flexibility in the framework has to primary motives. First, it recognizes that although the assessment must be broadly applicable, it must nonetheless be able to account for differing interests and practices among agencies conducting the assessment. For this reason, weighting factors are built into the prioritization process wherein agencies can tailor the assessment to their unique interests. Second, flexibility also enables the framework to adapt to new data inputs as they become available in the future. For example, as RCP-based climate projections replace SRES-based projections in the future, their integration into the framework is crucial. For this reason, the climate projection method used in the CCAAF, for example, is intended to be sufficiently general as to enable flexibility in its inputs.

This chapter begins by discussing the general approach and development of the CCAAF, as well as the case studies used to demonstrate the framework in this dissertation research (Section 5.1). It then discusses the individual components of the CCAAF; specifically, their structure, data inputs, analysis method, and outputs (Section 5.2 to Section 5.5). It concludes with a discussion of the prioritization of culverts by combining the constituent outputs of the CCAAF components into a series of Culvert Asset Prioritization (CAP) Indices (Section 5.6) that are used to produces the final Robust Culvert Asset Prioritization (R-CAP) Index.

5.1 General Approach and Framework Development

The development of the culvert climate adaptation framework (CCAAF) in this study uses as a foundation the findings of the literature review of existing risk-based climate change adaptation practices (Chapter 3). The review in Chapter 3 found that adaptation frameworks from the global transportation and infrastructure community were predominantly built around (or were consistent with) the principles outlined in the risk standard, *ISO 31000:2009 Risk Management – Principles and Guidelines*, (Figure 3.2). Therefore, the CCAAF is developed to accomplish primarily the risk assessment steps outlined in ISO 31000:2009, namely: (1) risk identification, (2) risk analysis, and (3) risk evaluation.

As discussed in Chapter 3, risk is traditionally defined as a function of an adverse event's likelihood (i.e. probability) and consequence. As has been noted, it is difficult to assign climate change impacts any quantitatively-robust likelihood of occurrence. However, this study proposes using other measures to specify a qualitative likelihood; specifically exposure and vulnerability. Exposure can be viewed as an indication of whether or not an asset within a defined region (e.g. geographical grid square) will be exposed to climate impacts, and the magnitude of those impacts, across a number of climate scenarios (both emission scenarios and impact timeframes). For example, if all climate scenarios under consideration indicate that extreme precipitation intensity will not increase in the coming years, exposure may be viewed as low. If all or several climate scenarios indicate that extreme precipitation intensity will increase significantly in the coming years, exposure may be viewed as higher. This is consistent with the discussion in Section 3.1.1 of scenario analysis and robust solutions.

Vulnerability addresses the question of whether or not an asset that is exposed to climate change impacts will be negatively affected by those impacts. Throughout the discussion of culvert management and rating systems in Chapter 4, all inspection methodologies sought to make a determination of culvert condition and performance, and assign a rank or index based on the deficiencies found. As the condition and functional performance deficiencies of a culvert system would be subjected to greater stress during extreme precipitation and flooding conditions, it may be reasonable to view various culvert condition and performance criteria as indicators of vulnerability. For example, culverts that have greater cross-sectional blockage or embankment deterioration (i.e. lower performance ratings) would be mechanistically more susceptible to failure under increased stress conditions, and therefore more vulnerable to impacts.

The other aspect of risk, consequence, addresses the value lost due to an asset's disruption. Much of the complexity of addressing consequence is in adequately bounding the myriad interests and stake-holders involved. Grossi and Kunreuther (2005) address the consequence aspect of risk in their catastrophe assessment model by examining criticality. For example, in the context of a transportation network, this may be how critical an asset is to the core functions of a viable network based upon several specified criteria. Asset criticality is a common measure in the transportation infrastructure sector when considering vulnerability or risk [for example, see Department of Homeland Security (2009) and AASHTO (2002)].

The framework described in this chapter seeks to address these three aspects, or "dimensions," of climate change impact risk (climate impact exposure, asset vulnerability, and asset criticality) in assessing and prioritizing culvert asset adaptation needs. Section 5.1.1 introduces the general structure and work-flow of the assessment framework, as well as its evaluation.

5.1.1 Framework Structure

The structure of the CCAAF is modeled on that of the catastrophe model (see Figure 3.3) presented by Grossi and Kunreuther (2005), and to a lesser degree, the FHWA's conceptual model (2012), both of which provide work-flows that seem well suited to assessing risk in specific classes of infrastructure assets. The catastrophe model (Figure 3.3) is also noted as being well suited to geospatial analysis using GIS software (Botzen and Van Den Bergh 2009), which is a key tool in the CCAAF process. The CCAAF structure is shown in Figure 5.1.

The general approach of the CCAAF is to evaluate each of the individual components of climate change impact risk (climate impact exposure, asset vulnerability, and asset criticality), and assign each culvert a relative rating (i.e., low/medium/high), called an Index value, for each of the three risk components. The three index values are then combined into a Culvert Asset Prioritization (CAP) Index that represents the relative, network-level climate change impact risk associated with culverts in the analysis area for a specific emission scenario and timeframe. These CAP Indices are then

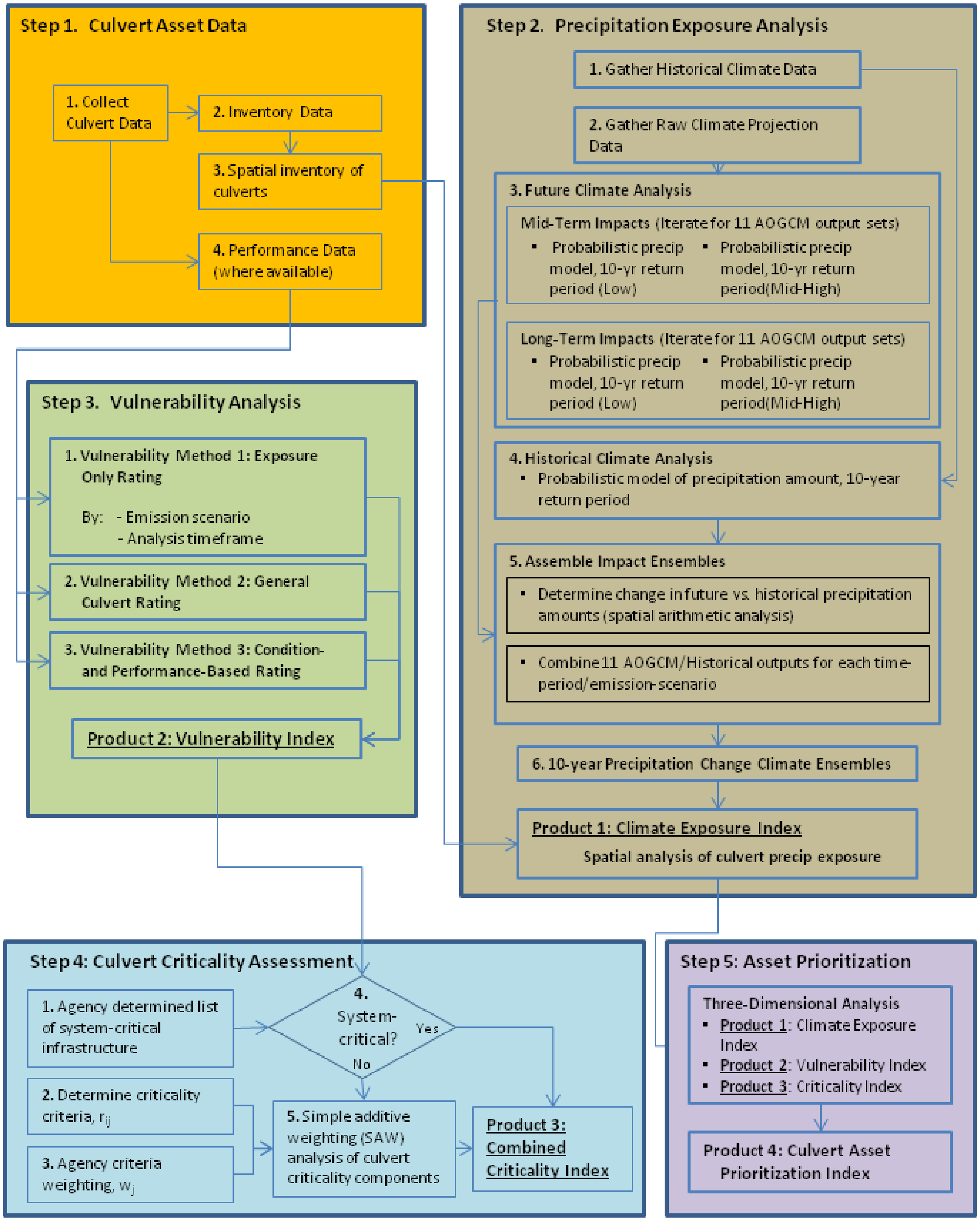


Figure 5.1 Culvert Climate Change Assessment Framework (CCCAF)

combined for to create Robust Culvert Asset Prioritization (R-CAP) Indices that consider CAP indices based on multiple emission scenarios for each timeframe. Briefly, the specific steps of the CCAAF are as follows:

Step 1 – Culvert Asset Data, collects and organizes culvert asset management data for the evaluation area. The culvert inventory data are used in the spatial analysis of culvert precipitation exposure (Step 2), and the culvert performance data are used in the vulnerability analysis (Step 3). The culvert asset data component is analogous to the inventory component of the catastrophe model. Step 1 – Culvert Asset Data is discussed in greater detail in Section 5.2.

Step 2 - Precipitation Exposure Analysis conducts a spatial analysis of regional climate change impacts to identify the exposure of assets to changes in extreme precipitation for multiple timeframes (mid-century, end-of-century) and emission scenarios (B1 – Low, A2 – Mid-high), and to determine Precipitation Exposure Index values. The precipitation exposure analysis is analogous to the hazard component (hazard analysis) of the catastrophe model. The precipitation exposure analysis is discussed in greater detail in Section 5.3.

Step 3 and Step 4 constitute the risk analysis component of the CCCAF. *Step 3 – Vulnerability Analysis* (Section 5.4) combines culvert condition and performance information (Step 1) with geospatial elements of the precipitation exposure information (Step 2) with to assess culvert vulnerability to regional changes in extreme precipitation impacts. Multiple vulnerability analysis methods are used to then assign each culvert a Vulnerability Index value. Separate Vulnerability Index values are assigned to each culvert: one for each combination of climate change timeframe and emission scenario.

The vulnerability analysis is consistent with the vulnerability component of the catastrophe model.

Step 4 – Culvert Criticality Assessment examines various socioeconomic, operational, and network aspects the roadways on which the culverts are located to determine the relative criticality of the asset. Multiple dimensions of criticality are combined to determine the Combined Criticality Index for each culvert. This is analogous to the consequence component of the traditional definition of risk as a relative measure of the asset's importance to network function, and is analogous to the loss component of the catastrophe model. The asset criticality assessment is discussed in greater detail in Section 5.5

The final step, *Step 5 – Asset Prioritization*, combines the outputs of the Exposure Analysis, Vulnerability Analysis, and Criticality Assessment to produce multiple Culvert Asset Prioritization (CAP) Indices. CAP Indices of 1, 2 or 3 are associated with risk-prioritizations of low, medium, and high, respectively. These CAP Indices are then combined into Robust Culvert Asset Prioritization (R-CAP) Indices, which represent the timeframe-specific risks of culverts to extreme precipitation across multiple emission scenarios. The Asset Prioritization step is discussed in greater detail in Section 5.6.

5.1.2 Case Studies

To evaluate the efficacy of the CCAAF, the framework is implemented in a series of case studies using data provided by four state DOTs. State DOTs were selected by first conducting a literature review of ancillary asset and culvert asset management practices (Akofio-Sowah 2011; Akofio-Sowah et al. 2012; FHWA 2007) to identify several states that maintain culvert asset databases. Recommendations were then solicited from the FHWA Office of Asset Management, Pavements, and Construction, to identify additional state DOTs (Gaj and Pan 2012). Several state DOTs were contacted and four agreed to participate in the study and to provide culvert asset data:

1. Minnesota DOT (MnDOT) (Peterson 2012)
2. New York State DOT (NYSDOT) (Allen and Koptsev 2013)
3. Oregon DOT (ODOT) (Trevis 2012)
4. Washington State DOT (WSDOT) (Beebe 2012)

Significant differences exist in the type, extent, and completeness of culvert data collected by the four participating state DOTs. These are discussed in greater detail in Section 5.2, which characterizes the inventory and attribute data recorded among the DOTs, as well as the extent of their inventories.

Additional state-specific data were required to complete the analyses described in the following sections of this chapter. The sources and types of data are noted in the relevant sections. Whenever possible, national datasets were used (particularly in determining precipitation exposure and asset criticality), but in a limited number of cases, state-specific data were solicited from the DOTs. These are also noted in the following sections.

5.2 Culvert Asset Data

The first step in the CCAAF is to collect and assemble the culvert asset data (Figure 5.2). This is consistent with the “inventory component” of the catastrophe model

(Figure 3.3) used to inform the structure of the CCAAF. Item 1 in Figure 5.2, collection of the culvert data, was described earlier in Section 5.1.2. The culvert asset data collected can be classified as one of two types: (1) inventory data, and (2) condition and performance (attribute) data. The culvert inventory data and geo-locating (Items 2 and 3) are discussed in section 5.2.1 for each of the case-study DOTs. The culvert performance and condition data (Item 4) are discussed in section 5.2.2 for each of the case-study DOTs.

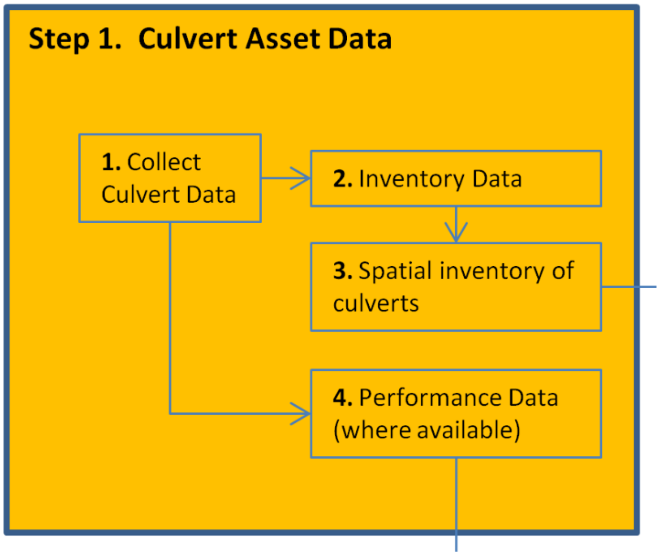


Figure 5.2 Culvert Asset Data Step

The spatial extent and completeness of culvert inventories vary among the four participating case-study DOTs. The culvert inventories in Minnesota and New York State maintain relatively complete statewide coverage for all major roadways (and some local roadways). Statewide coverage files were provided by these DOTs for use in this dissertation research. The culvert inventory in Washington State has statewide coverage, however four selected highways were provided by the WSDOT for use in this study. The four highways were selected on the basis of providing a representative cross-section of roadway types (i.e., state route, interstate highway, non-interstate national highway) and climate and terrain types (i.e., coastal, farmland, mountainous, arid, etc). The culvert inventory in Oregon covers selected segments along certain state routes, however all records maintained by ODOT were provided for use in this study.

It should be noted that culvert inventory and attribute data are collected with various levels of completeness among the four state DOT datasets. Generally, inventory data are consistently and completely collected; however, performance and condition data items are frequently incompletely recorded. Examining the four datasets, the pattern by which items are omitted appears to be random. Data omissions and incomplete data recording are discussed further in Section 5.4

5.2.1 Culvert Inventory Data

In the context of asset management, inventory data contains information about individual assets that, generally speaking, does not change over time due to deterioration and use. Examples of inventory data include: name, location, dimensions, jurisdictional data (e.g., ownership, responsible management entity), age, material, etc. AASHTO (2011) provides a detailed list of sample inventory data for multiple asset types and categories.

All four of the case-study DOT culvert inventory databases contain similar inventory data. Primary types of relevant culvert inventory data among the four participating DOTs are summarized in Table 5.1. Most relevant to the CCAAF are the location data and the route data information. Note that in the data provided, all DOTs indicate culvert location using linear referencing (i.e., route and mile-markers), however Minnesota, New York, and Washington provided XY coordinate (latitude, longitude), but Oregon did not.

Table 5.1 Summary of Case-Study State DOT Culvert Inventory Data

Culvert Inventory Item	State DOT			
	Minnesota	New York	Oregon	Washington
Identifier	x	x	x	x
Status	x	x	x	x
Age/Date Built	x	x		
Date Discovered	x			
Last Inspection Data	x	x		x
Route System	x	x	x	x
Route Number	x	x	x	x
Route Reference (Mile Post)	x	x	x	x
XY Coordinate	x	x		x
County/District/Region	x	x		
Inspector	x	x		
Department/Owner		x		
Roadway Lane Configuration		x		
Material	x	x	x	
Shape	x	x	x	
Span Length	x	x	x	
Abutment Dimensions		x		
Cover Dimensions		x		
Number of Barrels/Sequencing		x	x	
End Treatment/Type		x	x	
Bank Protection		x		
Stream Bed Material		x		

The asset inventory data for each state were imported into ESRI ArcGIS 10.1® (the GIS software used throughout this research study) to develop state-wide point-feature maps of the culvert assets. With the exception of Oregon, the XY coordinate systems were used to geo-locate the culvert assets. In Oregon, the linear-referencing system was used in conjunction with a statewide highway network layer map obtained from the ODOT GIS FTP website[3].

5.2.2 Culvert Performance and Condition Data

Condition and performance (attribute) data contains information about the functional performance and conditional deterioration of assets. Generally speaking, condition and performance data is information about an asset that changes over time due to aging and deterioration, both through normal usage wear and tear, and natural environmental interaction. Common examples in culvert inventories are: scour, embankment erosion, pipe invert condition, corrosion, channel alignment, etc.

WSDOT does not currently maintain performance and condition data records for the culverts in its inventory. Remote video-inspection recordings are available for selected culverts on a project-by-project basis (Beebe 2012), but such data is not widely available nor particularly useful to a network-level assessment.

ODOT maintains limited performance and condition data for the culverts in its inventory. These data are limited to three items pertaining to flow restriction and barrel blockage (Trevis 2013):

1. **Vegetation Obstruction Rating –** Rates the vegetation obstructing the inlet and outlet of the culvert, including (a) vegetation accumulation to cross sectional area of the culvert, (b) restriction of flow due to vegetation obstruction, and (c) larger vegetation such as large bushes or trees that are causing damage to the structure

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[3] ftp://ftp.odot.state.or.us/tdb/trandata/GIS_data/

2. **Drift Rating** - Rates debris on or near the water surface that blocks the inlet or interior of the culvert
3. **Inside Blockage Rating –** Rates blockage inside cross sectional area of the culvert, such as accumulation of silt, sand, gravel, or roadway material inside the culvert

These three items are assigned ratings on a scale from 1 (critical) to 4 (good), which correspond to the percentage blockage of the cross-sectional area of the culvert barrel at the worst section. Table 5.2 shows the ratings and associated cross-sectional area percentages used for ODOT culverts.

Table 5.2 Oregon DOT Culvert Blockage Ratings by Percentage of Cross-Sectional Area Blocked

Blockage Rating Item	Rating Value			
	1	2	3	4
Inside Blockage Rating	> 75%	30% - 75%	10% - 30%	0% - 10%
Drift Rating	> 75%	50% - 75%	25% - 50%	0% - 25%
Vegetation Obstruction Rating	> 75%	50% - 75%	25% - 50%	0% - 25%

Both MnDOT and NYSDOT maintain comparatively more extensive records of culvert performance and condition data. Generally speaking, both states maintain data that rate various structural, roadway, embankment, and channel items according to condition and performance. Complete listings of the condition and performance data are given for Minnesota in the *HydInfra Inspection Manual* (MnDOT 2013), and for New York State in the *Culvert Inventory and Inspection Manual* (NYSDOT 2006). It should be noted that the NYSDOT maintains two separate databases, depending on the size of the culvert. The large culvert database contains a complete inventory of culverts with a maximum width greater than 5 ft. The small culvert database contains a partial (although nonetheless extensive) inventory of culverts with maximum widths of 5 ft. or less.

Culvert condition and performance data items are relevant in this study to assessing a culvert’s vulnerability to climate impacts (increased precipitation) and potential for failure as a result of these impacts. This is accomplished in the Culvert Vulnerability Analysis (Section 5.4) portion of the CCAAF. Relevant culvert condition and performance rating items are discussed in greater detail in Section 5.4, and are therefore not listed here in their entirety.

5.3 Precipitation Exposure Analysis Component

The Precipitation Exposure Analysis component of the CCAAF (shown in Figure 5.3) determines the spatial extent of changes in extreme precipitation across an analysis region. This allows for differentiation of impacts among specific areas within the region. Generally, the precipitation exposure analysis involves first processing raw 24-hour precipitation projection data into annual maximum precipitation amounts for a prescribed time period (i.e., several decades). These data are then used to calculate the expected 24-hour precipitation amounts for events of a prescribed return-period (e.g., the 10-year event), and compared with historical precipitation events with the same return period to determine relative changes in precipitation amounts. Items 1 and 2 in Figure 5.3, which gather the relevant climate data, are discussed below in Section 5.3.1. Item 3, which develops projections of future climate is discussed in Section 5.3.2.1; and Item 4, which develops the historical baseline of climate conditions is discussed in Section 5.3.2. The comparison of historical and projected climate (Item 5) is discussed in Section 5.3.2.3. The final ensemble projections of precipitation exposure (Item 6) are discussed in Section 5.3.3.

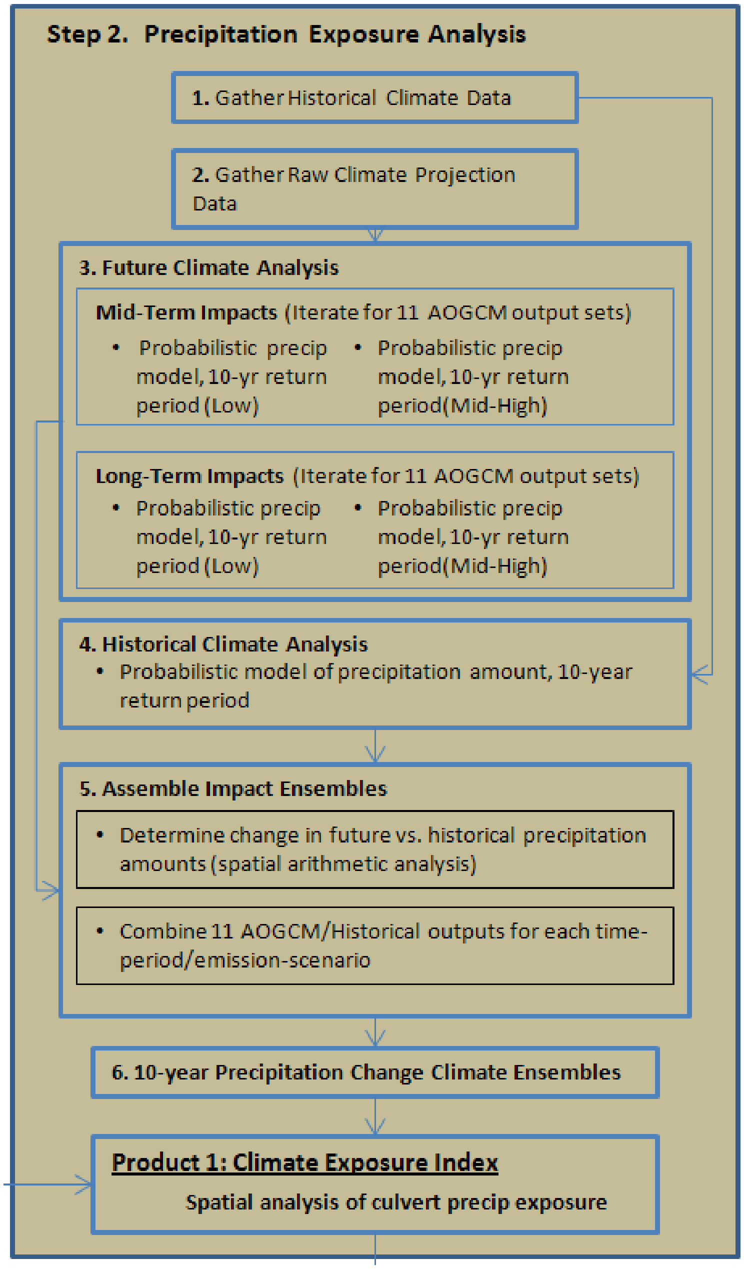


Figure 5.3 Precipitation Exposure Analysis

One unique aspect of this approach is the use of higher-frequency extreme events as indicators of areas where projected changes in extreme precipitation events may be greater. This use of indicators is due to limitations in the types of projected precipitation data (i.e., uncertainty) that are available and the need to examine particular impact timeframes.

The most commonly available precipitation projections reflect cumulative 24-hour precipitation amounts for individual spatial grid squares. In hydrology and meteorology, n-year events are commonly calculated by fitting a probability distribution (i.e., approximating various distribution parameters for a given dataset) to the maximum annual precipitation events over a given time-period [for example, see Bedient and Huber (2002)]. In projecting climate change impacts, however, there is a need to examine relatively short time-periods (e.g. 30 years) to generate projections for relevant time-frames (e.g. mid-century, end-of-century). As low-frequency extreme events (e.g. the 100-year) occur near the tail of the probability distribution, they are more sensitive to small changes in the distribution parameters than higher-frequency extreme events (e.g. the 10-year event) that occur nearer to the middle of the distribution. Thus, given the need to approximate distribution parameters from relatively short time-periods, using a higher-frequency event as an *indicator* of projected changes in extreme events should provide more consistent results than the use of lower-frequency events that are more sensitive to slight changes in estimated distribution parameters. A comparison of the calculated 10-year event and the 25-year event for Washington State is presented and discussed in Section 5.2.4 to further support this use of high-frequency extreme events as indicators.

5.3.1 Climate Data Types and Sources

Two primary types of climate data are used in the analysis: (1) projected future precipitation data, and (2) historical precipitation data. Downscaled climate change projections for the United States are publically available through the United States Geologic Survey (USGS) Geo Data Portal (GDP) (USGS 2013) as downloadable Network Common Data Format (netCDF) files. At present, users may select climate data from eight datasets containing historical climate data, statistically downscaled climate projections, and dynamically downscaled climate projections at various temporal resolutions (e.g., daily, monthly, seasonal; these vary with dataset). Within each dataset, users must define several attributes:

1. The GCM(s) used to generate the dataset's results (~11 to 13 models, varies with dataset)
2. The SRES scenario(s) for the selected climate model and dataset (available scenarios vary with dataset)
3. The analysis timeframe of interest (typically present day to 2100, ranges varies with dataset),
4. Climate impact/stressor, typically: maximum temperature (Tmax, °C), minimum temperature (Tmin, °C), and precipitation (mm/day)
5. The area of interest, defined either through a geographical user interface, or by uploading an ESRI® shapefile

The climate projection dataset used in this study consists of downscaled climate projections for the contiguous United States (CONUS) and Alaska, developed by Stoner et al. (2013) using a modified statistical asynchronous regression downscaling method (Stoner et al. 2013). This statistical downscaling method is also discussed further in the Southeast Regional Assessment Project report (Terando et al. 2010). The data's spatial resolution is 1/8° (~12km) grid squares for the CONUS, and 1/2° for Alaska; the temporal resolution is daily records for a 365-day year (i.e., leap years are treated as regular years). Climate projection data were downloaded for two SRES scenarios – A2 (high-mid) and B1 (low) – each driven by modeling runs from 11 separate GCMs. Each SRES-scenario/GCM dataset contains two data subsets, each corresponding to two 30-year analysis time periods (mid-century, 2040-2069; end-century, 2070-2099). In total, this projected climate data consists of 44 individual netCDF data files (two timeframes, two SRES scenarios, 11 GCMs) containing gridded daily precipitation data for the study area.

The second type of data used in the analysis is historical precipitation data (1950-1999), which provides a baseline for analysis of future impacts. These data, developed by Maurer et al. (2002), provide daily gridded observations of temperature (maximum, minimum, average), average daily precipitation (mm/day), and average wind-speed (m/s) at 1/8° grid spatial resolution for the contiguous United States (the spatial grid in this data aligns with the spatial grid in the projected dataset discussed above). These data are also made publically available through the USGS-GDP described above (USGS 2013) as netCDF data files. Within this dataset, users must define the area of interest and the climate impact/stressor of interest. This study used only the observed historical average daily precipitation data (mm/day) in the study area, and examined the entire historical period (1950-1999).

5.3.2 Climate Data Processing

The general approach to data processing in this study is to determine the magnitude of precipitation in each grid square for an event with return period, *n*, for two future time periods (mid-century and end-of-century), and then to determine the difference in magnitude as compared with baseline (i.e., historical) conditions. This section discusses the individual steps in data processing in greater detail.

5.3.2.1 Multi-Model Projected n-Year Event Processing

The *n*-year maximum cumulative 24-hour precipitation amount is determined by converting the daily precipitation projections at each grid square for the 30-year period into peak annual 24-hour precipitation values. The peak annual precipitation values at each grid square for the 30-year period are then fitted to the generalized extreme value (GEV) distribution to estimate the location (μ), scale (σ) and shape (ξ) parameters. The cumulative distribution function for the GEV takes the following form (Kotz and Nadarajah 2000) to evaluate the precipitation event value, x (i.e., peak annual daily precipitation in mm):

$$F(x \mid \mu, \sigma, \xi) = \exp\left[-\left[1 + \xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right]$$

The precipitation value associated with an annualized probability of occurrence corresponding to the *n*-year event is then calculated using the estimated GEV parameters. This approach is similar to that used in determining peak event-based stream flow rates in surface hydrology, which can use various statistical distributions (Bedient and Huber

2002). The GEV distribution was selected as it has been widely used in approximating expected precipitation maxima under current conditions (Bonnin et al. 2011) and also under climate change (Fowler et al. 2010; Kharin and Zwiers 2005; Millington et al. 2011; Russo et al. 2010).

The methodology to approximate the GEV distribution parameters for each grid square within the evaluation area is implemented using MathWorks MATLAB R2013a® to evaluate the netCDF files. The MATLAB script is run individually for each of the 44 individual netCDF files (each corresponds to a combination of SRES scenario, timeframe, and GCM). This evaluation produces 44 corresponding new netCDF files containing the gridded precipitation associated with the *n*-year maximum cumulative 24-hour precipitation for each SRES scenario, timeframe, and GCM combination.

The MATLAB® script estimates the GEV distribution parameters μ, σ and ξ for the 30-year period of projected peak annual precipitation at each grid square using 95% confidence intervals. In a limited number of cases (~0.018%), the distribution parameters estimated for a given grid square could not be estimated with 95% confidence given the annualized 30 year data set. In these instances, the *n*-year precipitation estimate for the given grid square, within that individual netCDF file, is eliminated from further analysis (i.e., projected grid square precipitation in some case may be based on fewer GCM outputs than the full 11 sets).

5.3.2.2 Historical n-Year Event Processing

The methodology used to project the *n*-year maximum cumulative 24-hour precipitation is also used to determine historical/baseline peak *n*-year precipitation. The

MATLAB® script is run for the gridded daily observed precipitation dataset discussed above, for the entire 50 year period (1950-1999). Thus, the key difference is that the baseline data processing fits the GEV distribution to 50 annual maximum cumulative 24-hour precipitation values, instead of 30 as in the case of projected precipitation. Additionally, the baseline data processing does not require the evaluation of multiple input files.

5.3.2.3 Comparison of Projected and Baseline Precipitation

The netCDF files containing the projected *n*-year event precipitation data are then compared to the baseline *n*-year event precipitation to determine for each grid square whether a positive change (increase), negative change (decrease), or zero change in peak *n*-year precipitation magnitude is projected to occur. This is done for each of the 44 netCDF files. This comparison is implemented in ESRI ArcGIS 10.1® by importing each of the netCDF files as single-band raster layers, and then using the ‘Raster Calculator’ tool to calculate the arithmetic difference between corresponding grid squares, which are then saved as new raster layers.

The raster layers containing the projected change in precipitation are then combined for each SRES scenario and evaluation timeframe by calculating the simple mean for each grid square across the 11 GCMs. This step is implemented in ArcGIS® using the ‘Cell Statistics’ tool to produce a set of four new raster layers, each corresponding to an SRES scenario and evaluation timeframe combination, which contain the maximum projected 24-hour precipitation values from the multi-model average.

5.3.3 Climate Data Processing Expectations and Outcomes

Roadway drainage assets, such as culverts, are typically designed to account for flow conditions associated with the 25-year to 100-year event, depending on the size of the culvert. For example, the Minnesota DOT uses a 50-year design frequency for minor culverts (≤48” diameter), and a 500-year design frequency for major culverts (>48” diameter), although the 100-year frequency is sometimes allowable (MnDOT 2000). Similarly, the Washington State DOT considers both the 25-year and 100-year storm in culvert design (WSDOT 2010). However, the use of low-frequency events (e.g., the 100-year storm) in the procedure outlined above may lead to questionable results. These low-probability/low-frequency events are located at the tail of the GEV distribution, and are therefore likely to be more sensitive to small changes in the estimated location, shape and scale parameters of the distribution. Therefore, it may be more appropriate to examine medium- to high-probability events (e.g., the 10-year storm) as these events are located nearer the center of the distribution (and are therefore less sensitive to parametric changes). As discussed at the beginning of this section, these medium-frequency events are then treated as indicators of projected changes in extreme precipitation events.

Grid squares are assigned to discrete precipitation categories associated with specific ranges of precipitation change. This step reflects an approach used widely in the risk analysis and evaluation steps of the risk-based adaptation frameworks discussed above. That is, general climate risks are typically assigned qualitative (e.g., low/medium/high) or semi-quantitative (e.g., 1 to 5) risk scores, as opposed to absolute quantitative values, to facilitate comparison. Assigning grid squares to discrete precipitation ranges also regionalizes the precipitation changes within a study area.

In this study, the 10-year precipitation event was evaluated as an indicator of projected regional changes in major precipitation events (this selection is discussed in the next section). Changes in daily precipitation events in Washington State (which showed the widest range in precipitation changes of the four case-study states) for the 10-year event typically ranged between -41mm (i.e., drier) and 110mm, depending on SRES scenario and timeframe, although the majority of grid squares exhibited precipitation changes between 0mm - 30mm. Thus, the following five ranges were selected for this study: ≤ 0mm; 0 – 10mm; 10 – 20mm; 20 – 30mm; and ≥ 30mm. These ranges are selected for illustrative purposes only; further research is required to determine ranges that would provide more meaningful insight in impact studies.

To assign Precipitation Exposure Index values, the culvert inventory datasets (which contains geospatial location data) for each of the case-study DOTs were overlaid with the range-assigned 10-year precipitation output data, and spatially joined. Four Precipitation Exposure Index values are assigned to each culvert (according to Table 5.3): one for each combination of time-frame and emission scenario.

Table 5.3 Precipitation Exposure Indexes and Corresponding Precipitation Ranges

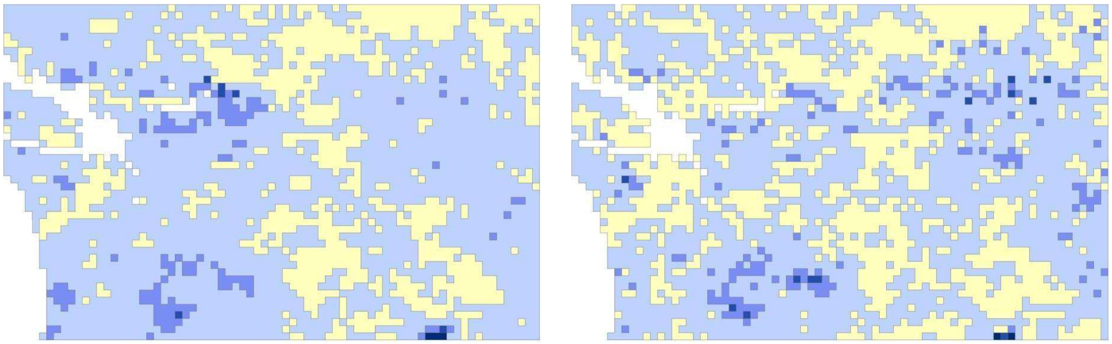
Change in 10-year Event Precipitation	Precipitation Exposure Index
≤ 0mm	0
0 – 10mm	1
10 – 20mm	2
20 – 30mm	3
≥ 30mm	4

5.3.4 Comparison of Event Frequency Calculation Outcomes

In the previous discussion, the 10-year event has been used as the primary indicator of areas where extreme precipitation events may be more likely to occur in the future. As discussed, the 10-year event is used instead of lower-frequency/higher-intensity events (e.g. the 25-year, or 50-year event) as it is less sensitive to slight changes in the distribution parameters (location, μ; scale, σ; and shape, ξ) estimated using the 30-year time period datasets, and should therefore yield more consistent results.

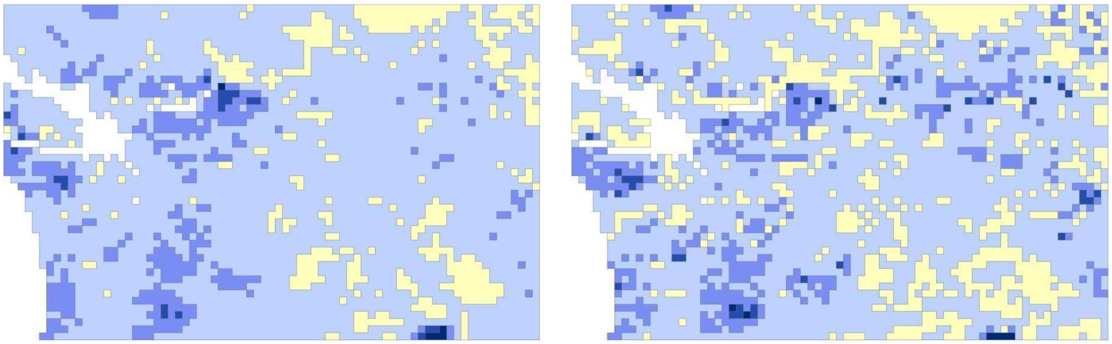
To test this, however, the 10-year and 25-year precipitation events (both are return periods commonly used in engineering design) were calculated using the procedure described above for Washington State, and compared. Figure 5.4 shows the 10-year (left) and 25-year (right) precipitation events for both mid-century and end-of-century timeframes, for both the B1 (low) and A2 (mid-high) emission scenarios. Although some similarities are evident between corresponding projections of the 10- and 25-year precipitation events, note that the changes in precipitation for the 10-year event form somewhat more distinct regions than do the projections for the 25-year event.

A likely explanation for this has to do with the length of the data record used in the analysis (30-year periods) and the precipitation event return period. The 10-year event, by definition, has an annualized probability of occurrence of 0.1 (i.e., once every 10 years). It can therefore reasonably be expected to occur multiple times within the 30-year record period. Conversely, the 25-year event, with an annualized probability of occurrence of 0.04 (i.e., once every 25 years) may not occur within the 30-year record period, or may occur only once. The greater uncertainty in the prediction of the 25-year event from the 30-year record (as opposed to the 10-year event from the 25-year period)



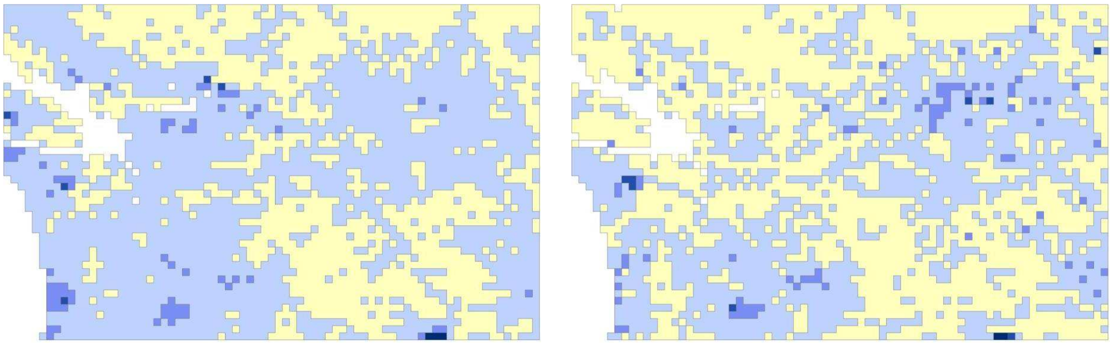
B1 Scenario, Mid-Century, 10-Year Event

B1 Scenario, Mid-Century, 25-Year Event



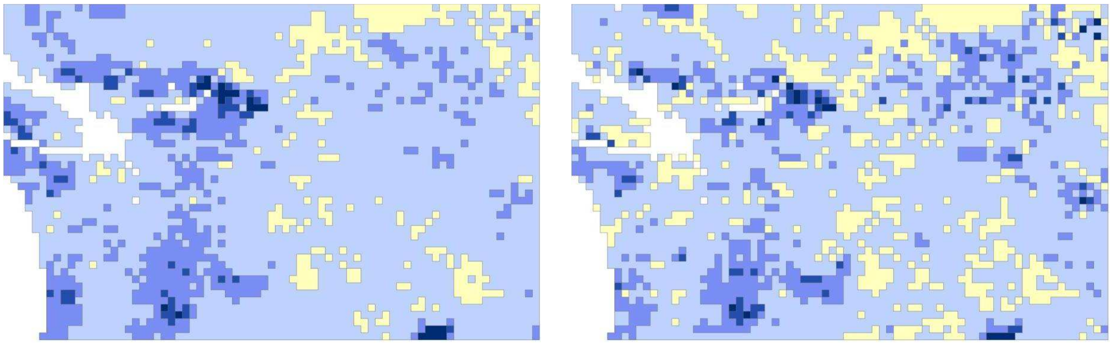
B1 Scenario, End-Century, 10-Year Event

B1 Scenario, End-Century, 25-Year Event



A2 Scenario, Mid-Century, 10-Year Event

A2 Scenario, Mid-Century, 25-Year Event



A2 Scenario, End-Century, 10-Year Event

A2 Scenario, End-Century, 25-Year Event

Figure 5.4 Comparison of Projected 10-year and 25-year Precipitation Events results in greater uncertainty, and therefore variability, in projected precipitation amounts. In other words, the 10-year event has the benefit of being less sensitive to changes in the parameters that define the probability distribution, and also contains less model uncertainty given the relatively short 30-year projected precipitation record used to estimate distribution parameters. Evaluating the 10-year event may thus yield less variability in approximating real-world conditions given the shorter projected precipitation record, and therefore increase regional definition.

One apparent solution to the greater variability and uncertainty in lower-frequency events using this method would be to extend the projected climate record period. Admittedly, the use of a relatively short, 30-year record of projected precipitation limits accuracy in fitting the GEV curve to approximate real-world conditions. A longer record period, 100 years for example, would enable less uncertainty in projecting the 25-year event (which reasonably could be expected to occur multiple times in a 100 year period). The challenge with this solution is that it requires stationary mean climate conditions, but under climate change, mean climate is non-stationary. Thus, to evaluate relevant future impact timeframes (e.g., mid-century, end-of-century), record periods must be necessarily truncated into representative time period for each impact horizon (e.g., a 30-year period from 2035 to 2065 to evaluate 2050 impacts). With this method, a simplifying assumption must then be that mean climate is stationary within the evaluation time-period, which, although likely untrue, is nonetheless an unavoidable statistical assumption.

5.4 Culvert Vulnerability Analysis

The Culvert Vulnerability Analysis component of the CCAAF (Figure 5.5) examines the culvert asset data (Section 5.2) in conjunction with the precipitation exposure analysis output (Section 5.3) to determine the vulnerability or failure potential of culverts that are exposed to projected increases in extreme precipitation. Vulnerability, as defined by the (IPCC 2007) "is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity." In this analysis, vulnerability is primarily assessed excluding an assessment of adaptive capacity, which would likely require project-level assessments of culvert design adequacy and a network-analysis of available detour routes.

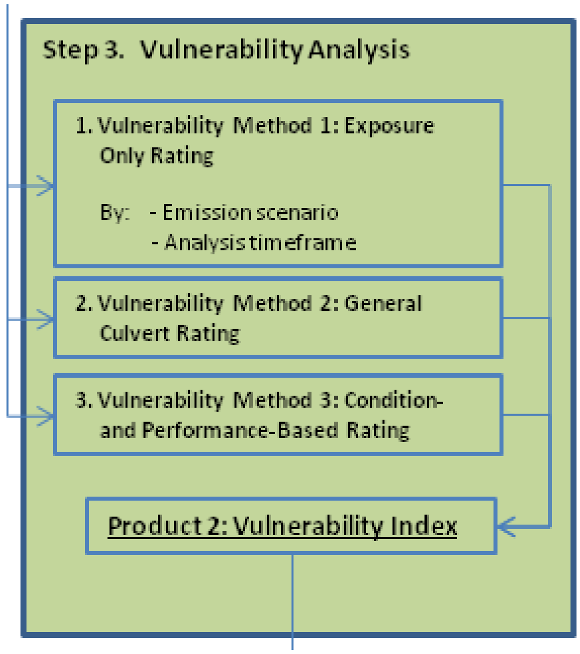


Figure 5.5 Culvert Vulnerability Analysis

The Culvert Vulnerability Analysis builds upon the discussion of culvert inspection rating systems (Section 4.2) and culvert failure (Section 4.4) do determine a relative measure of culvert vulnerability, the Vulnerability Index. The culvert vulnerability analyses in this study employ three separate potential methods of determining vulnerability, each with increasing levels of detail. This allows for a relative comparison of the apparent gains in outcome from pursuing various levels of vulnerability analysis and data collection (these conclusions are discussed in Chapter 7).

It is recognized that the three culvert vulnerability assessment methods developed in this section to define the Vulnerability Index are simplified measures of vulnerability. They build upon the discussion of culvert failure modes and mechanisms discussed earlier in Section 4.4 (particularly the general classification of indicators as either embankment-related indicators, or blockage-related indicators) to develop a broad measures of vulnerability as relevant to network-level assessments. Although project-level investigations of specific sites may provide deeper insight into individual culvert vulnerabilities, the network-level methods developed below may be used to motivate such project-level investigations at specific sites.

5.4.1 Method 1 – Exposure Only Rating

The first method, "Method 1 – Exposure Only Rating," does not explicitly assign culvert a Vulnerability Index rating. Instead, it relies solely on the Precipitation Exposure Index values (Section 5.3) assigned to individual culverts to provide location-specific indications of climate impact. This is discussed in greater detail in the context of overall culvert prioritization in Section 5.6. The exclusion of a relative measure of vulnerability in favor of sole reliance on exposure is necessitated in applications where culvert asset data is limited to inventory data (i.e., no condition or functional performance data are collected). Among the case-study DOTs, WSDOT is an example of an agency for which this method is necessary due to inventory data only. However, the Method 1 approach will be applied to all four case-study DOTs for comparison purposes.

5.4.2 Method 2 – Overall Culvert Rating

The second method to determine culvert vulnerability to increased flows, "Method 2 – Overall Culvert Rating," bases culvert Vulnerability Index ratings on the overall condition of a culvert, as assigned during field inspection. Of the four case-study DOTs, MnDOT and NYSDOT assign some form or overall condition/performance rating; Minnesota records an "Overall Condition" rating and New York State records a "General Recommendation" rating for all culverts in their inventories. In light of the discussion of data collection completeness in Section 5.2, it should be noted that General or Overall ratings are among the few items for which values are consistently assigned in the MnDOT and NYSDOT databases.

Washington State excludes condition and performance criteria from its culvert inventory, and Oregon examines some performance criteria, but does not assign an overall condition rating. Therefore, Method 2 is only applied to MnDOT's and NYSDOT's culvert inventories, as discussed below.

5.4.2.1 NYSDOT and MnDOT Overall Culvert Condition Ratings

The NYSDOT (2006) notes that the inspection item "General Recommendation For Culvert" is an "assessment of the overall condition of the culvert...[giving] maximum weight to items of most importance such as span barrel, abutment & pier, scour, etc." It also notes that “the general recommendation should not be lower than the lowest rating given to any individual item,” and that the general recommendation never be specified as “not applicable,” or “unknown.” (NYSDOT 2006) The NYSDOT assigns General Recommendation values using a scale from 1 to 7 based upon the narrative descriptions shown in Table 5.4.

Table 5.4 NYSDOT General Recommendation For Culvert Rating System

Adapted from **(NYSDOT 2006)**

Rating Value	Rating Value Description
7	Culvert is in like-new condition with no deterioration. No work needed other than routine maintenance.
6	Only minor deterioration is present. May require very minor repairs to pavement, guide rail, shoulders, etc.
5	Span barrel and abutment & pier are in good condition. Load capacity is not reduced. Headwalls and wingwalls may require minor repairs. May require removal of light vegetation growth around culvert openings. Scour may have exposed, but not undermined, footings.
4	Span barrel and/or abutment & pier have moderate deterioration but do not yet need extensive reconditioning. Load capacity is not substantially reduced. Headwalls and wingwalls may require significant repair work. Pavement may require replacement with the addition of backfill material to correct minor roadway settlement problems yet the structure shows no signs of deformation. There may be some minor substructure undermining. Minor channel work may be required.
3	Span barrel and/or abutment & pier have considerable deterioration. Steel members have considerable section loss. Slight deformation or settlement of the structure may exist. Concrete members are spalled with rebar exposure over large portions of their surface area. The culvert may no longer be able to support original design loads. Load posting may be needed. Extensive footing undermining may have occurred. Extensive work on the culvert is required. Replacement could be considered a better long term option.
2	Span barrel and/or abutment & pier are extensively deteriorated. Replacement of the structure may be necessary due to serious deformation and/or settlement. Short-term, remedial action such as pavement replacement or installation of additional backfill material may be required. The culvert can no longer safely carry original design loads. The culvert may still be open to traffic but with a posted load restriction. Temporary shoring or bracing may be necessary. Replacement of headwalls and/or wingwalls may be required. Water flow may be greatly restricted by constriction or obstruction of the culvert opening. Scour and undermining may be extensive enough to threaten the stability of the culvert.
1	Deterioration is so extensive that partial or total collapse is imminent. There is little or no live load capacity and the structure may be closed to traffic. For the culvert to remain open to traffic, substantially reduced load posting and temporary shoring are necessary. Structure may be in danger of failing due to extensive undermining.

The MnDOT assigns Overall Condition Ratings based upon a five point scale from 0 to 4 to describe the structural integrity of the culvert system (MnDOT Undated). MnDOT rates most condition and performance items using a simple Y/N (i.e., yes/no) notation, which it terms an item “inspection flag;” the Overall Condition rating is based upon several of these flags. For a complete list of inspection flags affecting the Overall Condition rating, see (MnDOT Undated). It is important to note that the General Condition rating does not consider any inspection flags associated with barrel blockage, or the need for cleaning (e.g., plugging, sediment, silt, etc.) (MnDOT 2013; MnDOT Undated). Instead, the MnDOT Overall Condition Ratings are associated repair needs, as specified in Table 5.5.

Table 5.5 MnDOT Overall Condition Rating System

Adapted from **(MnDOT Undated)**

Rating Value	Rating Value Description	Repair Necessary
1	Excellent - Like new condition	No - Pipe like new, most inspection flags are "N"
2	Fair - Some wear, but structurally sound	No - Pipe may be worn, but functionally okay; minor condition problems
3	Poor - deteriorated, consider for repair or replacement	Yes - Repairs needed, but road won't fail
4	Very poor - serious deterioration	Yes - Repairs needed very soon, roadway may be in danger from loss of fill or from piper deterioration
0	Not able to rate, not visible	(blank) - Pipe is submerged, buried, or out of sight

5.4.2.2 Method 2 - Overall Condition Rating Vulnerability Index Development

To determine Vulnerability Index values using Method 2, the overall condition rating values used by NYSDOT and MnDOT (Table 5.4 and Table 5.5, respectively) are translated into low/medium/high vulnerability values. A Vulnerability Index value of 3 indicates high vulnerability; a Vulnerability Index value of 2 indicates medium vulnerability; a Vulnerability Index value of 1 indicates low vulnerability.

The MnDOT assigns some culverts a value of 0 due to inabilities to complete inspection (e.g., pipe is submerged), effectively not rating overall condition. For these culverts, no Vulnerability Index is assigned, and their database entries are flagged. Additionally, although the NYSDOT states that culvert general recommendations must never be assigned values corresponding to "unknown," or "not applicable" (9 and 8, respectively), in practice, some culvert general recommendations are assigned these values. Similarly, these culverts are also assigned no Vulnerability Index rating, and their database entries are flagged.

The assignment of overall condition ratings to a low, medium, or high vulnerability classification is based upon the discussion of blockage-based indicators and embankment-based indicators of failure in Section 4.4.4, as well as the narrative descriptions of overall condition provided by the DOTs, and supplemental discussions in the respective inspection manuals (MnDOT 2013; MnDOT Undated; NYSDOT 2006). The assignment of Vulnerability Index values to culverts to corresponding overall condition ratings are shown in Tables 5.6.

The Vulnerability Index values corresponding to NYSDOT General Recommendation values are further reinforced by the inspection frequency requirements given in the NYSDOT *Culvert Inventory and Inspection Manual* that group various general recommendation ratings into need-based inspection frequencies . General Recommendation ratings of 1 and 2 (poor) require annual inspections; General

Recommendation ratings of 3 or 4 (fair) require biennial inspections; and General Recommendation ratings of 5, 6, or 6 require quadrennial inspections.

Table 5.6 MnDOT and NYSDOT Rating Scales and Corresponding Vulnerability Indices

Vulnerability Index	Vulnerability Descriptor	MnDOT Overall Condition Rating Values	NYSDOT General Recommendation Rating Values
3	High	4	1, 2
2	Medium	3	3, 4
1	Low	2, 1	5, 6, 7
0 (Flagged)	Unable To Rate	0	8, 9, or 0

5.4.3 Measure 3 – Condition and Performance Criteria-Based Rating

The final measure of culvert vulnerability to increased flow, "Measure 3 - Condition and Performance Criteria-Based Rating," assigns Vulnerability Index values to culverts based upon the individual culvert condition and functional performance data provided by the case-study DOTs. The three DOTs that maintain some record of culvert condition and performance (MnDOT, NYSDOT, and ODOT) collect similar types of data, with some common data items. This allows for a common foundation in developing a performance-based Vulnerability Index for each state. However, sufficient differences in specific items, and the scales used to rate them, require some DOT-specific variation in developing a condition- and functional performance-based Vulnerability Index. The state-specific scales are described in the following sections.

The common foundation of the state-specific performance-based culvert Vulnerability Index measures is the discussion of culvert failure modes and indicators of vulnerability or failure potential from Section 4.4. The categorization of potential failure criteria as either embankment-based or blockage-based (see Table 4.16) is an important distinction and suggests that criteria from both categories (when available) should be included in the measure.

The network-level focus of the culvert vulnerability analysis, in conjunction with the somewhat general nature of the culvert condition and functional performance data collected by state DOTs, places several limitations on the development of a performance-based measure. First, it is difficult to assign relative weights to any of the indicators of vulnerability or failure potential. Weighting of such items would require more in-depth, site-specific knowledge of conditions, and also the compounding effects of multiple conditions. In this research study, all criteria are weighted equally, with the understanding that weighting should be addressed in future research.

A second limitation is data completeness within each state DOT's inspection database. In many cases, certain criteria are more consistently assessed and recorded than others. While some of the criteria contained in these databases may provide more appropriate measures of vulnerability or failure potential, many must be excluded from the analysis due to poor data completeness of those records in the inspection databases.

5.4.3.1 Performance-Based Vulnerability Index: Minnesota DOT Culvert Data

The MnDOT culvert condition and performance criteria were first reviewed to identify items that provide both explicit and implicit indication of culvert embankment and blockage conditions, consistent with the discussion of explicit versus implicit indicators in Section 4.4.4. These items are shown in Table 5.7. The explicit indicators were then reviewed in the database to identify those that were most consistently recorded, and thus better candidates for use in determining Vulnerability Index ratings. Items 1, 2, 4, 5 and 6 (bold text in Table 5.7) were selected, which provide two blockage-related indicators, and three embankment-related indicators.

Table 5.7 Selected MnDOT Culvert Condition and Performance Criteria

Rating Item	Rating Category	Rating Type	Rating Scale
1. Sediment Percentage	**Blockage**	**Primary**	**Percentage**
2. Plugged	**Blockage**	**Primary**	**Yes / No**
3. Deformed	Blockage	Secondary	Yes / No
4. Erosion	**Embankment**	**Primary**	**Yes / No**
5. Piping	**Embankment**	**Primary**	**Yes / No**
6. Inslope Cavity	**Embankment**	**Primary**	**Yes / No**
7. Void In Roadway	Embankment	Primary	Yes / No
8. Infiltration	Embankment	Secondary	Yes / No
9. Barrel Misalignment	Embankment	Secondary	Yes / No
10.Joint Separation	Embankment	Secondary	Yes / No
11.Holes	Embankment	Secondary	Yes / No

MnDOT rates sediment blockage percentage numerically as a percentage of the cross-sectional area of the culvert. For all other condition and performance criteria, MnDOT uses a binary (Yes / No) scale to indicate whether the condition exists or not, but does not provide any indication of the extent of the condition. This prevents incorporating any assessment of condition severity into a performance-based Vulnerability Index for MnDOT culverts. Also, as stated earlier, it is beyond the scope of this study to identify any interrelationships among the criteria as that would likely require a more detailed, project-level assessment of site conditions.

The "Sediment Percentage" ratings were converted to a 1 (low) to 3 (high) rating scale based upon guidance from the *Hydraulic Design of Highway Culverts* manual

(Schall et al. 2012) and the *FLH Culvert Assessment and Decision-Making Procedures Manual* (Hunt et al. 2010). These documents suggest that debris and vegetation blockages should be noted if they "reduce the opening area by roughly 33% or more." (Hunt et al. 2010) Further, sedimentation blockages less than 1/3 of the rise of the culvert will likely clear out "as a self-cleaning mechanism," and blockages "greater than or equal to 1/3 but less than or equal to 3/4 of the rise of the barrel" should be noted for maintenance and cleaning, as "self cleaning may not occur." (Hunt et al. 2010) Therefore, culverts with a Sediment Percentage less than 33% were rated 1 (low); those with Sediment Percentages between 33% and 75% were rated 2 (medium); those with Sediment Percentages greater than or equal to 75% were rated 3 (high).

The four binary-rated items were assigned values of 1 (low) to correspond with a "No" rating, and a value of 3 (high) to correspond with a "Yes" rating. As no additional information is provided, ratings of 2 (medium) cannot be assigned, therefore the restriction to only high and low values is a necessary simplifying assumption. However, the use of multiple criteria for each both rating categories may enable some assessment of intermediate conditions. For example, culverts where Piping is rated "Yes," but Erosion and Inslope Cavity are both rated "No," may suggest a condition where embankment deterioration is moderate, but not high.

One additional value, termed here as the "Certainty Rating," is calculated to provide some insight into the relative reliability of the Vulnerability Index given the often incomplete nature of condition and performance criteria recording. The Certainty Rating simply reflects the number of criteria for each culvert (from the five criteria used in the vulnerability assessment) for which there is a usable database entry, thus excluding blank or erroneous entries. For example, a culvert for which all five records have a value recorded would receive a Certainty Rating of 5 (indicating higher reliability). Conversely, a culvert for which only Erosion and Piping values are present in the database would receive a Certainty Rating of 2.

The overall culvert Vulnerability Index is then calculated by summing the five individual criteria ratings and then normalizing the result to a value from 1 (low) to 3 (high), and assigning that value to a Vulnerability Index rating using the scale shown in Table 5.8.

Table 5.8 MnDOT Culvert Vulnerability Index Scale

Low	**Medium**	**High**
< 1.6	**1.6 – 2.3**	**≤ 2.3**

5.4.3.2 Performance-Based Vulnerability Index: New York State DOT Culvert Data

The NYSDOT condition and performance criteria for both large culvert and small culvert datasets were first reviewed to identify items that provide both explicit and implicit indication of culvert embankment and blockage conditions. These items are shown in Table 5.9. The explicit indicators were then reviewed to identify those that were commonly recoded in both large culvert and small culvert databases, and also to identify those that were most consistently recorded within the two individual databases. One blockage-related and one embankment-related criterion were selected as common to both datasets, and also as more consistently collected within each dataset: items 1, 3, 8, and 9 (bold in Table 5.9).

Table 5.9 Selected NYSDOT Culvert Condition and Performance Criteria

Rating Item	Rating Category	Rating Type	Rating Scale
Small Culverts			
1. Channel Opening	**Blockage**	**Primary**	**1 to 7**
2. Channel Silt/Debris/ Vegetation	Blockage	Primary	1 to 7
3. Channel Scour	**Embankment**	**Primary**	**1 to 7**
4. Roadway Settlement	Embankment	Primary	1 to 7
5. Roadway Embankment	Embankment	Primary	1 to 7
6. Structural Span	Embankment	Secondary	1 to 7
7. Channel Alignment	Embankment	Secondary	1 to 7
Large Culverts			
8. Channel Waterway Opening	**Blockage**	**Primary**	**1 to 7**
9. Channel Erosion and Scour	**Embankment**	**Primary**	**1 to 7**
10. Approach Settlement	Embankment	Primary	1 to 7
11. Approach Embankment	Embankment	Primary	1 to 7
12. Channel Stream Alignment	Embankment	Secondary	1 to 7

NYSDOT rates all culvert condition and performance items using a scale from 1 (poor/potentially hazardous) to 7 (good/as-new condition); values of 8 (not applicable) and 9 (unable to rate) are also available. The 1 to 7 ratings for the channel opening and scour condition criteria identified in Table 5.9 are assigned to a 1 (low) to 3 (high) rating scale using the same system discussed in Section 5.4.2.2 for overall condition ratings (see also Table 5.6). As stated before, the conversion from a 1 to 7 scale to a 1 to 3 scale is based upon the inspection frequency requirements given in the NYSDOT *Culvert Inventory and Inspection Manual* that group rating values into need-based inspection frequencies that likely reflect the urgency of conditions; ratings of 1 and 2 (poor) require annual inspections; ratings of 3 or 4 (fair) require biennial inspections; ratings of 5, 6, or 7 (good) require quadrennial inspection.

As with the MnDOT condition and performance data, an additional value, the "Certainty Rating," is calculated to provide insight into the relatively reliability of the Vulnerability Index given inconsistent recording of condition and performance criteria. In the case of the NYSDOT data, the Certainty Rating reflects the number of criteria for each culvert, from the two used, for which there is a useable database entry. This excludes entries that are blank or erroneous (i.e., outside the rating range), as well as values equal to 8 (not applicable), or 9 (unable to rate).

The overall culvert Vulnerability Index is then calculated by summing the two individual criteria rating values and then normalizing the result to a value from 1 (low) to 3 (high), and assigning that value to a Vulnerability Index rating using the scale shown in Table 5.8.

5.4.3.3 Performance-Based Vulnerability Index: Oregon DOT Culvert Data

ODOT culvert databases contain three types of functional performance data, all of which are blockage-related indicators of vulnerability or failure potential: (1) the Inside Blockage Rating, (2) the Drift Rating, and (3) the Vegetation Obstruction Rating. All three ratings are assigned values from 1 to 4, which correspond to percentages of the culvert's cross-sectional area blocked (Table 5.2). These blockage-based values were assigned Vulnerability Index values of 3 (high), 2 (medium), and 1 (low) by associating them with cross-sectional percentage obstruction values using the ranges shown in Table 5.10. Note that the percentage ranges associated with Vulnerability Indices of 1 and 2 differ among the three criteria; this is due to ODOT's differing definitions of percentage ranges for each item, as given above in Table 5.2.

Table 5.10 Oregon DOT Culvert Blockage Rating Range Assignment to Vulnerability Index Values

Blockage Rating Item	Corresponding Rating Value		
	1	2	3
Inside Blockage Rating	0% - 30%	30% - 75%	> 75%
Drift Rating	0% - 25%	25% - 75%	> 75%
Vegetation Obstruction Rating	0% - 25%	25% - 75%	> 75%

The Vulnerability Index ratings shown in Table 5.10 are based upon guidance from the *Hydraulic Design of Highway Culverts* manual (Schall et al. 2012) and the *FLH Culvert Assessment and Decision-Making Procedures Manual* (Hunt et al. 2010), explained earlier in Section 5.4.3.1 in reference to the MnDOT sediment percentage performance criterion.

The Method 3-based Vulnerability Index values are assigned to ODOT culverts by considering each of the individual percentage-based blockage rating values (ranging from 1 to 3) given in Table 5.10. Culverts are assigned a Vulnerability Index corresponding with the worst (highest) blockage rating value from the three items listed in Table 5.10. For example, a culvert with an inside blockage rating of 3, but drift and vegetation obstruction ratings both equal to 1 is assigned a Vulnerability Index of 3.

The decision to assign culvert Vulnerability Indices according to the worst of the three criteria ratings is based upon the judgment that any cross-sectional constriction of flow, independent of the obstructing material-type, will reduce the culvert's flow capacity. Any reduction in flow capacity could lead to overtopping, increased hydrostatic pressure on the embankment, and increased erosion. Absent a more in-depth, project-level inspection to better understand the nature of the blockages, how they may or may not compound one another, and other aspects of the culvert condition and functional performance, the worst blockage rating approach must suffice.

5.5 Culvert Criticality Assessment

The previous steps in the CCAAF have sought to determine plausible future scenarios for climate impact exposure, and the relative vulnerability of culvert assets to those impacts. The culvert asset criticality assessment component of the CCAAF (Figure 5.6), builds upon these earlier analyses by seeking to determine the relative criticality or importance of culvert assets based upon several selected criteria. This is analogous to the consequence component of the general definition of risk (Section 3.3), or the loss component of the catastrophe model (Figure 3.3).

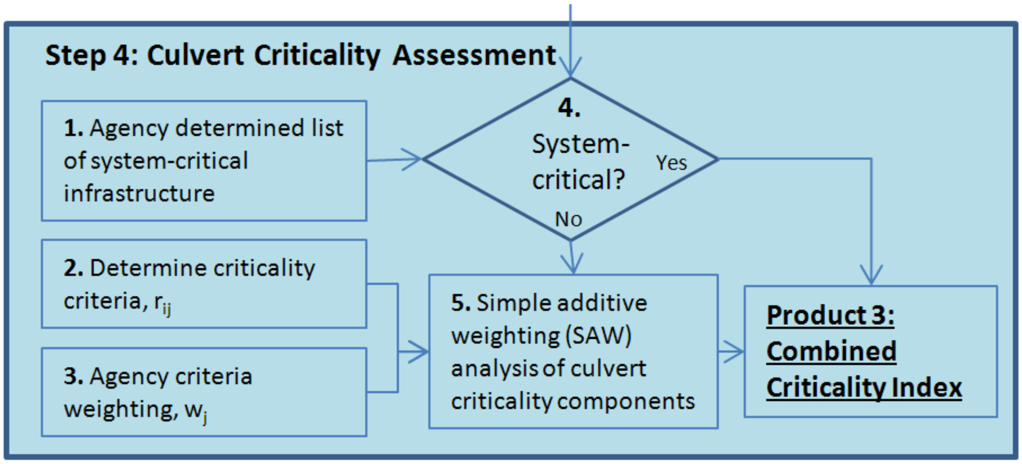


Figure 5.6 Culvert Criticality Assessment Section of CCAFF

For this discussion, the criticality assessment begins with Item 2 (Sections 5.5.1 to 5.5.3) to determine relevant criteria of asset criticality. Criteria weights are then determined in Item 3, which applies locally-determined weighting factors to the criticality criteria determined in Item 2, enabling the assessment to recognize unique local interests and values (Section 5.5.4). These criticality criteria and weighting factors are then combined in Item 5 (Section 5.5.4) to produce a Combined Criticality Index for each asset. Items 1 and 4 in Figure 5.6 provide agencies with a means to further incorporate local knowledge into the assessment process and are discussed in Section 5.5.5.

The determination of asset criticality can be a complex endeavor, which is often dependent upon varying goals and the interests of multiple stakeholders, in both public and private sectors (May and Koski 2013). In the past decade, much of the infrastructure asset criticality research in the transportation sector has focused on security and terroristic threat risks [see, AASHTO (2002); Department of Homeland Security (2009)], although evaluation of asset criticality in response to other impacts (e.g., climate change impacts, earthquakes, tsunamis, other natural disasters) has also progressed [for example, Antelman et al. (2008); Barami (2013); ICF International and Parsons-Brinkerhoff (2011); Khaled et al. (2013); Lu et al. (2013)].

This study recognizes the complexity associated with identifying critical assets, and therefore seeks to introduce a simplified criticality assessment component. The simplified assessment is intended to demonstrate how such an analysis can be integrated into climate change risk assessments, with the understanding that future research is required to broaden the scope of any criticality assessments.

The criticality assessment component in the CCAAF uses as a guide several outcomes from the FHWA-sponsored *Gulf Coast Study, Phase 2* (ICF International and Parsons-Brinkerhoff 2011), hereafter referred to simply as “*Gulf Coast 2.*” *Gulf Coast 2* assessed urban transportation infrastructure criticality in Mobile, AL in the context of climate change impacts and adaptation. Specifically, it identified 10 criticality criteria divided among three criticality assessment categories relevant to highway network assets, shown in Table 5.11.

Table 5.11 Gulf Coast Study, Phase 2 Asset Criticality Criteria

Criticality Category	Criticality Criteria
Socioeconomic	Locally Identified Priority Corridors
	Functions as Community Connection
	System Redundancy
	Serves Area Economic Centers
Operational	Functional Classification
	Usage
	Intermodal Connectivity
Health & Safety	Identified Evacuation Route
	Component of the Disaster Relief and Recovery Plan
	Component of the National Defense System
	Provides Access to Health Facilities

A key outcome of *Gulf Coast 2* is the identification of three "Criticality Categories," shown in Table 5.11. These criticality categories form the basis of the Asset Criticality Assessment in the CCAAF. As the CCAAF seeks to implement a simplified criticality assessment, three criteria are selected for use in critical asset assessment; one criticality criterion is selected from each of the three criticality categories, although socioeconomic criticality is re-characterized as economic criticality. These three criticality criteria, their context, and their assessment are described in the sections below.

5.5.1 Economic Criticality

The four socioeconomic criticality criteria used for highways in *Gulf Coast 2* require an in-depth, ad-hoc analysis of local and regional factors in relation to infrastructure systems. In that study, such analyses were frequently conducted through expert panel discussions. For example, locally-identified priority corridors were identified in a discussion between the study team and the local MPO's Climate Change Working Group (CCWG). However, in its general discussion of socioeconomic criticality factors, *Gulf Coast 2* discusses an additional criterion that is applicable to highway networks: whether or not infrastructure is a component of the national/international commerce system. Consistent with this criterion, this dissertation research uses roadway freight movement (part of the national and regional commerce systems) as a simplified measure of economic criticality. The social aspect of socioeconomic criticality, as the *Gulf Coast 2* demonstrated, is perhaps best addressed through expert panel discussions. For this reason, the social aspect of socioeconomic criticality is omitted from this analysis and the evaluation of socioeconomic criticality in these case studies is more accurately an evaluation of *economic* criticality only.

Freight transportation is a significant contributor to economic productivity (Jones 2007). Highway truck freight is the "dominant domestic freight mode" in the United States in terms of both volume and value (Dobbins et al. 2007); 64 percent of domestic commodities are carried by truck (Ross et al. 2009). Disruption of highways due to culvert failure, or other impacts, could therefore have serious adverse implications for regional economic activity. In Washington State, for example, the disruption of Interstate 5 in 2007 due to flooding impacts caused an estimated $500-$850 in additional costs per truckload due to detouring (Ivanov et al. 2008). Regionally, the three-day interstate closure caused an estimated $24.87 million in direct economic impacts, with an additional $22.21 million in indirect and induced impacts (Ivanov et al. 2008). A three-day closure of a major interstate may constitute an extreme case of economic disruption, but it serves to underscore the significant regional economic impacts associated with disrupted freight movement.

5.5.1.1 Freight Analysis Framework and Highway Performance Monitoring System

To determine freight movement on the case-study roadways, roadway network and truck volume data from the FHWA Freight Analysis Framework (FAF) were used, in addition to truck volume data from the FHWA Highway Performance Monitoring System (HPMS) contained within the FAF datasets.

The FAF consists primarily of two datasets: the FAF Network dataset, and the FAF Output dataset. The FAF Network dataset is a national roadway network model maintained by the FHWA Office of Freight Management and Operations. It contains 447,808 miles of primary and secondary roadways in the United States (Sprung 2011). The FAF Output assignment dataset is a flow model that "estimates commodity movements by truck and weight for truck-only, long distance moves...based on geographic distributions of economic activity." (FHWA 2013) However, Meyer and Miller (2001) note that freight travel is predominantly regional or local (95% of truck travel is distances less than 200 miles), and therefore local and regional trucking must also be considered; hence, HPMS data is also considered.

In addition to the FAF model outputs, the FAF dataset also contains truck volume estimates for all links in the FAF network that are "estimated using a combination of HPMS 2008 database, State truck percentage, and functional class specific defaults," (FHWA 2013) and not limited to long-distance trucking. The HPMS is maintained by the FHWA in compliance with Federal law (23 U.S.C. 502(h)) to provide a “conditions and performance estimate of the future highway investment needs of the nation...” (Office of Highway Policy Information 2013). One aspect of this is maintaining a database of truck volumes for the full extent of the National Highway System (NHS). However, the HPMS truck volume minimum reporting requires only sample or summary volumes for non-NHS roadways and roadways with lower functional classifications (Office of Highway Policy Information 2013). For this reason, the FAF dataset supplements HPMS truck volume data with the State truck percentage and functional classification specific defaults to provide a measurement-based, complete-network estimate of roadway truck volumes.

5.5.1.2 FAF Data, HPMS Data, and GIS Processing

Data from the most recent version of the Freight Analysis Framework, FAF 3.1, is published online by the FHWA Office of Operations, Freight Management and Operations Division (FHWA 2013). The data contains an ESRI ArcGIS shapefile of the FAF roadway network for the contiguous United States, Alaska, and Hawaii. The roadway network is based upon the National Highway System Version 2009.11 (delivered to the FHWA in October 2010). This dataset is commonly referred to as the FAF Network Data.

The FHWA also publishes a dBase data file containing various freight volume data for each link in the FAF Network dataset. This dataset is commonly referred to as the FAF Output Data, or the FAF Assignment Data. Relevant to this study, the FAF Output Dataset contains the “AADTT07” data field, which is the “year 2007 Truck

Volume estimated using a combination of HPMS 2008 database, State truck percentage, and functional class specific defaults," (FHWA 2013) as assigned to each FAF network link (volume/day/route).

The FAF Network and Output datasets were first joined in ArcGIS and then clipped and exported into four separate shapefiles, one for each state in the case study. For each state, the FAF Network layer was overlaid with the state's culvert layer, and the culverts were associated with the FAF Network layer roadway links. A visual inspection of each state's data revealed that not all culverts are located on FAF Network links. Non-FAF Network culverts were first identified by cross-referencing roadway route numbers in the FAF Network with roadway route numbers in the culvert layers. A visual inspection and judgment of the culvert and FAF Network layers then identified additional culverts that were not associated with the FAF Network (e.g., culverts located ~1000 ft. from area roadway links). This visual inspection was only necessary for the MnDOT and NYSDOT culvert datasets, which are much more extensive than the ODOT and WSDOT culvert datasets. Roadway culverts were then associated with individual links in the roadway network layer by executing a 'Spatial Join' in ArcGIS. This assigned the AADTT07 freight volumes for each roadway link to the culverts located along that link.

5.5.1.3 Freight Truck Volume Classification

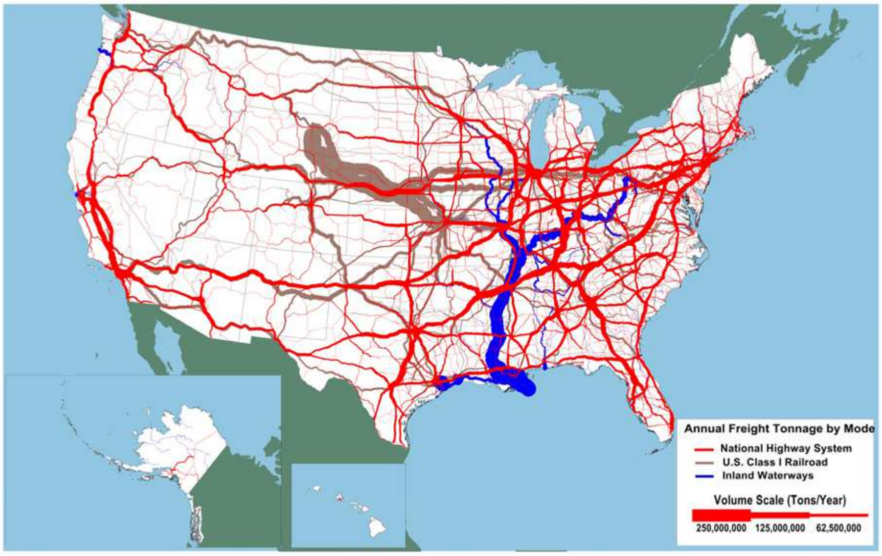
Freight volumes are classified and assigned to Economic Criticality Index (EC Index) values correlating to low/medium/high criticality. Three general classification schemes were considered to assign freight volumes to classifications:

1. Static volume-based intervals

    a. Based on national freight volume ranges
    b. Based on state-specific freight volume ranges
2. Frequency of link-based statewide volume intervals
3. Frequency of culvert-based statewide volume intervals

The first scheme, static volume-based classifications, simply chooses intervals based upon the nation-wide range of AADTT values. For example, AADTTs above 10,000 are classified as high, volumes below 2,000 are classified as low, and intervening values are classified as medium. However, one significant issue with this scheme is that it may introduce bias towards more urbanized locations. Figure 5.7 shows annual freight tonnage (tons/year), with the red lines representing the highway mode. Note that generally more freight volume is moved via highway trucking in eastern and southern states than in western states. For example, the highest-volume truck link in New York State has an AADTT of ~71,000, whereas the highest-volume truck link in Washington State has an AADTT of ~21,000. If freight volumes in this analysis were assigned to discrete intervals and applied nationally as an indicator of economic criticality, the analysis would likely show bias towards eastern states where volumes are generally higher.

The second option for a static volume-based interval scale is to use state-wide volumes instead of national volumes. This may address the bias associated with using nation-wide freight volumes to define intervals, however it does not address the issue of selecting sufficient interval boundary values, which would require additional research and likely result in state-specific definitions. Ideally, interval boundary selection would be tied to some measure of statewide economic impact. However, as the primary metric available in the FAF Output dataset is volume of freight trucks, and not value of freight, it is difficult to assign meaningful boundaries from the data available.



Source: (FHWA 2012)

Figure 5.7 Domestic Annual Freight Tonnage for 2007

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The second two approaches seek to define intervals by examining the frequency of AADTT volumes in the datasets, and visually or systematically determining natural break points within a freight volume histogram. The first approach plots the frequency of link-specific volumes (i.e., how many links within the network have a particular AADTT) for an entire state. Figure 5.8, for example, shows the histogram of link volumes in New York State by assigning volumes to 50 equal-interval bins. The second approach plots the frequency of culvert-specific volumes (i.e., how many culverts are associated with a particular AADTT, recognizing that many or culverts may be located on any given link). Figure 5.9, for example, shows the histogram of culvert-specific volumes in New York State by assigning volumes to 50 equal-interval bins.

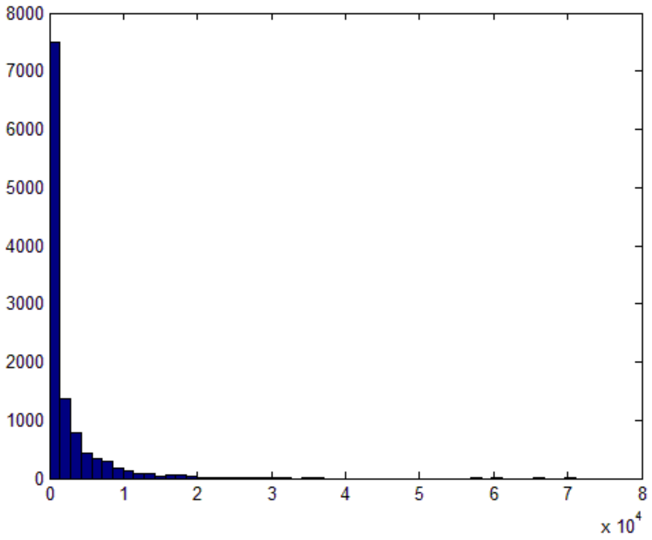

Figure 5.8 Histogram of Highway Links by AADTT in New York State

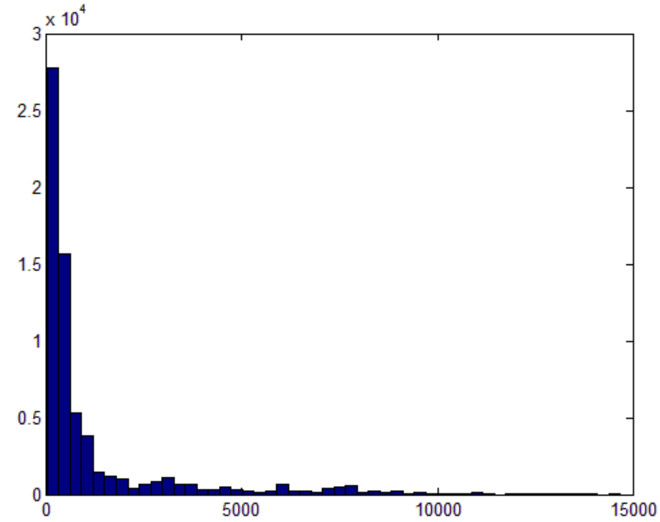

Figure 5.9 Histogram of Culverts by AADTT in New York State

While both Figure 5.8 and 5.9 show similar trends, with greater numbers of roadway links and roadway culverts associated with lower freight volumes, the tails of these distributions differ significantly. The highest truck volume link in New York State has an AADTT of 71,082. However, no culverts are located on that link, or similarly along many of the few other high-volume links; the highest volume link containing a culvert in New York State has an AADTT of 14,683. Additionally, most highway links (Figure 5.8) appear to have AADTT values less than ~20,000, whereas most culverts (Figure 5.9) appear to have AADTT values less than ~7,500.

The fundamental question in deciding between these two schemes is whether the AADTT associated with the culvert or the roadway link is the relevant concern. Both methods have advantages and disadvantages. If the link AADTT is the primary concern, then selection of interval break points is based on the importance of the individual links with respect to disruption, independent of whether or not a culvert is located on any given link. This has the advantage that additional culverts constructed or inventoried at some point in the future do not require any recalculation of intervals – culverts are simply assigned to the interval based on the volume of the link upon which they are installed. However, inconsistent lengths of roadway links within the network, or parts of the network, could introduce bias. For example, if lower-volume areas of the network are constructed out of significantly more links than higher-volume areas of the network, it could skew the histogram towards lower volumes (and vice versa).

The underlying purpose of the CCAAF is the ordinal network-wide comparison of climate risk to culverts. Therefore, in comparing economic importance it makes some sense that the AADTT associated culverts themselves should be the primary concern, not that associated with the link. However, completeness of the culvert inventory must be considered. The four case study states have different levels of completeness in their culvert inventories. MnDOT and NYSDOT have relatively complete inventories of their culverts, whereas ODOT has inventories along select routes, and WSDOT, for this study, provided inventories for select routes. In states where inventories are mostly complete, the use of AADTT associated with culverts may be a non-issue with respect to inventory completeness. However, in states where culvert inventories are under development, culvert-based freight volume intervals would require recalculation as additional culverts (and therefore, additional AADTT values) are added to the analysis.

Just as the size of links within a network was an issue above, the number of culverts located on any given link (and therefore, associated with the same AADTT) is a similar issue. Consider two roadway links: one with 10 culverts and one with one culvert. In either case, if one culvert fails, the entire link is disrupted irrespective of the condition of the remaining nine culverts. Therefore, the remaining nine culverts may become irrelevant to the analysis. On the other hand, it could be argued that the link with 10 culverts has 10 points where failure (and therefore, disruption) is possible, as opposed to only one, as is the case with the link containing only one culvert.

As stated, both link-based AADTT and culvert-based AADTT histograms have advantages and disadvantages. For the purposes of the CCAAF, the culvert-based AADTT was selected under the reasoning that culverts, not roadway links, are the assets under analysis. In studies that compare the climate risks across multiple asset types, it may be advantageous to consider link-based AADTT values given that method’s independence from the number of assets within each type. However, as the CCAAF limits its comparison of risks only to a single asset class, the culvert-based AADTT is appropriate.

5.5.1.4 Culvert-Based AADTT Classification and Index Assignment

Freight volumes for each state are assigned to three classification intervals: low, medium, and high. Intervals were determined separately for each state based upon the frequency of culvert-based AADTT in each state, as discussed in the previous section. Culvert data for each state were organized according to their individual associated AADTT values and three intervals were defined based on natural breaks data classification optimization. Natural breaks (Jenks 1967) is an optimization method that classifies data by minimizing variance within classes, but maximizing variance between classes. Table 5.12 shows the SE Index assignments by state and freight volume, as determined by natural breaks optimization conducted for each state.

Table 5.12 SE Index Classification Intervals for Culvert-Based AADTT

SE Index Value	SE Description	AADTT Value Ranges by State			
		Minnesota	**New York**	**Oregon**	**Washington State**
3	High	< 6641	< 5527	< 2321	< 4154
2	Medium	2246 - 6441	1919 - 5527	942 - 2321	1482 - 4154
1	Low	0 - 2245	0 - 1918	0 - 941	0 - 1481

5.5.2 Operational Criticality

To assess a culvert asset's operational criticality, the roadway Functional Classification criterion was selected. This criterion was one of the operational criticality measures used in *Gulf Coast 2* and was also considered in the Utah DOT culvert assessment framework discussed in Section 4.2.4. Functional Classifications are assigned to highways and streets "primarily based on motor vehicle travel characteristics and the degree of access provided to adjacent properties." (AASHTO 2011) Functional

Classifications have historically been divided into separate classification schemes for rural and urban highways (see Table 5.13) (AASHTO 2011). However, recent reassessment of the Highway Performance Monitoring System has provided interim guidance that condenses Functional Classifications into non-location specific designations (FHWA 2010) as shown in Table 5.14.

Table 5.13 Highway Functional Classifications (Location-Specific)

Rural		Urban	
Rural Interstate	1	Urban Interstate	11
Rural Principal Arterial	2	Urban Freeway or Expressway	12
Rural Minor Arterial	6	Urban Principal Arterial	14
Rural Major Collector	7	Urban Minor Arterial	16
Rural Minor Collector	8	Urban collector	17
Rural Local Road	9	Urban Local Road	19

Table 5.14 HPMS Interim Guidance on Functional Classification

Functional Classification Code	Functional Classification
1	Interstate
2	Other Freeways & Expressways
3	Other Principal Arterial
4	Minor Arterial
5	Major Collector
6	Minor Collector
7	Local Roadway

Functional Classifications are designated according to relative traffic volumes and roadway mileage. Relative traffic volume is measured as the roadway's VMT, taken as a percentage of statewide VMT. Roadway mileage is similarly measured as the roadway's mileage, taken as a percentage of statewide route mileage. Current guidance specifies (FHWA 2010):

> “All Arterials and Collectors combined – maximum of 35 percent of statewide route mileage. (Rural Minor Collector mileage and VMT does not contribute, but it is included here as "Collectors" because the existing extent guidance does not break out any separate guidance for them.) All Arterials and Collectors combined – between 70 percent and 80 percent of statewide VMT. Related to NHS apportionment: Rural Principal Arterials – maximum of 4 percent of statewide route mileage and between 30 percent and 55 percent of statewide VMT. Urban Principal Arterials – maximum of 10 percent of statewide route mileage and between 40 percent and 65 percent of statewide VMT.”

Although Functional Classification does not provide a direct measure of actual facility usage (e.g. AADT), it does provide an indication of the network-wide operational significance of the roadway, as well as an indication of relative usage of the roadway in comparison to the system. As the purpose of this dissertation research is to conduct a network-level assessment that compares relative risk to climate change across a region, the use of Functional Classification as a criterion for operational criticality seems appropriate.

Highway Functional Classifications were first specified in the 1968 National Highway Functional Classification Study Manual, and later legislatively required under the Federal-Aid Highway Act of 1973 (FHWA 1989). As a federally required statewide highway classification system, (i.e., nationally replicable) functional classification is well suited as a measure of operational criticality in this dissertation research.

The four case-study state DOTs have provided, or have otherwise published, functional classification data as ESRI shapefiles that can be analyzed in ArcGIS. The Functional Classification data gathered from, or provided by, the four case study state DOTs were not yet updated to the new classification scheme, but instead adhere to the urban/rural classification scheme shown in Table 5.13.

To translate functional classifications into relative measures of operational criticality, the CCAAF assigns each of the state DOT Functional Classification codes to a CCAAF Operational Criticality Index, or OP Index. The OP Index assignment used here is consistent with the simplification scheme used for roadway Functional Classification in *Gulf Coast 2*. The coded designation schemes for MnDOT, NYSDOT, ODOT and WSDOT are shown in Table 5.15. In the criticality analysis, culvert assets are assigned the OP Index value associated with the functional classification of the roadway upon which they are located.

Table 5.15 State DOT Functional Classification Code Scheme

Functional Classification	Rural Code	Functional Classification	Urban Code	CCAF Operational Criticality Index
Rural Interstate	1	Urban Interstate	11	**3**
Rural Principal Arterial	2	Urban Freeway or Expressway	12	
Rural Minor Arterial	6	Urban Principal Arterial	14	**2**
Rural Major Collector	7	Urban Minor Arterial	16	
Rural Minor Collector	8	Urban collector	17	**1**
Rural Local Road	9	Urban Local Road	19	

State roadway network GIS data containing Functional Classification information for Washington State and Oregon are published on the WSDOT GeoData Distribution Catalog website[4] and ODOT GIS FTP website[5], respectively. Functional Classification GIS data for Minnesota and New York State are not published on the respective state

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[4] http://www.wsdot.wa.gov/mapsdata/geodatacatalog/default.htm

[5] ftp://ftp.odot.state.or.us/tdb/trandata/GIS_data/

DOT websites, however Functional Classification GIS network data were provided by the relevant offices at MnDOT and NYSDOT upon request.

The state Functional Classification roadway network datasets were first overlaid with the corresponding states culvert layers. Roadway culverts were then associated with individual links in the state functional classification network layers by executing a 'Spatial Join' in ArcGIS, which assigns each culvert the functional classification of the associated roadway. Functional classification records for each culvert were then updated to reflect the OP Index values shown in Table 5.15 by executing a series of SQL queries in Microsoft Access for the GIS databases.

5.5.3 Health & Safety Criticality

To assess a culvert asset's health and safety criticality, the *Gulf Coast 2* criterion "Component of the National Defense System" was selected. *Gulf Coast 2* somewhat simplistically divides roadways into two categories: Interstate and non-Interstate. The former of these are then designated as part of the National Defense System, and assigned higher criticality. However, the Department of Defense (via the United States Army) identifies that numerous non-Interstate routes are also important to national defense interests, and therefore designates a more extensive national defense network: the Strategic Highway Network (STRAHNET) (United States Army 2009). STRAHNET "is a system of public highways that...provides defense access, continuity, and emergency capabilities for movements of personnel and equipment in both peace and war." (FDOT Undated)

STRAHNET consists of the Strategic Highway Network and STRAHNET Connector Routes, which typically link STRAHNET to important off-network facilities (e.g., ports, military installations, etc) (FDOT Undated). In total, 44,376 miles of interstate highway and 15,015 miles of non-interstate highway in the continental United States are part of STRAHNET.

In the CCAAF, Health and Safety Criticality is assigned to culverts by designated them as either: (1) located on STRAHNET highways, or (2) not located on STRAHNET highways. STRAHNET highway designations in this study were determined by conducting a geospatial analysis of the culvert and STRAHNET highway locations using ESRI ArcGIS 10.1. Although the National Highway Planning Network (NHPN) (maintained by the FHWA) has multiple designations for STRAHNET roadways (e.g., STRAHNET Priority 1 Connector, Priority 2 Connector, etc) designations were condensed in this study into two categories: part of STRAHNET, and not part of STRAHNET.

ArcGIS shapefiles of the NHPN for each of the four case-study states were obtained from the FHWA NHPN website (FHWA 2013). Culverts were then associated with STRAHNET highway links by conducting a ‘Spatial Join’ in ArcGIS (similar to the process described for FAF assignment in Section 5.5.1.3), and updating the Health and Safety Criticality Index (HS Index) field in the associated culvert data tables for each state. Those culvert assets located on STRAHNET highways were assigned an HS Index value of 3 (indicating greater criticality); those culvert assets located on non-STRAHNET highways are assigned HS Index values of 1 (indicating lesser criticality).

Note that in the HS Index analysis, a roadway's inclusion in the STRAHNET is a binary distinction, and therefore no middle, or medium criticality value (i.e., 2) is assigned.

5.5.4 Combined Culvert Asset Criticality

The culvert criticality assessment, as part of the larger CCAAF framework, assigns an overall criticality value to culverts, called the Combined Criticality Index. This index combines the economic, operational, and health and safety criticality index, and assigns a combined criticality value of 1 (low), 2 (medium), or 3 (high). In practice, component criticality values are combined using simple additive weighting (SAW) (Yoon and Hwang 1995). As different rating scales are used among the three component criticality scores, the scores must first be normalized. They are normalized to a 0 to 1 scale by dividing each component index score by three. Scores are then combined through SAW using the following equation:

$$V_i = \sum_{j=1}^{n} w_j r_{ij}, \qquad i = 1, \ldots, m$$

where: V_i is the combined criticality score

w_j is the weighting factor for each criticality component j

r_{ij} is the component criticality score for the index j, with value i

This equation creates a range of possible overall criticality scores from one to three, which is subdivided into Low, Medium, and High sub-ranges. A similar approach was used to calculate combined criticality scores in *Gulf Coast 2* (ICF International and

Parsons-Brinkerhoff 2011); the subdivision of a criticality range into Low, Medium, and High regions is also similar in approach to the climate change risk evaluation methodology in Maurer et al. (2011), as shown earlier in Figure 3.5. The Low, Medium, and High combined criticality values are then assigned Combined Criticality Index scores of 1 (low), 2 (medium) and 3 (high) according to the ranges in Table 5.16. These Combined Criticality Index scores will be used in the culvert prioritization component of the CCAAF, described in the next section.

Table 5.16 Combined Culvert Criticality Score Range and Sub-Ranges

Low		**Medium**			**High**	
1	**1.333**	**1.667**	**2**	**2.333**	**2.667**	**3**

The weighting value, w_j, in the SAW equation above provides a mechanism by which agencies can incorporate local knowledge, experience, and values into the asset criticality determination. For example, if regional freight projections indicate a significant future increase in roadway freight movement, agencies or DOTs may seek to increase the relative weight of the freight volume component of economic criticality. Weighting factors should be applied to individual criticality criteria as opposed to the overall criticality categories shown in Table 5.11.

In this application, the three component criticality criteria were equally weighted (i.e., $w_j = 1$ for all components, j). Local stakeholder involvement is required to further develop agency weighting schemes and is an area for future research.

5.5.5 System-Critical Asset Determination

The Culvert Criticality Assessment component of the CCAAF framework (Figure 5.6) contains a decision-making mechanism that is designed to enable the greater incorporation of local knowledge and experience in the culvert prioritization process. Specifically, Figure 5.6 contains a decision process that allows practitioners to compile a list of links or culvert assets that are “system-critical.” These are assets for which any disruption is a wholly unacceptable outcome from an operational, health and safety, or economic perspective. For example, if a large community is primarily served by one highway system, local officials and decision makers conducting the analysis may choose to designate that link a “system-critical.” System-critical assets are automatically assigned a Combined Criticality Index score of 3 (High), bypassing the determination of Economic, Operational, and Health and Safety Criticality Indices (Section 5.5.1 to 5.5.3).

Any agency or organization conducting the culvert climate change assessment should prepare a list of critical assets prior to beginning the CCAAF evaluation process to mitigate bias in criticality determination. Consistent with practices in *Gulf Coast 2* (ICF International and Parsons-Brinkerhoff 2011), and others [for example, Maurer et al. (2011); Nguyen et al. (2011); Parsons-Brinkerhoff (2009)], this may best be facilitated by convening expert panels of local stakeholders.

This research study does not seek to determine assets within the case-study areas that are “system-critical.” However, its incorporation into the assessment process should be further investigated in future research concerning the implementation of the CCAAF.

5.6 Culvert Asset Prioritization

The Culvert Asset Prioritization step is the final step in the CCAAF. It combines the Precipitation Exposure Index (from the Precipitation Exposure Analysis), the Vulnerability Index (from the Vulnerability Analysis), and the Combined Criticality Index (from the Culvert Criticality Assessment) into an overall Culvert Asset Prioritization (CAP) Index. The CAP Index represents the relative, network-level climate change impact risk associated with culverts in an analysis area, according to climate impact timeframe (i.e., mid-century, end-of-century), and emission scenario (i.e., B1, A2). The determination of the CAP Index scores is similar to the risk-evaluation step of risk management (see Section 3.4.2, or Figure 3.2), and combines elements from the Hazard, Vulnerability, and Loss components of the catastrophe model (Figure 3.3) to help identify risk priorities.

Combination of the Climate Exposure, Vulnerability, and Combined Criticality Indices employs the general notion of a risk matrix, which in itself is a form of simple additive weighting (SAW). Risk matrices are a common means of evaluating risks in climate change adaptation studies (see Section 3.4.2). Each of the three indices may be viewed as three separate “dimensions” of risk, thus necessitating the use of a multi-dimensional matrix similar to that used by Major and O'Grady (2010) in Figure 3.6. Regions of the three-dimensional risk matrix are defined as “high,” “medium,” and “low,” depending upon various combinations of scores for the Climate Exposure, Vulnerability, and Combined Criticality Indices.

CAP Indices are determined separately for each analysis timeframe (i.e. mid-century, end-of-century) and for each emission scenario (i.e. B1, A2), resulting in four

CAP Index scores for each culvert. These scores, on their own, may provide useful information to decision-makers and infrastructure managers. However, a Robust Culvert Asset Prioritization Index (R-CAP Index) score is also determined for each of the two timeframes by combining the two emission scenario-specific CAP Index scores for each timeframe. The R-CAP thus provides additional information about the timeframe-based climate impact risk associated with each culvert across multiple climate scenarios. Thus the CAP Indices should be viewed as intermediate outcomes, and the R-CAP Indices should be viewed as final outcomes of the CCAAF.

The use of three separate methods to determine Vulnerability Index scores (Method 1 - Exposure-only; Method 2 – Overall Condition Rating-based; Method 3 - Performance-based) is also considered. Within each set of timeframe- and emission-specific indices, separate sets of CAP and R-CAP Indices are determined. MnDOT and NYSDOT culverts are assigned three separate sets of CAP and R-CAP Indices for the mid-century and end-of-century time periods (based on the three Vulnerability Index methods). ODOT culverts are assigned two sets of CAP and R-CAP Indices for each time period (Method 2 is excluded as ODOT does not assign overall culvert condition ratings). WSDOT culverts are assigned one set of CAP and R-CAP Indices for each time period (Method 2 and Method 3 are excluded as WSDOT data collection is limited to inventory information.)

The sections below discuss the calculation of the individual CAP Index scores using the three-dimensional risk-matrix theory, and also the determination of the R-CAP Index scores.

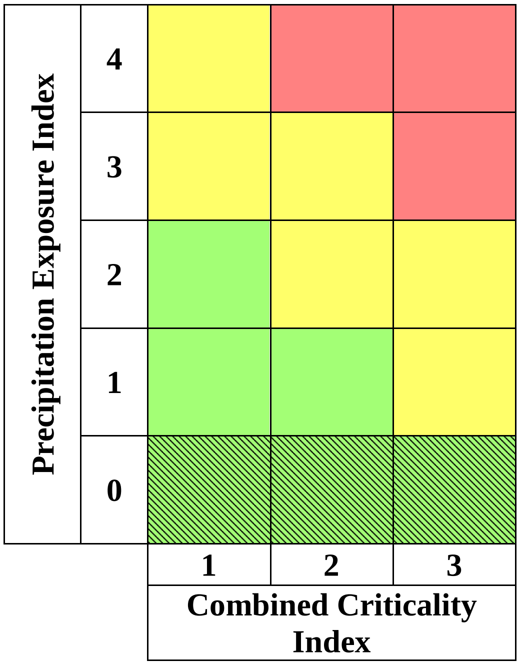
5.6.1 Individual Culvert Asset Prioritization (CAP) Index Score

This section discusses the calculation of the CAP Index scores using each of the three Vulnerability Index methods. The CAP Index score calculation methods described below were applied identically to all relevant case-study DOT datasets (e.g., WSDOT was excluded from Method 2 and Method 3, as discussed above); therefore discussion is generalized to all.

5.6.1.1 CAP Index Method 1

The first CAP Index calculation excludes the Vulnerability Index value (as discussed in Section 5.4.1) and instead calculates the CAP Index solely as a function of the Precipitation Exposure Index and the Combined Criticality Index. This is the only available CAP Index calculation for state DOTs that do not collect culvert condition and functional performance data (e.g., WSDOT), however it is calculated here for all participating case-study DOTs for comparison purposes.

Determination of the Method 1 CAP Index uses the matrix shown in Figure 5.10, which assesses the summation of the Combined Criticality Index and the Precipitation Exposure Index. CAP Index scores equal to 6 or 7 fall within the “high” risk region (red, upper right) and are assigned a CAP Index of 3; scores equal to 4 or 5 fall within the “medium” risk region (yellow, middle diagonal band) and are assigned a CAP Index of 2, scores less than 4 fall within the “low” risk region (green, bottom left) and are assigned a CAP Index of 1. Note that the bottom row of the low risk region is cross-hatched. This row is associated with Precipitation Exposure Indices equal to 0. Precipitation Exposure Indices of 0 imply regions where climate projections suggest either a zero change, or a decrease in 24-hour high-precipitation event magnitudes. They are included in Figure 5.10 as "low" risk (as there is always some possibility of an impact), but culverts rated in this bottom row assigned a CAP Index equal to 0.



Precipitation Exposure Index	**4**	🟨	🟥	🟥
	3	🟨	🟨	🟥
	2	🟩	🟨	🟨
	1	🟩	🟩	🟨
	0	▨	▨	▨
		1	**2**	**3**
		Combined Criticality Index		

Figure 5.10 Method 1 CAP Index Matrix

CAP Index scores were calculated using this method for culverts in all four case-study DOT databases. Separate sets of CAP Indices were calculated with this method, corresponding to each of the two emission scenarios (B1 and A2) and timeframes (mid-century, end-of-century) for each culvert.

5.6.1.2 CAP Index Method 2 and Method 3

Calculation of the CAP Index using Method 2 and Method 3 Vulnerability Indices employ the same theory and method, and are therefore discussed here together. Both Method 2- and Method 3-based Vulnerability Index values are determined using the theoretical construct of a three-dimensional matrix (Figure 5.11), similar to that proposed by Major and O'Grady (2010). The three axes of the matrix are the three constituent Indices – Precipitation Exposure, Vulnerability, and Combined Criticality – determined by the analyses discussed in Sections 5.3, 5.4, and 5.5, respectively. Those culverts with higher-value combinations of the three component indices fall within or nearer to the "high" risk region (red, upper middle), and those with lower combinations of component indices fall nearer to the "low" risk regions (blue).

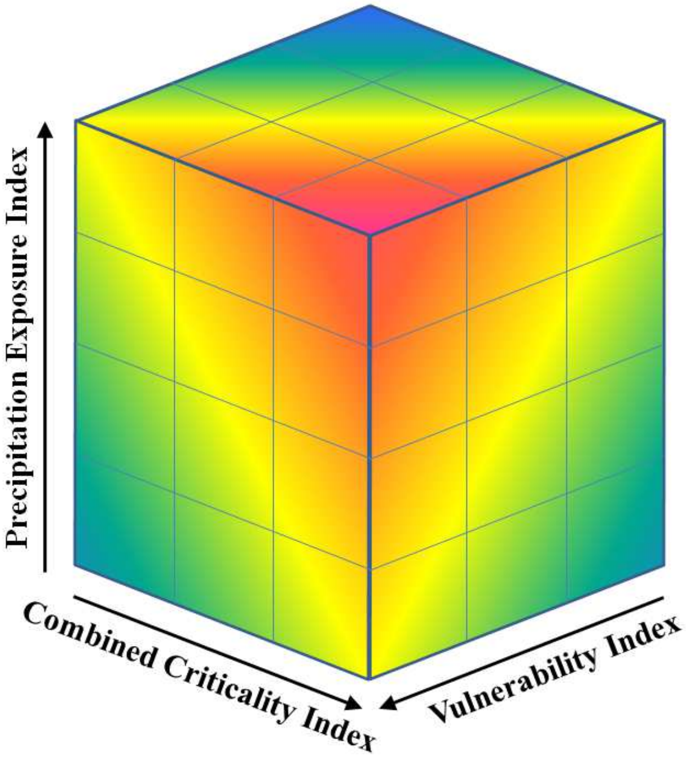


Figure 5.11 Three-Dimensional CAP Index Matrix

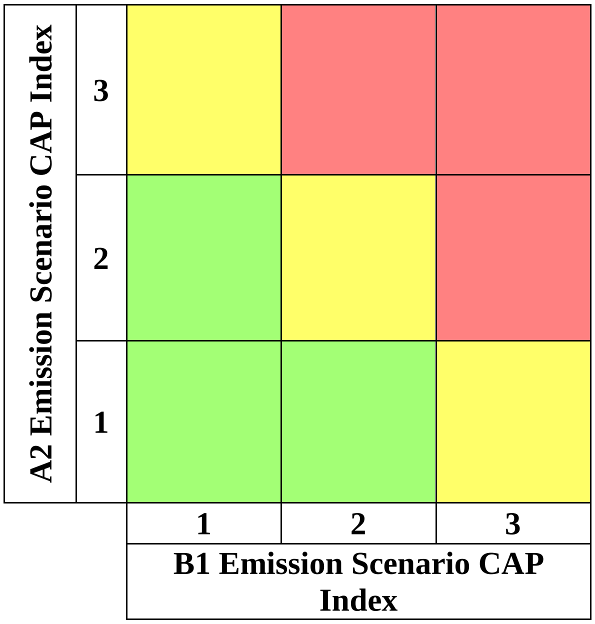
In practice, CAP Index scores determined using Method 2 and Method 3 Vulnerability Index scores are calculated as the summation of the three consistent component indices. For Method 2 CAP Indices, the Method 2 Vulnerability Index (i.e., based on the overall culvert ratings) is used; for the Method 3 Cap Indices, the Method 3 Vulnerability Index (i.e., performance-based ratings) is used. Summation values of the three component indices can fall along a scale from 3 (low) to 10 (high). Those culverts with summation values greater than or equal to 8 are designated as “high” risk and are assigned a CAP Index equal to 3; culverts with summation values of 5, 6, or 7 are designated as “medium” risk and are assigned a CAP Index equal to 2; culverts with summation values of 4 or less are designated as “low” risk and are assigned a CAP Index equal to 1. As with the calculation of Method 1-based CAP Indices, any culvert with a Precipitation Exposure Index value equal to 0 (implying a zero change or decrease in precipitation) is assigned a CAP Index equal to 0.

Method 2 CAP Index scores were calculated for culverts in the MnDOT and NYSDOT databases, as both DOTs assign overall culvert ratings. Method 3 CAP Index scores were calculated for culverts in the MnDOT, NYSDOT, and ODOT databases, as all three DOTs provide some performance-based data. Separate sets of Method 2 and Method 3 CAP Indices were calculated corresponding to each of the two emission scenarios (B1 and A2) and analysis timeframes (mid-century, end-of-century) for each culvert.

5.6.2 Robust Culvert Asset Prioritization (R-CAP) Index Score

The R-CAP Index score is intended to combine CAP Index scores from common time periods to illustrate the robustness of an outcome across two emission scenarios. R-CAP Index values are determined by summing CAP Indices and evaluating the simple matrix shown in Figure 5.12. Culverts with A2 and B1 Emission Scenario-based CAP

Indices (within the same analysis timeframe) summing to 5 or 6 fall within the “high” risk region (red, upper right), culverts with CAP Indices summing to 4 fall within the “medium” risk region (yellow, diagonal band); culverts with CAP Indices summing to 3 or less fall within the “low” risk region (green, lower left).



		B1 Emission Scenario CAP Index		
		1	2	3
A2 Emission Scenario CAP Index	3	🟨	🟥	🟥
	2	🟩	🟨	🟥
	1	🟩	🟩	🟨

Figure 5.12 R-CAP Index Matrix

Calculation of the R-CAP Index does not exclude culverts with CAP Indices equal to 0. Instead, the true summation of the CAP Index values is taken. For example, a culvert with a B1 Scenario CAP Index of 0, but an A2 Scenario CAP Index of 3 is assigned an R-CAP index of 1. This enables better accounting of climate risks for culverts that lie within regions where low emission scenario projections suggest dryer conditions, but mid-high emission scenario projections suggest wetter conditions (or vice versa).

Separate R-CAP Indices are calculated for each culvert, one associated with each vulnerability analysis method. Additionally, separate sets of R-CAP Indices are calculated for each of the two time periods. This results in a total of six R-CAP Indices for each culvert in the MnDOT and NYSDOT databases, four R-CAP Indices for each culvert in the ODOT database (Method 2 is excluded), and two R-CAP Indices for each culvert in the WSDOT database.

CHAPTER 6

CASE STUDY RESULTS AND DISCUSSION

This chapter presents the results of the four case study analyses conducted using the CCAAF methodology described in Chapter 5. Results are presented in several sections, with each section corresponding to the successive steps of the CCAAF. Section 6.1 presents the results of the Climate Exposure Analysis; Section 6.2 presents the results of the Vulnerability Analysis; Section 6.3 presents the results of the Criticality Analysis; Section 6.4 presents the results of the Culvert Asset Prioritization. Section 6.5 then discusses the significance of these results with respect to the assessment of climate change impact risks to culverts and the methodology of the CCAAF.

The results in each section are discussed for each of the case study DOTs, including a comparison of results among the DOT datasets. Additional results and data are also contained in Appendices G through K, as noted in the sections below.

6.1 Climate Exposure Analysis

The climate analyses described in Section 5.3 – Precipitation Exposure Analysis were conducted for the four case-study states. Each state was analyzed for the B1 (low) SRES emission scenario, and the A2 (mid-high) SRES emission scenario. Additionally, each SRES emission scenario was analyzed for mid-century precipitation projections (2040-2069) and end-of-century precipitation projections (2070-2099). The results from each state's analysis are presented in the sections below showing just the climate projection data. The assignments of Precipitation Exposure Indices to individual culverts within the respective states are then summarized in Section 6.1.5. The full output of maps containing the geospatial distribution of projected climate overlaid with the culvert datasets are given in Appendix G.

The 10-year 24-hour precipitation event is used as an indicator of potential changes in the spatial extent and magnitude of future extreme event precipitation events. The values associated with changes in precipitation magnitude given in the sections below should not be interpreted as the absolute or actual changes in precipitation event magnitude, but are instead associated with relative ranges of precipitation event exposure (i.e., no change, low, medium, high) as discussed in Section 5.3.

6.1.1 Minnesota 10-Year 24-Hour Precipitation Event Projections

The results of the Minnesota precipitation exposure analyses are shown below in Figure 6.1 through 6.4. Figure 6.1 shows the 10-year 24-hour precipitation ensemble projection using the B1 SRES emission scenario for the mid-century (2040-2069) analysis timeframe. Figure 6.2 shows the 10-year 24-hour precipitation ensemble projection using the B1 SRES emission scenario for the end-of-century (2070-2099) analysis timeframe. Figure 6.3 shows the 10-year 24-hour precipitation ensemble projection using the A2 SRES emission scenario for the mid-century (2040-2069) analysis timeframe. Figure 6.4 shows the 10-year 24-hour precipitation ensemble projection using the A2 SRES emission scenario for the end-of-century (2070-2099) analysis timeframe.

Note that both mid-century projections generally predict less change in the magnitude of the 10-year 24-hour precipitation event than do the end-of-century

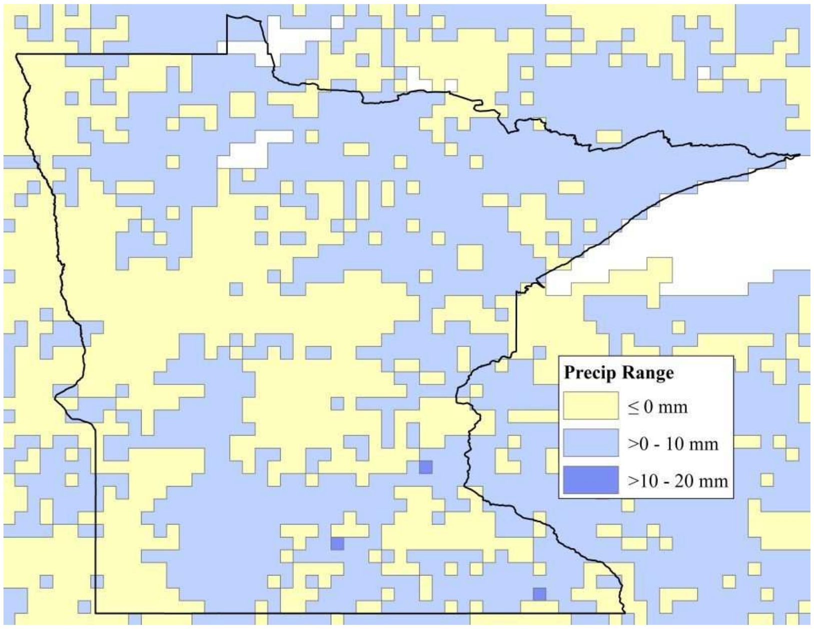


Figure 6.1 Minnesota 10-yr Precipitation, B1 Scenario, Mid-Century (2040-2069)

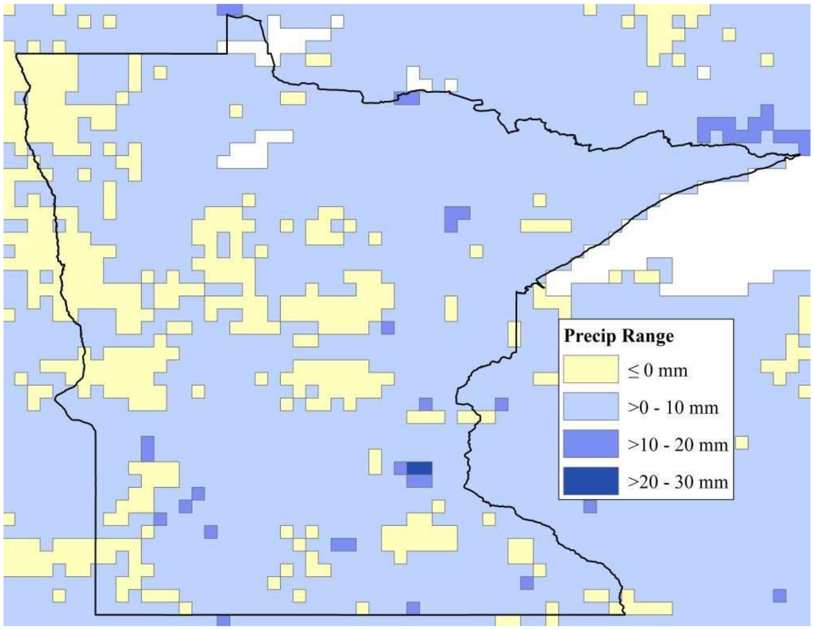


Figure 6.2 Minnesota 10-yr Precipitation, B1 Scenario, End-Century (2070-2099)

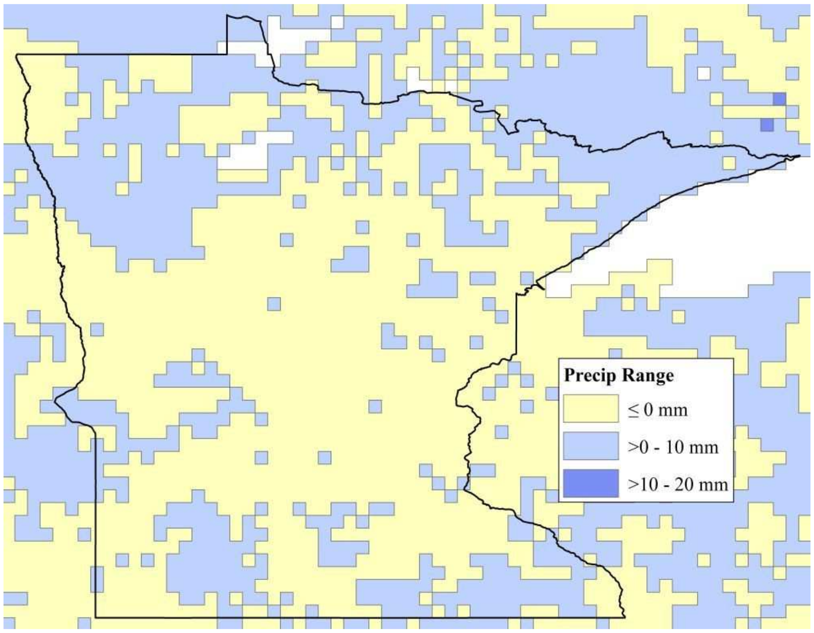


Figure 6.3 Minnesota 10-yr Precipitation, A2 Scenario, Mid-Century (2040-2069)

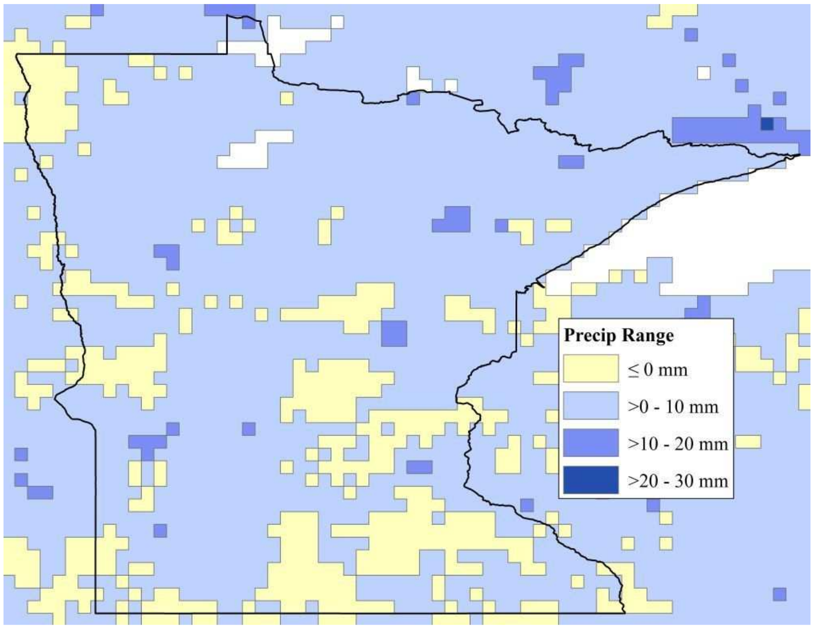


Figure 6.4 Minnesota 10-yr Precipitation, A2 Scenario, End-Century (2070-2099)

projections. This is generally consistent with the expected impacts of climate change in North America discussed in Chapter 2. In both mid-century projections, the maximum precipitation range in the map extent is the 10-20mm (medium) range whereas in the end-of-century projections, the maximum precipitation range in the map extent is the 20-30mm (high) range (in Figure 6.3 and Figure 6.4, grid squares associated with that highest ranges are located outside of the state boundaries).

6.1.2 New York State 10-Year 24-Hour Precipitation Event Projections

The results of the New York State precipitation exposure analyses are shown below in Figure 6.5 through 6.8. Figure 6.5 shows the 10-year 24-hour precipitation ensemble projection using the B1 SRES emission scenario for the mid-century (2040-2069) analysis timeframe. Figure 6.6 shows the 10-year 24-hour precipitation ensemble projection using the B1 SRES emission scenario for the end-of-century (2070-2099) analysis timeframe. Figure 6.7 shows the 10-year 24-hour precipitation ensemble projection using the A2 SRES emission scenario for the mid-century (2040-2069) analysis timeframe. Figure 6.8 shows the 10-year 24-hour precipitation ensemble projection using the A2 SRES emission scenario for the end-of-century (2070-2099) analysis timeframe.

All ensemble climate change projections exhibit similar spatial trends in the distribution of climate impacts. Generally, all projections also indicate both a mid-century and end-of-century increase in event precipitation across New York State in the 0-10mm (low) and 10-20mm (medium) ranges, however only the A2 end-of-century ensemble projections (Figure 6.8) suggests that regional increases in the 10-year 24-hour precipitation event magnitude may reach the 20-30mm (high) range.

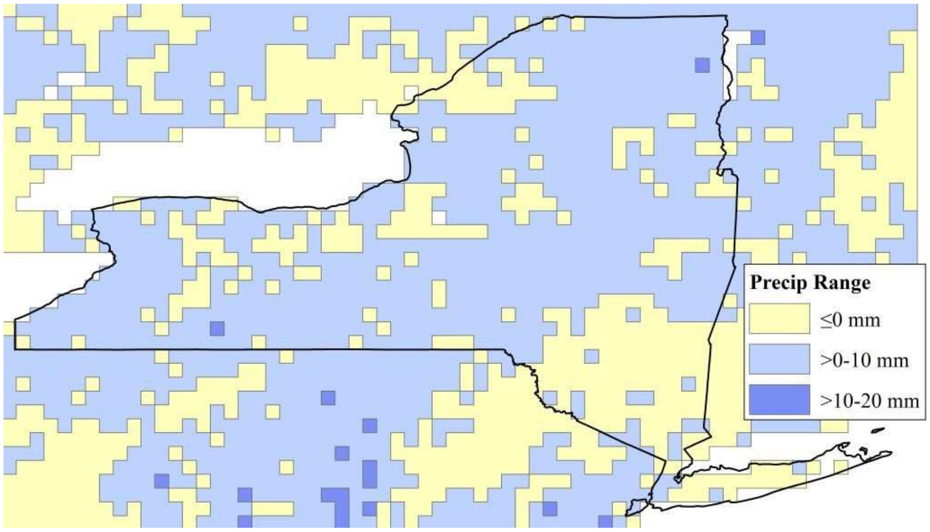


Figure 6.5 New York 10-yr Precipitation, B1 Scenario, Mid-Century (2040-2069)

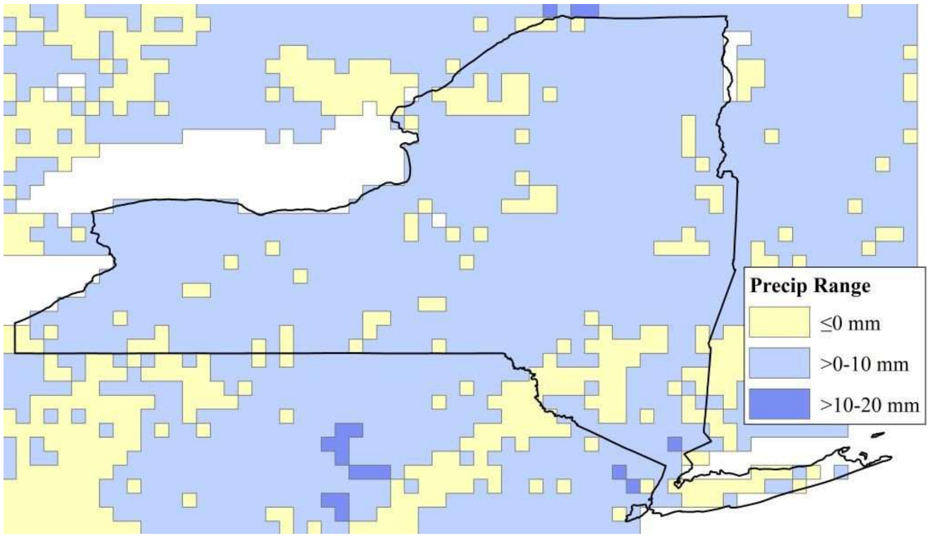


Figure 6.6 New York 10-yr Precipitation, B1 Scenario, End-Century (2070-2099)

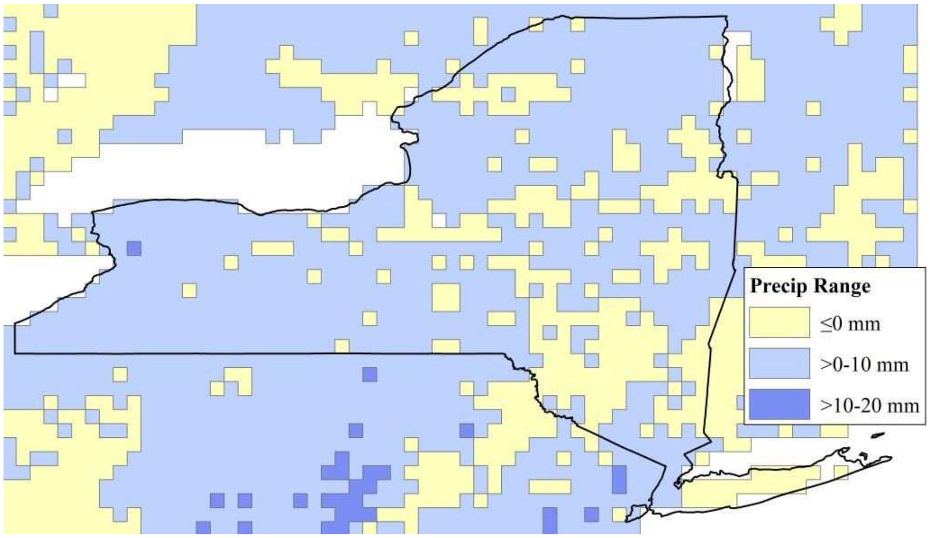


Figure 6.7 New York 10-yr Precipitation, A2 Scenario, Mid-Century (2040-2069)

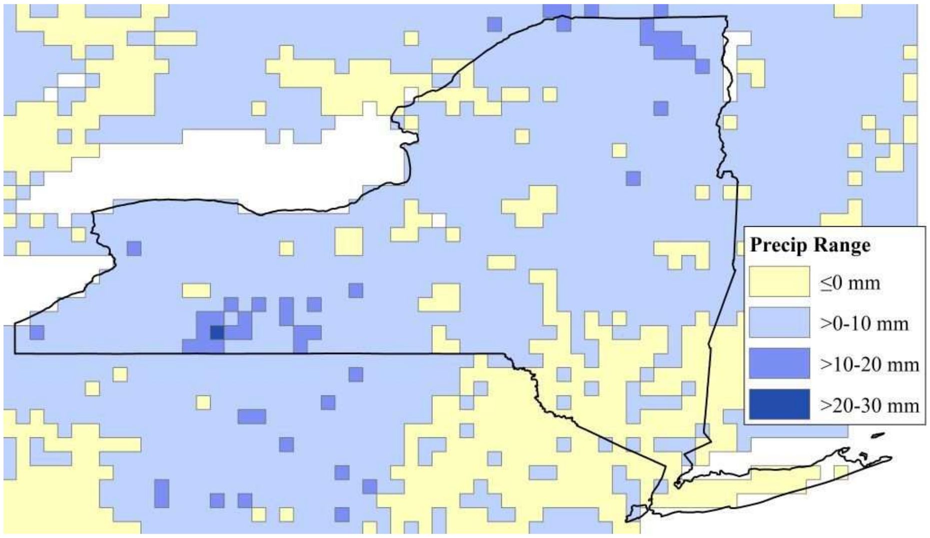


Figure 6.8 New York 10-yr Precipitation, A2 Scenario, End-Century (2070-2099)

6.1.3 Oregon 10-Year 24-Hour Precipitation Event Projections

The results of the Oregon precipitation exposure analyses are shown below in Figure 6.9 through 6.12. Figure 6.9 shows the 10-year 24-hour precipitation ensemble projection using the B1 SRES emission scenario for the mid-century (2040-2069) analysis timeframe. Figure 6.10 shows the 10-year 24-hour precipitation ensemble projection using the B1 SRES emission scenario for the end-of-century (2070-2099) analysis timeframe. Figure 6.11 shows the 10-year 24-hour precipitation ensemble projection using the A2 SRES emission scenario for the mid-century (2040-2069) analysis timeframe. Figure 6.12 shows the 10-year 24-hour precipitation ensemble projection using the A2 SRES emission scenario for the end-of-century (2070-2099) analysis timeframe.

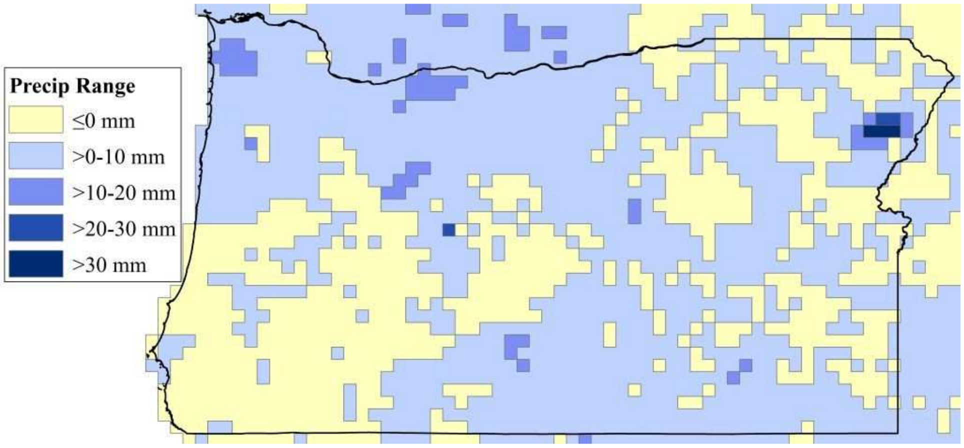


Figure 6.9 Oregon 10-yr Precipitation, B1 Scenario, Mid-Century (2040-2069)

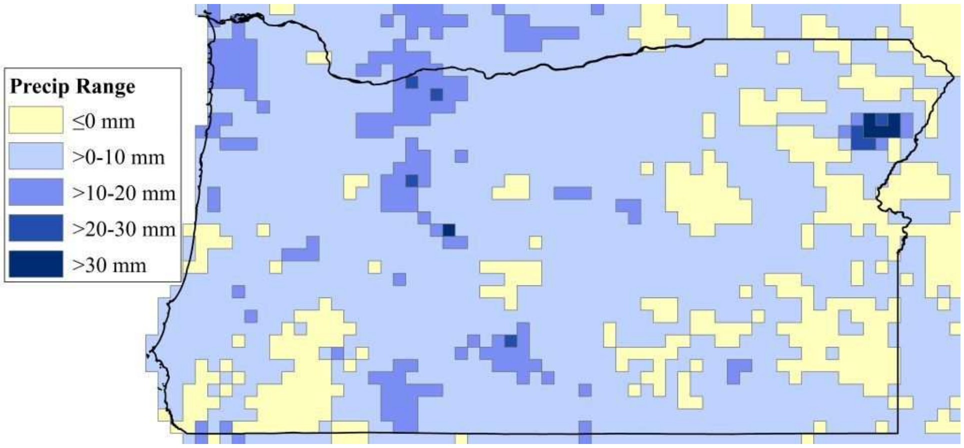


Figure 6.10 Oregon 10-yr Precipitation, B1 Scenario, End-Century (2070-2099)

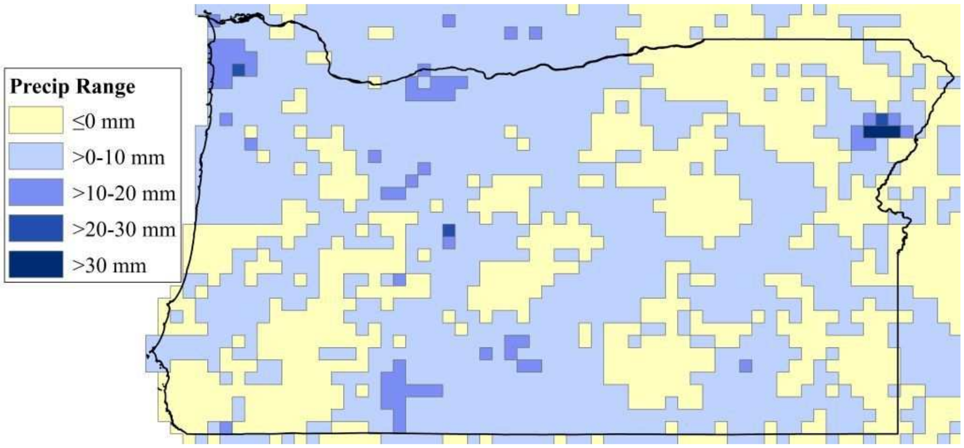


Figure 6.11 Oregon 10-yr Precipitation, A2 Scenario, Mid-Century (2040-2069)

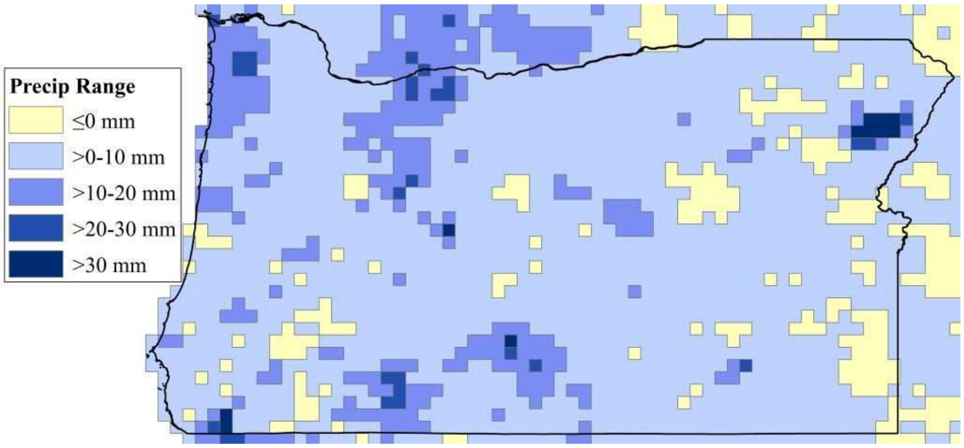


Figure 6.12 Oregon 10-yr Precipitation, A2 Scenario, End-Century (2070-2099)

The ensemble projection models generally exhibit similar trends with respect to the spatial distribution of changes in precipitation across the state. Figure 6.10 and Figure 6.12 (B1 end-of-century and A2 end-of-century, respectively) both show greater changes in projected extreme event precipitation magnitude in the more mountainous areas of the state (Coastal Mountain Range to the northwest, Cascade Mountain Range central-west, and Wallowa Mountains in the northeast). Central and Eastern Oregon both exhibit generally smaller changes in extreme event precipitation across all scenarios, with greater distribution of positive changes in precipitation (as opposed to no changes, or decreases) in the end-of-century analysis timeframes.

All ensemble climate projections for Oregon suggest that the magnitude of change in precipitation event magnitude will be greater than that which was indicated in the Minnesota and New York State projections. All timeframes and emission scenarios in the Oregon projections exhibit precipitation changes across the full range of classification ranges (no-change, low, medium, high, and extreme).

6.1.4 Washington State 10-Year 24-Hour Precipitation Event Projections

The results of the Washington State precipitation exposure analyses are shown below in Figure 6.13 through 6.16. Figure 6.13 shows the 10-year 24-hour precipitation ensemble projection using the B1 SRES emission scenario for the mid-century (2040-2069) analysis timeframe. Figure 6.14 shows the 10-year 24-hour precipitation ensemble projection using the B1 SRES emission scenario for the end-of-century (2070-2099) analysis timeframe. Figure 6.15 shows the 10-year 24-hour precipitation ensemble projection using the A2 SRES emission scenario for the mid-century (2040-2069) analysis timeframe. Figure 6.16 shows the 10-year 24-hour precipitation ensemble projection using the A2 SRES emission scenario for the end-of-century (2070-2099) analysis timeframe.

Both of the end-of-century ensemble climate projections (Figure 6.14 and Figure 6.16) exhibit the general trend of widespread increases in extreme event precipitation. Increases are generally greater in western Washington than in eastern Washington, and

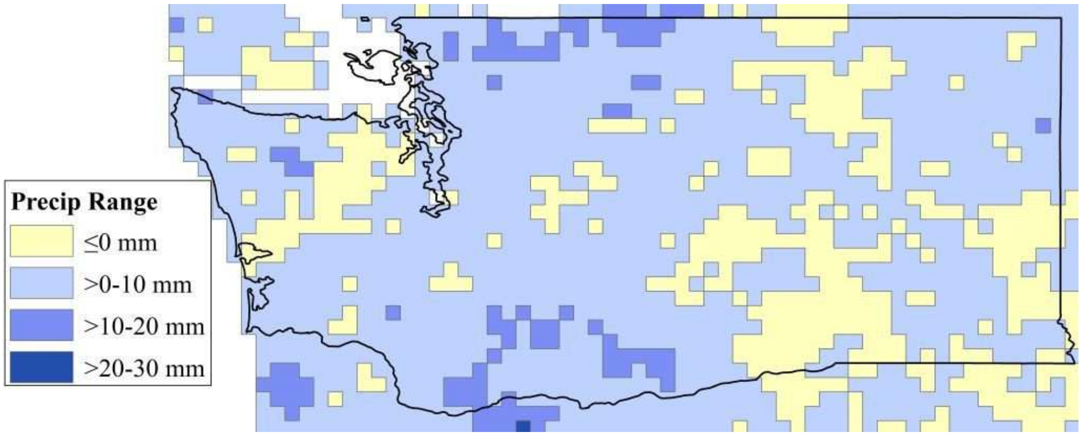


Figure 6.13 Washington 10-yr Precipitation, B1 Scenario, Mid-Century (2040-2069)

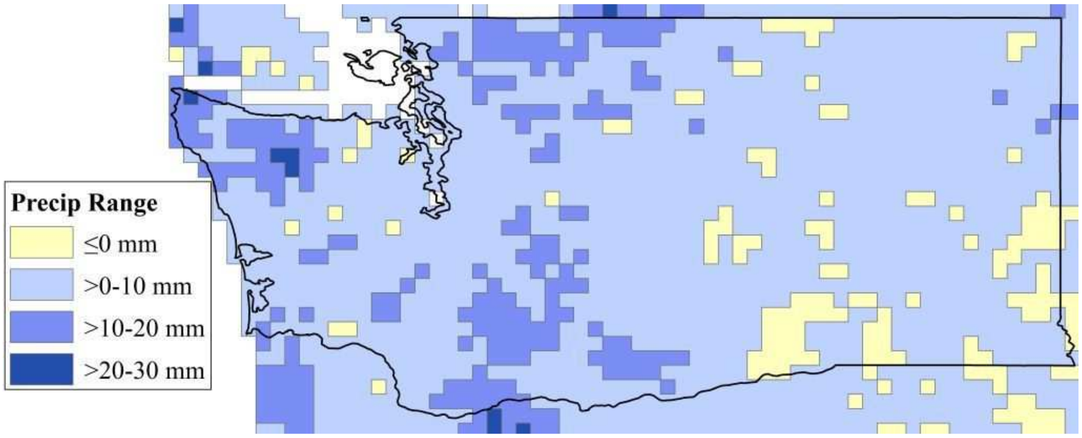


Figure 6.14 Washington 10-yr Precipitation, B1 Scenario, End-Century (2070-2099)

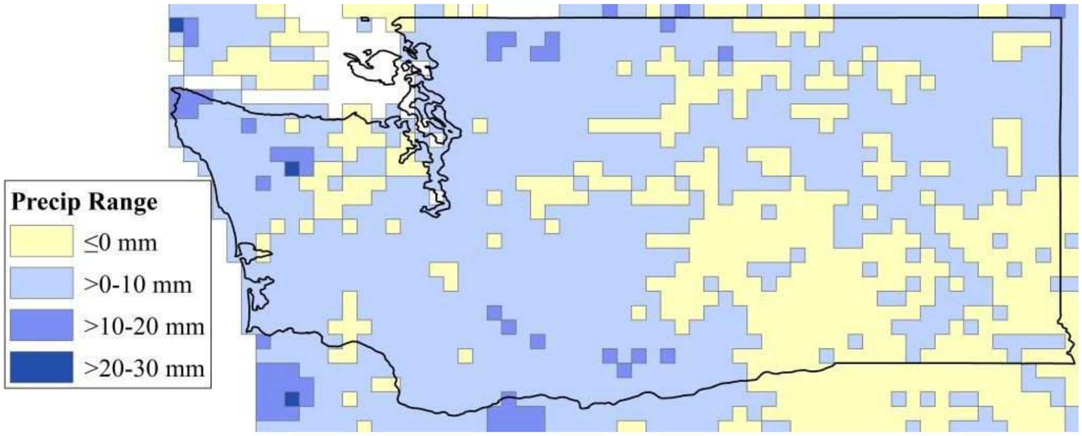


Figure 6.15 Washington 10-yr Precipitation, A2 Scenario, Mid-Century (2040-2069)

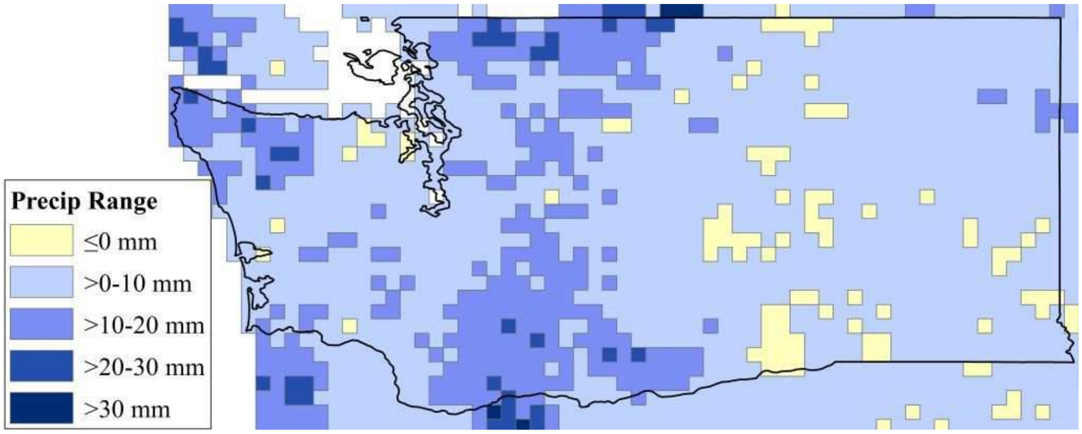


Figure 6.16 Washington 10-yr Precipitation, A2 Scenario, End-Century (2070-2099)

particularly in the Cascade Mountain range (bisecting the state north-south) and the Olympic Mountain (northern coastal region). Consistent with the North American climate projections discussed in Chapter 2, climate projections based on higher emission scenario and later analysis timeframes suggest greater changes (generally increases) in precipitation event magnitude. As with Oregon, the ensemble projections for Washington State generally suggest a wider range of changes in precipitation event magnitude across the state than is seen in the projections for Minnesota and New York State.

6.1.5 General Indications of these Results

The culverts in each of the four case-study states were assigned to the precipitation ranges associated with changes in the 10-year 24-hour precipitation event, as discussed in Section 5.3. Table 6.1 through Table 6.4 summarize the number of culverts associated with the various Precipitation Exposure Index values, organized according to SRES emission scenario and analysis timeframe. Table 6.1 shows the results for MnDOT culverts; Table 6.2 shows the results for NYSDOT culverts; Table 6.3 shows the results for ODOT culverts; and Table 6.4 shows the results for WSDOT culverts. Maps showing the geospatial distribution of culverts associated with each of the PE Indices, SRES scenarios, and analysis timeframes are given in Appendix G for each state.

Within the MnDOT and NYSDOT culvert datasets, 259 and 508 culverts, respectively were located outside off the precipitation exposure areas. In all cases, these were culverts located along shorelines that were not completely covered by the climate dataset grid squares, or near large inland bodies of water that were similarly not covered by climate dataset grid squares. In both states, the culverts located outside of the precipitation exposure analysis area account for less than 0.8% of the culvert inventory, and have been omitted from the summary tables.

None of the four case-study states contained culverts that were assigned Precipitation Exposure Index values of 4 (i.e., >30mm precipitation change), and therefore the columns associated with these PE Indices are omitted. An examination of the precipitation projection maps shown in Figures 6.1 through 6.16 reveals that precipitation ranges associated with an index value of 4 only occurred in Oregon and Washington State in a very limited number of grid squares, and only in the end-of-century timeframe in Washington State. Given the limited inventories of culverts used for analysis in these states it is perhaps not surprising that no culverts were assigned Precipitation Exposure Indices of 4.

Table 6.1 MnDOT Culvert Precipitation Exposure Summary

Scenario/Timeframe	Precipitation Exposure Index 0		1		2		3	
B1 / Mid-Century	31233	43.3%	38617	53.5%	2305	3.2%	-	-
A2 / Mid-Century	54083	75.0%	18072	25.0%	-	-	-	-
B1 / End-Century	11282	15.6%	53259	73.8%	4108	5.7%	3506	4.9%
A2 / End-Century	16409	22.7%	51773	71.8%	3973	5.5%	-	-

n = 72414; 259 outside of exposure extent

The precipitation exposure summary for MnDOT (Table 6.1) shows several notable trends. First, between the analysis timeframes, there is a shift towards increased Precipitation Exposure Indices from mid-century to end-of-century. For example, under the A2 SRES scenario, three-quarters of culverts are assigned a Precipitation Exposure Index of 0 (no change, or decreasing precipitation) for the mid-century timeframe. However, this shifts to nearly three-quarters of culvert assigned a Precipitation exposure Index of 1 (0-10mm increase in the 10-year, 24-hour precipitation event magnitude) for the end-of-century timeframe. Interestingly, the greatest number of culverts subjected to positive changes in precipitation exposure is seen in the B1 (low) emission scenario for the end-of-century timeframe, not the A2 (mid-high) emissions scenario, as might have been expected given the discussion in Chapter 2.

Table 6.2 NYSDOT Culvert Precipitation Exposure Summary

Scenario/Timeframe	Precipitation Exposure Index 0		1		2		3	
B1 / Mid-Century	16918	25.6%	48938	74.1%	169	0.3%	-	-
A2 / Mid-Century	18883	28.6%	47115	71.4%	27	0.0%	-	-
B1 / End-Century	9214	14.0%	56757	86.0%	54	0.1%	-	-
A2 / End-Century	11689	17.7%	52412	79.4%	1889	2.9%	35	0.1%

n = 66533; 508 outside of exposure extent

The Precipitation Exposure summary for NYSDOT culverts (Table 6.2) exhibits similar trends to that for MnDOT culverts, albeit to a lesser extent. As with MnDOT culverts, there is a shift towards more culverts that are assigned higher Precipitation Exposure Indices when moving from the mid-century to end-of-century analysis timeframes (particularly Precipitation Exposure Index values of 1). When examining the Precipitation Exposure Index 2 and 3 columns, changes between timeframes are negligible under the B1 scenario, and minor under the A2 scenario. Also similar to the MnDOT data, greater numbers of culverts are exposed to increases in the 10-year, 24-hour precipitation event magnitude under the B1 scenario than under the A2 scenario.

Table 6.3 ODOT Culvert Precipitation Exposure Summary

Scenario/Timeframe	Precipitation Exposure Index							
	0		1		2		3	
B1 / Mid-Century	1286	40.3%	1725	54.1%	179	5.6%	-	-
A2 / Mid-Century	1250	39.2%	1628	51.0%	312	9.8%	-	-
B1 / End-Century	299	9.4%	2425	76.0%	466	14.6%	-	-
A2 / End-Century	185	5.8%	2292	71.8%	637	20.0%	76	2.4%

n = 3190

The ability to draw generalizations about the exposure of culverts in Oregon (Table 6.3) and Washington State (Table 6.4) to changes in the 10-year 24-hour precipitation event magnitude is somewhat limited by the use of limited or incomplete culvert inventories. More complete culvert datasets with broader, statewide coverage would enable more robust observations. However, some trends can be noted in the data that are available. In the ODOT precipitation exposure data, the majority of culverts under all emission scenarios and analysis timeframes are assigned Precipitation Exposure

Index values of 1, implying some increased exposure to extreme precipitation in the future among the culverts in the dataset. The precipitation exposure maps for Oregon (Figures 6.9 to 6.12) show that significant portions of the state are associated with Precipitation Exposure Index values of 0 (no change or decreasing precipitation) under the mid-century timeframe, but that that area decreases significantly under the end-of-century timeframe. This trend is reflected in the percentage changes of Precipitation Exposure Index assignment in Table 6.3. However, given the partial nature of the culvert inventories, the values of the percentage precipitation exposure of culverts may not be as significant as the trends they suggest.

Table 6.4 WSDOT Culvert Precipitation Exposure Summary

Scenario/Timeframe	Precipitation Exposure Index							
	0		1		2		3	
B1 / Mid-Century	1983	19.0%	8218	78.9%	212	2.0%	-	-
A2 / Mid-Century	2047	19.7%	8327	80.0%	39	0.4%	-	-
B1 / End-Century	95	0.9%	9275	89.1%	1043	10.0%	-	-
A2 / End-Century	189	1.8%	8445	81.1%	1751	16.8%	28	0.3%

n = 10413

The incomplete nature of the WSDOT culvert inventory dataset similarly makes it difficult to draw generalizations about the exposure of WSDOT's culvert inventory to changes in extreme event precipitation. An examination of the precipitation exposure maps (Figure 6.13 to 6.16), and the culvert inventory maps for Washington State (see Appendix G) reveal that the selected routes in this case-study are generally located in wetter parts of the state, where positive changes in the 10-year 24-hour precipitation event magnitude are projected. This is reflected in the WSDOT precipitation exposure summary (Table 6.4) in that at least 80% of culverts, under all emission scenarios and analysis timeframes, are assigned a Precipitation Exposure Index of 1.

One notable trend in both the ODOT and WSDOT data is the increase in the number of culverts assigned Precipitation Exposure Index values of 2 (and decrease in culverts assigned Precipitation Exposure Index values of 0) between the mid-century and end-of century timeframes. This suggests general agreement between emission scenarios that culverts will be exposed to increasing extreme precipitation event magnitudes over time under both climate scenarios. It also suggests that that projected increases in extreme event precipitation in Oregon and Washington State may possibly be greater than in Minnesota and New York State.

6.2 Vulnerability Analysis

The Culvert Vulnerability Analyses described in Section 5.4 were conducted for the four case-study DOT culvert datasets. The three vulnerability analysis methods (Method 1 – Exposure Only; Method 2 – Overall Culvert Condition Rating; Method 3 – Performance-Based) were applied to each state, where data were available, as follows:

- **MnDOT:** Method 1, Method 2, Method 3
- **NYSDOT:** Method 1, Method 2, Method 3
- **ODOT:** Method 1, Method 3
- **WSDOT:** Method 1

Recall from the discussion in Section 5.4 that ODOT does not assign overall condition ratings to culverts, preventing analysis using Method 2. Similarly, WSDOT does not rate condition or functional performance criteria, preventing analysis using Method 2 and Method 3.

Due to incomplete data recording within several of the data sets, not all culverts could be rated using all of the methods given above for each state DOT. For example, several culverts in the MnDOT and NYSDOT inventories were not assigned overall condition ratings (preventing Method 2 analysis) and were therefore omitted from the analysis. Also, several culverts in the MnDOT, NYSDOT and ODOT inventories were not assigned ratings for several of the condition and performance criteria used in the Method 3 vulnerability analysis. MnDOT and NYSDOT culverts with low Certainty Ratings (see Section 5.4.3.1 and 5.4.3.2), indicating that a number of the relevant criteria were not rated, were omitted from the vulnerability analysis. In MnDOT, culverts with Certainty Ratings below 3 (out of 5) were omitted from the analysis. In NYSDOT, culverts with Certainty Ratings below 2 (out of 2) were omitted. In ODOT, culverts with no assigned blockage ratings (out of three possible items) were omitted. The numbers of omitted culverts for each state are noted in the summary tables below.

Vulnerability analysis Method 1 does not assign a Vulnerability Index, but instead relies on the Precipitation Exposure Index and Combined Criticality Index to calculate the R-CAP Index. Precipitation Exposure Index values were summarized earlier in Section 6.1, and are not discussed further here. Maps showing the geospatial distribution of culverts associated with each of the Vulnerability Indices are given in Appendix H, for each state and method.

6.2.1 Vulnerability Index – Method 2

Vulnerability analysis results using Method 2 (Overall Culvert Rating-based analysis) for MnDOT and NYSDOT are summarized in Table 6.5. In both states, the majority of culverts are rated with low vulnerability (Vulnerability Index = 1), whereas less than 5% in each state are rated with high vulnerability (Vulnerability Index = 3). In both states, more than 11% of culverts were not assigned an overall condition rating, and could therefore not be analyzed using Method 2.

As overall culvert condition ratings in each state are determined according to different criteria (see Section 5.2), it is difficult to draw any comparisons between the Vulnerability Indices determined using Method 2 for MnDOT and those for NYSDOT. However, one notable outcome is that both states need more completeness in assigning overall condition ratings to culverts given that over 11% of culverts were unrated in each.

Table 6.5 Vulnerability Index – Method 2 Summary by State DOT

State DOT	Vulnerability Index - Method 2								Total Culverts
	1		2		3		Unrated		
MnDOT	54557	75.3%	6254	8.6%	3554	4.9%	8049	11.1%	72414
NYSDOT	37603	56.5%	19345	29.1%	1755	2.6%	7830	11.8%	66533

6.2.2 Vulnerability Index – Method 3

Vulnerability analysis results using Method 3 (functional performance-based analysis) for MnDOT, NYSDOT, and ODOT are summarized in Table 6.6. As with Method 2, the majority of culverts across all three case-study DOTs are rated with low vulnerability. The ODOT Vulnerability Indices in Table 6.6 show that more culverts are rated as medium or high vulnerability than the other DOTs. One explanation for this is likely the incomplete nature of the ODOT culvert inventory. Culverts in Oregon were inventoried by ODOT along selected routes across the state. It is possible that routes perceived as higher priority, or where greater conditional and performance-based deficiencies were expected, were inventoried first. However, more information is required to determine if this is a factor in the ODOT Method 3 Vulnerability Index ratings, or if other factors are contributing to generally greater vulnerability among the culverts inventoried in that state.

Table 6.6 Vulnerability Index – Method 3 Summary by State

State	Vulnerability Index - Method 3								Total Culverts
	1		2		3		Low Certainty/ Unrated*		
MnDOT	63677	87.9%	1766	2.4%	152	0.2%	6819	9.4%	72414
NSYDOT	45203	67.9%	4122	6.2%	336	0.5%	16872	25.4%	66533
ODOT	2119	66.4%	835	26.2%	188	5.9%	48	1.5%	3190

***** **(MN)** Certainty < 3; **(NY)** Certainty < 2; **(OR)** Overall Rating – Unrated

6.2.3 Comparison of Vulnerability Analysis Outcomes

One notable outcome of conducting the Culvert Vulnerability Analysis using multiple methods is the ability to compare outcomes across methods. The MnDOT and NYSDOT datasets were the only to which both vulnerability analysis Method 2 and Method 3 were applied. Table 6.7 summarizes the number of culverts that experienced changes in Vulnerability Index values between rating methods. The top half of Table 6.7 shows the complete accounting of changes in culvert Vulnerability Index ratings from Method 2 to Method 3. Note that the columns refer to changes in actual Vulnerability Index values. The bottom half of Table 6.7 then summarizes the total number of culverts that received either upgraded or downgraded Vulnerability Index ratings when moving from Method 2 to Method 3.

Table 6.7 Method 2 and Method 3 Vulnerability Analyses Comparison

<table>
<tr><th rowspan="2">State</th><th colspan="3">Upgraded Vulnerability Index</th><th colspan="3">Downgraded Vulnerability Index</th></tr>
<tr><th>From 1 to 2</th><th>From 2 to 3</th><th>From 1 to 3</th><th>From 3 to 2</th><th>From 2 to 1</th><th>From 3 to 1</th></tr>
<tr><td>MnDOT*</td><td>447</td><td>26</td><td>30</td><td>564</td><td>5590</td><td>2862</td></tr>
<tr><td>NYSDOT**</td><td>871</td><td>175</td><td>25</td><td>856</td><td>14254</td><td>354</td></tr>
<tr><th>State</th><th colspan="3">Total Culverts with Upgraded Vulnerability</th><th colspan="3">Total Culverts with Downgraded Vulnerability</th></tr>
<tr><td>MnDOT*</td><td>503</td><td colspan="2">0.69%</td><td>9016</td><td colspan="2">12.45%</td></tr>
<tr><td>NYSDOT**</td><td>1071</td><td colspan="2">1.61%</td><td>15464</td><td colspan="2">23.24%</td></tr>
</table>

*Excludes culverts with Certainty Ratings < 3;   **Excludes culverts with Certainty Ratings < 2

In both the MnDOT and NYSDOT datasets, substantially greater numbers of culverts were downgraded when moving from Method 2-based vulnerability analyses to Method 3-based vulnerability analyses. One possible explanation for this is the general exclusion of criteria in Method 3 not directly related to the functional performance of the culvert. That is, the overall condition rating for culverts in MnDOT and NYSDOT considers myriad other criteria beyond those selected for use in the Method 3 analysis. These include ratings of pavement condition, guardrails, wingwall, headwall, and other criteria that may affect structural aspects of the culvert, but not functional performance (i.e., blockage-based and embankment-based items). Culverts with higher overall condition ratings may nonetheless have some blockage-related deficiencies related to lack of maintenance, or other factors, which would assign Method 3 Vulnerability Index values lower than Method 2-based values.

Another possible explanation for greater downgrading of culvert Vulnerability Indices when moving from Method 2- to Method 3-based vulnerability analyses could also be the system of translating overall condition rating values into Vulnerability Indices under Method 2 (Table 5.6 and Section 5.4). In Table 5.6, the two top condition ratings for MnDOT culverts (scale from 1 to 4), and the top three condition ratings for NYSDOT culverts (scale from 1 to 7) are assigned Vulnerability Index values of 1, or “low” vulnerability. In both cases, fewer overall rating classifications are assigned to the medium and high Vulnerability Index values. Therefore, the calibration of the scale used to translate the quantitative overall culvert condition ratings into qualitative Vulnerability Index ratings may have some affect over the Method 2-based vulnerability analysis outcomes. Further research should investigate the calibration of Method 2-based vulnerability ratings using different overall condition rating scales from various state DOT culvert management systems, as calibration may have some influence over vulnerability analyses and their outcomes

6.3 Culvert Criticality Assessment

The Culvert Criticality Assessment described in Section 5.5 was conducted for the four case-study culvert inventories do determine each culvert’s Combined Criticality Index. The results from the culvert criticality assessment are shown below in table 6.8. Maps showing the geospatial distribution of culvert Combined Criticality Index ratings for each of the case-study are given in Appendix I.

Table 6.8 Combined Criticality Analysis Outcomes by State

State	Combined Criticality Index						Total Culverts
	1		2		3		
MnDOT	36788	50.8%	23397	32.3%	12229	16.9%	72414
NYSDOT	43950	66.1%	15261	22.9%	7322	11.0%	66533
ODOT	344	10.8%	2763	86.6%	83	2.6%	3190
WSDOT	1861	17.9%	8134	78.1%	418	4.0%	10413

Table 6.8 shows that the majority of culverts in the MnDOT and NYSDOT databases were assigned “low” criticality, or a Combined Criticality Index of 1. A smaller proportion of culverts in these two DOTs were assigned “medium” criticality, and fewer still were assigned “high” criticality. In contrast, the majority of culverts in the ODOT and WSDOT databases were assigned “medium” criticality, or a Combined Criticality Index of 2. Both outcomes may be explained as a function of the completeness of the respective culvert inventories.

The WSDOT and ODOT culvert inventories, as discussed earlier, are partial inventories of statewide culverts. In Oregon and Washington State, the culverts analyzed were predominantly located on major roadways. For example, the Washington State database contained culverts located along one state route highway, two US route highways, and one Interstate. Given the three constituent components of criticality used in the assessment, the outcomes in Table 6.8 seem reasonable. For example, major roadways are assigned higher Functional Classifications (used in the OP Index), and may be expected to generally carry higher freight volumes (used in the SE Index) than minor roadways. Therefore, the higher criticality assigned to ODOT and WSDOT culverts as compared to MnDOT and NYSDOT culverts, may be a function of some bias in the culverts (and roadways) selected for use in this case-study.

The proportion of culverts assigned to the three criticality ratings in the MnDOT and NYSDOT databases (Table 6.8) is somewhat more intuitive given the completeness of the culvert datasets. However, an examination of the geospatial distribution of higher-criticality culverts in Minnesota and New York State reveals several trends. Figure 6.17 and Figure 6.18 show the high-criticality culverts in Minnesota and New York State, respectively. High-criticality culverts in Minnesota are located almost exclusively along interstate corridors. These include I-90 along the bottom of the state, I-94 diagonally bisecting the state, I-35 connecting I-90 with Minneapolis, and I-494 and I-694 near Minneapolis. In fact, 11,691 of the 12,229 high criticality culverts in Minnesota are located along Interstate corridors. A similar trend exists among high-criticality culverts in New York State where most are located along Interstate corridors; specifically, I-81, I-84, I-86, I-88, I-87, and I-390 (see Figure 6.18).

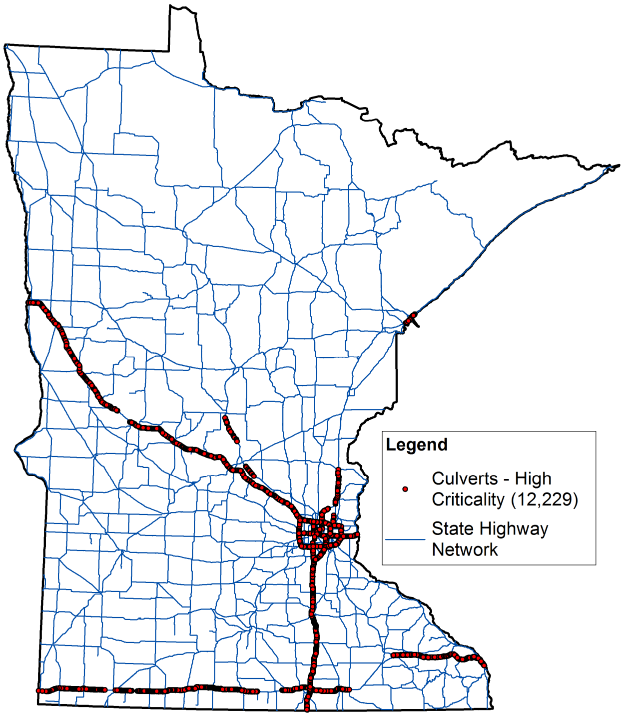


Figure 6.17 Minnesota High Criticality Culverts

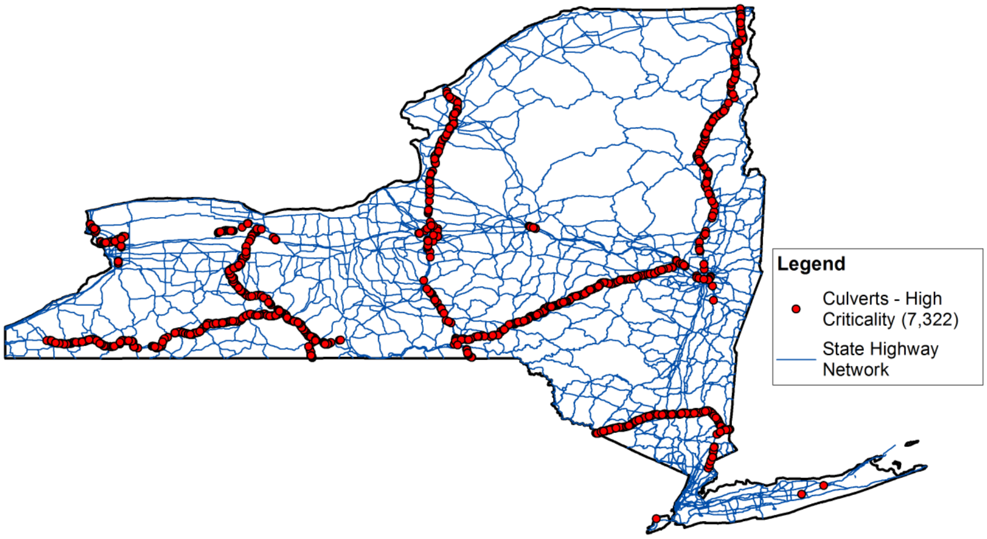


Figure 6.18 New York State High Criticality Culverts

6.4 Culvert Asset Prioritization Analyses

The Culvert Asset Prioritization analysis described in Section 5.6 was conducted for the four case-study culvert inventories. This consisted of first determining each culvert's Culvert Asset Prioritization (CAP) Index for each combination of SRES emission scenario and analysis timeframe. Within each combination of emission scenario and analysis timeframe, separate CAP Indices were determined using each of the three Vulnerability Analysis methods described in Section 5.4. The CAP Indices are viewed as intermediate results. The CAP Indices were then combined for each time-frame to generate a Robust Culvert Asset Prioritization (R-CAP) Index for each culvert. The R-CAP Index represents the relative timeframe-based risk of a culvert due to change climate impacts (i.e., extreme precipitation events) across multiple climate scenarios. The R-CAP Indices are viewed as the final results from the CCAAF, and are discussed below in greater detail.

The R-CAP Indices are presented in the following sections separately for each state. Results are presented here in tabular form. A comparison of R-CAP Index values determined using the varying vulnerability analysis methods for all four case-study DOTs are then presented and discussed. Appendix J contains maps showing the geospatial distribution of all R-CAP Index rated culverts among the four case-study DOTs according to relative risk level.

6.4.1 MnDOT R-CAP Index Results Summary

The R-CAP Index results of the MnDOT Culvert Asset Prioritization are shown in Table 6.9. For all analysis timeframes and vulnerability analysis methods, the majority of culverts (>71% in all cases) were found to have an R-CAP Index of 1, indicating low risk due to the climate change impacts associated with extreme precipitation. The percentage of culverts with R-CAP Indices equal to 2 and 3 in each analysis generally increase under the end-of-century analysis timeframe as compared with the mid-century timeframe. This is consistent with the results from the Precipitation Exposure Analysis for MnDOT culverts (Table 6.1), which show that the number of culverts exposed to larger increases in precipitation event magnitude is greater in the end-of-century timeframe than in the mid-century timeframe.

A discussion of the differences in R-CAP Index outcomes related to using different Vulnerability Analysis methods is given later in Section 6.4.5. However, an examination of the results given in Table 6.9 does indicate that the Vulnerability Index method chosen for analysis does influence the overall R-CAP outcomes, and that those outcomes are not apparently dominated entirely by the other two dimensions of risk (precipitation exposure and criticality).

Table 6.9 MnDOT Culvert Asset Prioritization Results Summary

Analysis Timeframe	Vuln. Index Method	Robust Culvert Asset Prioritization (R-CAP) Index							
		1		2		3		Low Certainty/ Unrated*	
Mid-Century	1	69832	96.4%	2323	3.2%	0	0.0%	-	-
End-Century	1	61680	85.2%	8924	12.3%	1551	2.1%	-	-
Mid-Century	2	60604	83.7%	3497	4.8%	9	0.01%	8045	11.1%
End-Century	2	51807	71.5%	12108	16.7%	195	0.3%	8045	11.1%
Mid-Century	3	63158	87.2%	2182	3.01%	0	0.0%	6815	9.4%
End-Century	3	55735	77.0%	9595	13.3%	10	0.01%	6815	9.4%

***(Method 2)** Unrated Overall Condition; **(Method 3)** Certainty < 3

An examination of the individual high-risk culverts in the dataset reveals some distinct trends. All 1,551 high-risk (R-CAP = 3) culverts rated using Method 1 for the end-of-century timeframe have Combined Criticality Indices equal to 3; all have a B1 Precipitation Exposure Indices equal to 3 and A2 Precipitation Exposure Indices equal to 2. Perhaps most notable is that all 1,551 are located in the metropolitan Minneapolis area (see Appendix J), and are predominantly (1,455 of the 1,551 culverts) located along Interstate corridors.

In considering the 195 high-risk (R-CAP = 3) culverts rated using Method 2 for the end-of-century timeframe, 191 are also located in the metropolitan Minneapolis area, and 162 are located along Interstate corridors. Combined Criticality Indices among the Method 2 end-of-century culverts are also predominantly equal to 3 (188 of 195 culverts). All have B1 Precipitation Exposure Indices equal to 2 or 3 (33 and 163 culverts, respectively), and A2 Precipitation Exposure Indices equal to 1 or 2 (35 and 160 culverts, respectively). However, Vulnerability Indices (Method 2) are predominantly equal to 2 (140 of 195 culverts). What this suggests is that criticality is a key factor in determining these culverts to be high risk, but also that vulnerability and exposure do contribute to R-CAP Index outcomes.

The 10 culverts identified as high-risk (R-CAP = 3) using Method 3 for the end-of-century analysis timeframe showed a more balanced contribution from the three dimensions of risk in establishing the high-risk rating. For example, although 9 of the 10 culverts were rated with high criticality, 4 of the 10 were rated with medium vulnerability (Method 3). For those 4 culverts, the Precipitation Exposure Indices of 3 (B1 scenario) and 3 (A2 scenario) balanced the medium vulnerability score to assign an overall R-CAP Index of 3 (high). Nonetheless, the common aspect of high criticality ratings appears to be a key factor in determining R-CAP Indices under Method 3 vulnerability analyses.

6.4.2 NYSDOT R-CAP Index Results Summary

The R-CAP Index results of the NYSDOT Culvert Asset Prioritization are shown in Table 6.10. Similar to the MnDOT results, the majority of culverts (>70% in all cases) were found to have an R-CAP Index of 1 for all analysis timeframes and vulnerability analysis methods. Note that nearly 25% of culverts could not be rated using Method 3 due to Certainty Rating values below 2. This data completeness issue may have the effect of skewing the R-CAP Index results associated with Method 3. However, it is noted that loosening the Certainty Rating criteria for Method 3 by dropping the threshold from 2 to 1 only reduces the percentage of unrated culverts to from 24.9% to 22.8% (16,558 culverts to 15,181 culverts).

Table 6.10 NYSDOT Culvert Asset Prioritization Results Summary

Analysis Timeframe	Vuln. Index Method	Robust Culvert Asset Prioritization (R-CAP) Index							
		1		2		3		Low Certainty/ Unrated*	
Mid-Century	1	62076	93.3%	3949	5.9%	0	0.0%	-	-
End-Century	1	60949	91.6%	5076	7.6%	0	0.0%	-	-
Mid-Century	2	51340	77.2%	6870	10.3%	0	0.0%	7815	11.7%
End-Century	2	50071	75.3%	8138	12.2%	1	0.002%	7815	11.7%
Mid-Century	3	46893	70.5%	2574	3.9%	0	0.0%	16558	24.9%
End-Century	3	46146	69.3%	3320	5.0%	1	0.002%	16558	24.9%

***(Method 2)** Unrated Overall Condition; **(Method 3)** Certainty < 2

Similar to the MnDOT R-CAP Index data, the percentage of culverts with R-CAP Indices equal to 2 and 3 in each analysis generally increase under the end-of-century analysis timeframe as compared with the mid-century timeframe. This is consistent with the results of the NYSDOT precipitation exposure analysis discussed above (Table 6.2).

Note that only one culvert in the NYSDOT database was rated with high risk (R-CAP Index = 3), and then only under the Method 2 and Method 3 vulnerability analyses in the end-of-century timeframe. Interestingly, the culverts designated as high risk by the Method 2 and Method 3-based analyses are not the same asset, although both are in western New York State (see Appendix J). In both cases, the Combined Criticality Index was 3 (high) and the respective Vulnerability Index was 3 (high). However, for both culverts, the B1 and A2 Precipitation Exposure Values were 1 and 2, respectively, suggesting that the Precipitation Exposure Index had lesser influence on the R-CAP Index for these culverts than did the other two dimensions of risk.

6.4.3 ODOT R-CAP Index Results Summary

The R-CAP Index results of the ODOT Culvert Asset Prioritization are shown in Table 6.11. ODOT does not assign culverts an overall condition rating, thus R-CAP Indices could not be determined using Method 2. Consistent with trends in the MnDOT and NYSDOT data, the majority of culverts in the ODOT database (>61%) are assigned an R-CAP Index of 1, indicating low climate change impact risk. However, different from the MnDOT and NYSDOT data, a substantially greater percentage of the culverts in the ODOT database were assigned medium risk (R-CAP Index = 2), particularly when using Method 3-based vulnerability analyses. Differences in the assignment of high risk (R-CAP = 3) as compared with the MnDOT results are somewhat smaller (mainly in number of culverts, not percentage of the inventory), and of negligible difference when compared with the NYSDOT R-CAP results.

Table 6.11 ODOT Culvert Asset Prioritization Results Summary

Analysis Timeframe	Vuln. Index Method	Robust Culvert Asset Prioritization (R-CAP) Index							
		1		2		3		Unrated*	
Mid-Century	1	3018	94.6%	172	5.4%	0	0.0%	-	-
End-Century	1	2715	85.1%	472	14.8%	3	0.09%	-	-
Mid-Century	3	2543	79.7%	598	18.7%	1	0.03%	48	1.5%
End-Century	3	1976	61.9%	1164	36.5%	2	0.06%	48	1.5%

***(Method 3)** No Rated Blockage Conditions;

One possible explanation for the slightly greater assignment of culverts to R-CAP Indices of 2 in Oregon as compared to MnDOT and NYSDOT culverts has to do with the general exposure to increases in the magnitude of the 10-year 24-hour precipitation event in Oregon. An examination the Precipitation Exposure figures for Oregon (Figures 6.9 to

6.12) shows generally greater increases in the magnitude of the 10-year 24-hour precipitation event, as compared with Minnesota and New York State.

This explanation is further supported by the significantly higher assignment of Precipitation Exposure Indices of 2 in Oregon (as a percentage of the culvert inventory) under all combinations of emission scenarios and analysis timeframes, than in Minnesota and New York for the same (as seen by comparing Table 6.3 with Tables 6.1 and 6.2). The greater assignment of higher Precipitation Exposure Indices in Oregon is also likely influenced by the generally more widely-spread projected increases in precipitation event magnitude in Oregon, but also by the fact that the culverts examined were generally located in parts of the state projected to become wetter, particularly in the end-of-century timeframe (see Appendix G).

Another possible explanation for the greater assignment of culverts to R-CAP Indices of 2 in Oregon has to do with the assignment of criticality to ODOT culverts. Table 6.8 shows that the Combined Criticality Indices for ODOT culverts were predominantly medium criticality (Combined Criticality Index = 2), and significantly more culverts in Oregon were rated as medium criticality than in Minnesota and New York. As discussed above in Section 6.3, the upward trend in criticality in Oregon is possibly due to the incomplete and possibly selective nature of the current ODOT culvert inventory.

Therefore, although the general trends of R-CAP Index assignment for ODOT culverts are consistent with those seen in the MnDOT and NYSDOT results, the greater assignment of R-CAP Indices equal to 2 in is likely due to the compounding effect of generally greater Precipitation Exposure and Combined Criticality Indices in Oregon.

The ODOT R-CAP Index results also exhibit the trend of generally increased risk (higher R-CAP Indices) among the end-of-century analysis timeframe culverts as compared with the mid-century timeframe. This is consistent with the MnDOT and NYSDOT results, the Precipitation Exposure Index results (Table 6.3) as well as with the general discussion of North American climate change impacts in Chapter 2.

6.4.4 WSDOT R-CAP Index Results Summary

The R-CAP Index results of the WSDOT Culvert Asset Prioritization are shown in Table 6.12. As WSDOT does not record condition and performance data for the culverts in its inventory, only R-CAP Indices determined as a function of Precipitation Exposure Indices and Combined Criticality Indices could be assigned. Consistent with the previous case-study results, the majority of culverts in the provided WSDOT database (>87%) were assigned low risk (R-CAP Index = 1).

Table 6.12 WSDOT Culvert Asset Prioritization Results Summary

Analysis Timeframe	Vuln. Index Method	Robust Culvert Asset Prioritization (R-CAP) Index					
		1		2		3	
Mid-Century	1	10017	96.2%	396	3.8%	0	0.0%
End-Century	1	9116	87.5%	1297	12.5%	0	0.0%

The distribution of WSDOT culvert R-CAP Index assignment is generally consistent with the results from the previous three case-study DOTs under Method 1-based vulnerability analyses (i.e., exposure only, omitting any measure of culvert vulnerability). However, given the substantially greater number of culverts rated with medium criticality (Combined Criticality = 2) in Washington State than in Minnesota and

New York (see Table 6.8) one might expect a greater number of medium and high risk culverts in Washington (as was seen in Oregon). One explanation for this is that the majority of medium criticality culverts (and in fact, most culverts overall) lie predominantly in regions with Precipitation Exposure Indices of 1 (see Table 6.4). Given the structure of the CAP Index matrix (Figure 5.10), low exposure culverts with medium criticality are assigned CAP Indices of 1. In Oregon, by comparison, substantially more culverts overall are assigned Precipitation Exposure Indices of 2 than in Washington. This results in greater numbers of medium risk culverts (R-CAP Index = 2) in Oregon than in Washington, which is consistent with the results seen in Tables 6.11 and 6.12

Lastly, the WSDOT R-CAP Index results exhibit the trend of generally increased risk (higher R-CAP Indices) among culvert in the end-of-century analysis timeframe as compared with the mid-century timeframe. This is consistent with the previous case-study results and with the general discussion of North American climate change impacts in Chapter 2 (i.e. greater changes over longer timeframes).

6.4.5 Comparison of R-CAP Index Values Using Multiple Vulnerability Methods

The R-CAP Index values determined using the three vulnerability analysis methods are compared in Table 6.13. The source tables used to construct Table 6.13, which contain changes in individual culvert ratings across vulnerability analysis methods, are provided in Appendix K.

Table 6.13 is arranged according to changes in culvert R-CAP Indices among vulnerability analysis methods. The top half of Table 6.13 shows changes in R-CAP Index ratings across vulnerability analysis methods for the mid-century analysis timeframe; the bottom half of Table 6.13 shows the same for the end-of-century analysis timeframe. Note that the values given in Table 6.13 exclude culverts that lie outside of the precipitation projection areas (MnDOT and NYSDOT), culverts for which a Method 2 Vulnerability could not be assigned (i.e., no overall condition rating was assigned), and culverts with insufficient Certainty Ratings (< 2 for NYSDOT, < 3 for MnDOT).

Table 6.13 Changes in R-CAP Index Values Among Vulnerability Analysis Methods

Change in Vuln. Method for R-CAP	**State**	**Mid-Century**					
		No Change		**Upgraded**		**Downgraded**	
Method 1 to 2	Minnesota	62630	97.7%	1480	2.3%	0	0.0%
	New York	54290	93.3%	3920	6.7%	0	0.0%
Method 1 to 3	Minnesota	65206	99.8%	134	0.21%	0	0.0%
	New York	48741	98.6%	726	1.5%	0	0.0%
	Oregon	2711	86.3%	431	13.7%	0	0.0%
Method 2 to 3	Minnesota	60943	97.8%	32	0.05%	1367	2.2%
	New York	45671	94.3%	202	0.42%	2558	5.3%
Change in Vuln. Method for R-CAP	**State**	**End-Century**					
		No Change		**Upgraded**		**Downgraded**	
Method 1 to 2	Minnesota	59674	93.1%	3376	5.3%	1060	1.7%
	New York	53636	92.1%	4574	7.9%	0	0.0%
Method 1 to 3	Minnesota	63671	97.4%	478	0.73%	1191	1.8%
	New York	48594	98.3%	873	1.8%	0	0.0%
	Oregon	2445	77.8%	696	22.2%	1	0.03%
Method 2 to 3	Minnesota	59052	94.7%	109	0.17%	3181	5.1%
	New York	45201	93.4%	250	0.52%	2980	6.2%

One noticeable trend shown in Table 6.13 is that the move to incorporate some measure of vulnerability (i.e., moving from Method 1 to either Method 2 or Method 3 vulnerability analyses) generally results in more culverts with upgraded R-CAP Index values (increasing the number of higher risk culvert) than with downgraded R-CAP Index values (decreasing the number of higher risk culverts). This is seen by comparing the percentage values of the "Downgraded" and "Upgraded" columns for each state and vulnerability method. In contrast, moving from R-CAP Indices based on Method 2 to those based on Method 3 vulnerability analyses has the opposite effect. That is, more culverts received downgraded R-CAP Index values than received upgraded R-CAP Index values. Each of these phenomena are discussed below.

The general effect of upgrading culverts to higher risk (i.e., higher R-CAP Indices) when moving from vulnerability analysis Method 1, to either Method 2 or Method 3 is possibly a function of adding a third risk dimension (vulnerability) to the R-CAP Index calculation, thus reducing the overall influence of the other two dimensions (precipitation exposure, and criticality). That is, Method 1 does not consider any measure of culvert vulnerability, but implicitly assumes that all culverts have equal vulnerability. Under Method 1, precipitation exposure and criticality are therefore equally weighted in the R-CAP Index calculation, each contributing half. When the third dimension of vulnerability is introduced, all three dimensions (precipitation exposure, criticality, and vulnerability) are still equally weighted, and therefore each now contributes one third to the R-CAP Index calculation.

An examination of Table 6.5 shows that 13.5% of MnDOT culverts, and 31.7% of NYSDOT culverts receive Vulnerability Indices of 2 or 3 (i.e., medium to higher vulnerability) under Method 2. Similarly, Table 6.6 shows that 2.6% of MnDOT culverts, 6.7% of NYSDOT culverts, and 32.1% of ODOT culverts receive Vulnerability Indices of 2 or 3 under Method 3. Therefore, when these culverts with greater vulnerability are factored in to the R-CAP Index calculation, the relative influence of the other two dimensions on the overall outcomes is decreased (as all three dimensions, which now includes vulnerability, are equally weighted), and the net effect is to increase the number of culverts with higher R-CAP Index values. A comparison of the percentage of culverts with higher Vulnerability Indices (Table 6.5 and Table 6.6) with the percentage of culverts with upgraded R-CAP Indices (Table 6.13) shows that the relative magnitudes of percent change are consistent across states. This is particularly apparent for the ODOT inventory where a substantial percentage of culverts (31.7%) received medium and high vulnerability indices (Table 6.5), and a substantial percentage similarly received upgraded mid-century (13.7%) and end-of-century (22.2%) R-CAP Indices.

The net downgrading of R-CAP Indices between Method 2 and Method 3-based analyses is possibly explained by the types of culvert condition and performance criteria used to generate the Method 2 and Method 3 Vulnerability Indices. As discussed in Section 6.2.3, the overall condition rating (upon which Method 2 vulnerability is based) for culverts in MnDOT and NYSDOT are influenced by criteria beyond those selected for use in the Method 3 analysis (such as, pavement condition, guardrails, wingwalls, headwall, etc). These criteria may not affect the functional performance of the culvert (upon which the Method 3 vulnerability is based), but are significantly greater in number than the relatively small number of functional performance criteria used in Method 3.

The suggestion is that by incorporating the ratings of other criteria into the overall condition rating, culverts with good overall condition ratings may receive high overall ratings, despite the presence of blockage-related or embankment-related deficiencies that would designate Method 3 Vulnerability Index values lower than Method 2-based values.

This explanation is further supported by an examination of the individual culverts in the MnDOT and NYSDOT databases. Specifically, the number of culverts in Minnesota that received higher Method 2-based Vulnerability Index ratings (9,016 culverts) was significantly higher than the number of culverts that received higher Method 3-based Vulnerability Index ratings (503) culverts. The same trend is evident in the NYSDOT database, where 15,552 culverts received higher Method 2-based Vulnerability Index ratings and 7,249 culverts received higher Method 3 Vulnerability Index ratings). These results generally suggest that the inclusion of more detailed data that more adequately accounts for functional performance of culverts may be more appropriate for use in vulnerability analyses. This raises the fundamental question as to which of the two Vulnerability Index rating methods provides a better approximation of a culvert's true vulnerability to increased flows. However, the current case study results do not provide sufficient information upon which to base such judgments. This is discussed in greater detail in Section 6.5, and Chapter 7.

Another notable comparison from Table 6.13 is between results from the mid-century and end-of-century analysis timeframes. In general, fewer culverts maintained their R-CAP Index ratings across vulnerability analysis methods in the end-of-century analysis timeframe than under the mid-century analysis timeframe. That is, a noticeably greater number of culverts were upgraded in the end-of-century analysis timeframe than in the mid-century timeframe, and a slightly greater number of culverts were downgraded in the end-of-century timeframe than in the mid-century timeframe. The initial implication of this is that the use of more detailed vulnerability analysis methods (i.e., Method 2 and Method 3) had a slight, but noticeable impact of increasing the number of upgraded and downgraded R-CAP Index values in the end-of-century timeframe as compared to the mid-century timeframe. Below these changes are discussed with respect to upgraded culverts, downgraded culverts, and the more substantial changes seen in the Method 2 to Method 3 results.

The greater percentage of culverts upgraded in the end-of-century timeframe as compared with the mid-century timeframe are most intuitively explained by changes in precipitation exposure between the two timeframes. Across all methods and timeframes in Table 6.13 (and in this analysis, in general), culvert criticality and culvert vulnerability do not change. Only precipitation exposure changes between analysis timeframes, generally increasing from the mid-term analysis period to the end-of century analysis period for all states and emission scenarios. Table 6.1 to Table 6.4 show that the number of culverts subject to medium to large increases in precipitation event magnitude (i.e., Precipitation Exposure Index = 2 or 3) constitute a small but notable percentage of the DOT culvert inventories. The greater frequency of culverts with medium and high Precipitation Exposure Indices in the end-of-century timeframe affects the CAP Index, and therefore R-CAP Index calculation, by increasing the index values. These increases in the number of culverts assigned medium and high Precipitation Exposure Indices between the mid- and end-of-century timeframes may reasonably account for the greater numbers of culverts that are upgraded between analysis timeframes in Table 6.13.

The explanation for the relatively small percentage of downgraded culverts in the end-of-century analysis timeframe is not as intuitive, but may essentially be attributed to a small number of culverts in high precipitation exposure areas with low vulnerability ratings. For example, Table 6.13 shows that 1.7% and 1.8% of MnDOT culverts received downgraded R-CAP Indices when moving from Method 1 to Method 2, and from Method 1 to Method 3-based vulnerability analyses, respectively. An examination of the MnDOT database reveals that all culverts downgraded when moving from Method 1 to both Method 2 and Method 3 received Combined Criticality Indices of 3. Similarly all culverts under both vulnerability analysis methods received a B2 scenario precipitation exposure of 3 (high) and an A2 scenario precipitation exposure of 2 (medium). However, all of the downgraded culverts, under both methods, received a vulnerability score of 1 from their respective methods. Consequently, all culverts downgraded between Method 1 and Method 2-based R-CAP Indices, and between Method 1 and Method 3-based R-CAP indices were downgraded from an R-CAP Index of 3 to an R-CAP Index of 2. The same phenomenon explains the downgrading of the ODOT culverts. As no culverts were downgraded in the NYSDOT database, no explanation is necessary. Interestingly, all of these downgraded culverts in the MnDOT inventory are in the metropolitan Minneapolis area and lie within the same two climate projection grid squares, see Figure 6.19.

Differences in the number of culverts downgraded in the mid-century and end-of-century timeframes between Method 2 and Method 3 are most likely explained by a combination of the effect of increased precipitation exposure (Table 6.1 and Table 6.2) and substantially decreased vulnerability (Table 6.7). Table 6.7 shows that both MnDOT and NYSDOT culverts were predominantly downgraded from a Vulnerability Index of 2 to a Vulnerability Index of 1. As the majority of culverts in both states received a Vulnerability Index of 1, under both vulnerability analysis methods, any expected increases in R-CAP Index when moving from the mid-century to end-of-century timeframe due to increasing Precipitation Exposure Indices (which accounts for a minor percentage, see Table 6.1 and Table 6.2) are far outweighed by the larger general decreases in Vulnerability Indices when moving from Method 2 to Method 3 (Table 6.7).

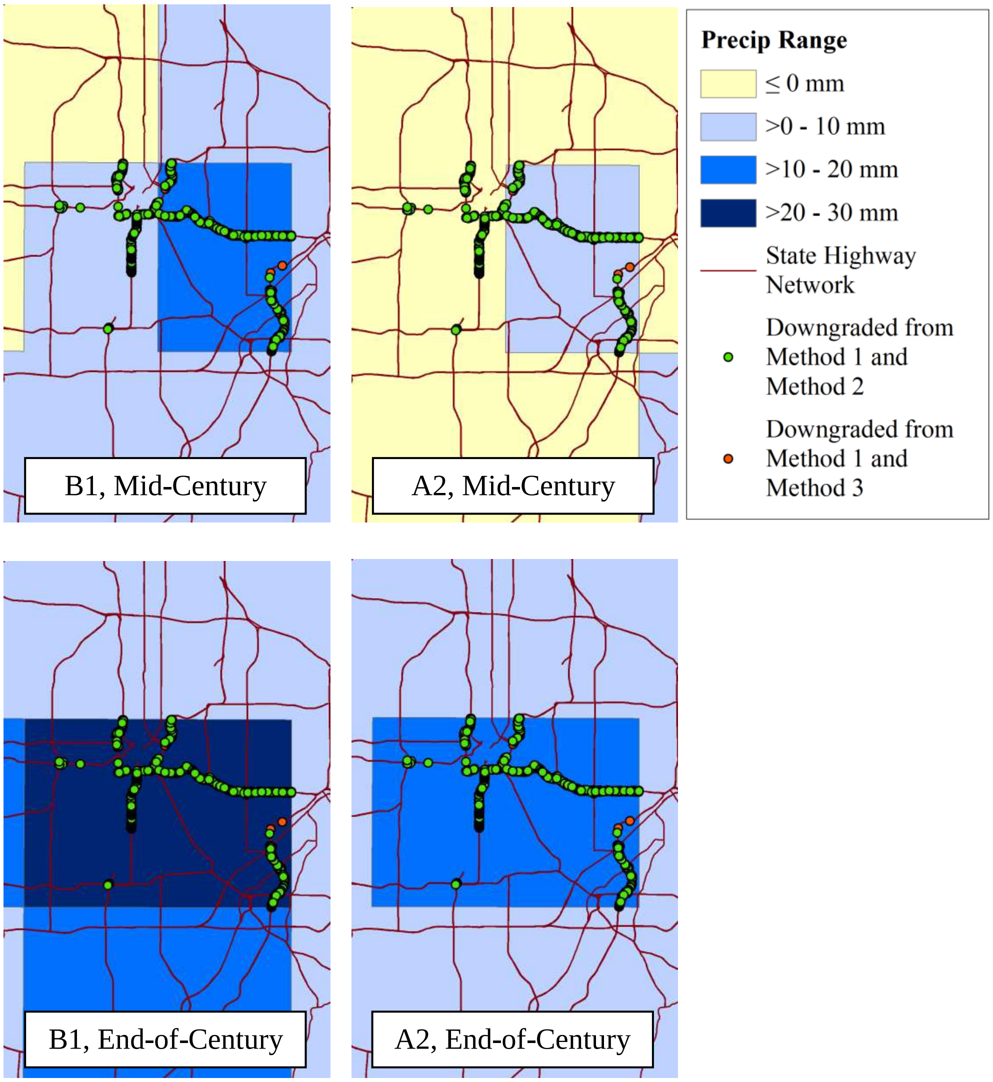


Figure 6.19 Downgraded MnDOT Culverts

6.5 Methodological Significance of Results

The results of the case-study implementation of the CCAAF described above offer several relevant insights into structural and methodological characteristics of the framework. Several of these insights were discussed briefly in the sections above, and are discussed in greater detail in the following sub-sections.

6.5.1 Completeness of Inventories and Data Recording

The results of the case studies illustrate the importance of complete culvert inventories, and of completeness in the data recorded for those inventories. This is particularly true given the network-level nature of the CCAAF and the individual analysis steps of which it is composed. As shown in the results of the Precipitation Exposure Analysis for ODOT and WSDOT culvert inventories (Section 6.1.3 and Section 6.1.4), the incomplete nature of those DOT culvert inventories makes it difficult to draw significant conclusions about the network-wide exposure of culvert assets to changes in precipitation. Additionally, as shown in the results of the Method 2-based Vulnerability Analyses for MnDOT and NYSDOT culvert inventories (Section 6.2.1), over 11% of culvert in both states were unrated with respect to overall culvert condition ratings, and therefore could not be assigned a Method 2-based Vulnerability Index. Therefore, although the culvert inventories were mostly complete in those states, the data within the inventories lacked completeness.

Lack of completeness in both culvert inventories and culvert data recording may lead to an inaccurate characterization of how the three dimensions of risk are distributed across the culvert inventories. This, in turn, may lead to inaccuracy in the assignment of R-CAP Indices across inventories. For states or agencies where culvert inventories only contain partial coverage of agency culvert assets, seeking to complete the spatial inventory of culverts should be a priority. Even without complete condition and functional performance information, the results of the Culvert Asset Prioritization (Section 6.4) indicate that R-CAP Index assignment under Method 1 (no measure of relative vulnerability) can still yield valuable insight. However, these results are strengthened by analyzing complete inventories, which allows for a more accurate view of the system-wide distribution of the two dimensions under consideration (exposure and criticality).

States and agencies with complete (or nearly complete) culvert inventories should seek to increase data recording completeness, filling in gaps where data items are missing. This is particularly important for the two vulnerability analysis methods proposed in this research project, which rely on a relatively few condition and functional performance data items to assess culvert vulnerability. Data completeness mitigates the possibility of a skewed or inaccurate characterization of culvert vulnerabilities at the network-level by ensuring that culverts with significant vulnerabilities (or without them) are not hidden within large percentages of unrated culverts.

6.5.2 Measures of Vulnerability

The case-study results (particularly the vulnerability analyses and the R-CAP Index assignments) illustrate that the assessment outcomes are highly influenced by several aspects of the vulnerability analyses. This is evident at several stages of the CCAAF assessment process and requires further refinement of the CCAAF.

One issue that the results suggest is the importance of calibration in applying the CCAAF to scale-based measures of culvert condition and functional performance. Poor calibration may result in qualitative Vulnerability and R-CAP Indices that do not accurately reflect the quantitative ratings assigned during culvert inspection and management activities. In turn, this may introduce unintended biases into the analyses wherein culvert vulnerability, or other characteristics, are systematically under- or over-estimated. For example, the results comparing the outcomes of Method 2- versus Method 3-based vulnerability analyses suggest that the calibration of the rating scale used to translate culvert overall condition ratings into Vulnerability Index ratings influenced the analysis outcomes (i.e., downgraded vulnerability when moving from Method 2 to Method 3).

Similarly, it is likely that the greater downgrading of culvert R-CAP Index values in the end-of-century timeframe than in the mid-century timeframe (when also moving from Method 2- to Method 3-based vulnerability) is also partially influenced by poor calibration. In this instance, the only risk dimension that changed between analysis timeframes is the precipitation exposure (which, generally speaking increases), yet the results suggest that differences in vulnerability analyses (when moving from Method 2 to Method 3) likely also contributed to assessment outcomes characterized by net downgrading of culvert R-CAP Indices. This serves to underscore the importance of rating scale calibration to ensure that external or unintended factors do not influence vulnerability analysis outcomes, and that Vulnerability Indies faithfully reflect the quantitative ratings they characterize. Another factor in this net downgrading was likely also the overall weighting of the three risk dimensions, which is discussed in the next section.

It is important that the method of translating DOT culvert rating scale values into Vulnerability Indices are sufficiently calibrated so that they faithfully reflect the information conveyed by the culvert condition and functional performance inspection data. However, at a higher level, it is also important that the vulnerability analysis methods developed provide accurate reflections (or sufficiently accurate approximations) of the true vulnerability of culverts to increased flow conditions given the culvert management data available. The differences in results between Vulnerability Analysis methods, although likely influenced by calibration-based issues, also illustrate that the data currently collected can be used in different types of vulnerability analysis methods to arrive at very different indications of culvert vulnerability. That is, different data items used to describe the condition of the same culvert asset, when used in different types of analyses, can give very different indications of vulnerability. Although both vulnerability analysis methods used in this study are based on knowledge of culvert failure modes, and utilize inspection data of the actual culverts, they may still not accurately reflect true vulnerability.

The inaccurate characterizations of a culverts' true vulnerability resulting from the use of various vulnerability analysis methods poses a challenge to assessment frameworks, particularly given the wide variety in the types and detail of culvert data currently collected. The diverse approaches to data collection likely reflect, to some degree, the location-, environment-, design-, and material-specific aspects of the culverts under an agencies' management. Given the significant diversity of design requirements, design environments, and the mechanistic impact of those environments on functional performance, it is reasonable that there would be a need for similarly diverse data collection practices. Thus, it may be unwise to seek nationally standardized vulnerability analysis methods. Instead, a better course may be to pursue national guidance with respect to culvert vulnerability analysis that still seeks to increase replicability of assessment practices, but recognizes the presence of location- and design-specific concerns and the need for flexibility in analysis methods; this is discussed more in the next chapter.

6.5.3 Overall Weighting of the Three Dimensions of Risk

One of the broadest methodological outcomes suggested by the case study results is the need for greater attention to the overall weighting of the three dimensions of risk during the CCAAF assessment process. The approach used in the case studies was to equally weight the three dimensions of risk. However, under this approach, several of the results indicated that R-CAP Index outcomes were frequently dominated by one or two of the dimensions of risk (i.e., one or two of the constituent indices). For example, the R-CAP Index results of the MnDOT culvert asset prioritization indicate that the Combined Criticality Index may have dominated the analysis. All of the culverts rated as high risk (R-CAP Index = 3) under Method 1- and Method 2-based analyses in the end-of-century timeframe were also all rated with high combined criticality. Although the results indicate that the other two indices (the Precipitation Exposure Index, and to a much lesser extent, the Vulnerability Indices) did influence the high R-CAP Index rating, these results suggest that an equal weighting of the risk dimension inputs did not necessarily equate to their equal influence over the R-CAP Index outcomes.

The results comparing R-CAP Indices between Method 2- and Method 3-based analyses are another example of the influence of risk dimension weighting on assessment outcomes. R-CAP Index assignment between mid-century and end-of-century analysis timeframes, when moving from Method 2- to Method 3-based analyses, resulted in a net downgrading of R-CAP Indices for MnDOT and NYSDOT culverts. Rating scale calibration, as discussed above in Section 6.5.2, likely influenced this to some extent. However, as discussed at the end of Section 6.4.5, the majority of MnDOT and NYSDOT culverts with downgraded R-CAP Indices were downgraded from a Vulnerability Index of 2, to a Vulnerability Index of 1. Yet, in spite of the general trend of increased precipitation (and thus generally increased Precipitation Exposure Indices, see Table 6.1 and Table 6.2), the net effect was one of downgraded R-CAP Indices. This suggests that although risk dimensions were equally weighted in these analyses, the Vulnerability Index exerted greater influence over the R-CAP Index outcomes than the Precipitation Exposure Index.

The implication of these results is that the weighting of risk dimensions can have a significant influence over the outcomes of the CCAAF, and that further research is necessary to better understand the relationship and interaction among the three dimensions. Sensitivity analyses of risk dimension weighting would likely clarify some of this relationship, and would be an important contribution to strengthen the fundamental methodology of this assessment framework. A better understanding of risk dimension weighting through these types of analyses would also lay a better foundation upon which to undertake the rating scale calibration, and to further develop vulnerability analysis methods as discussed in the previous two sections. In short, while this dissertation research has demonstrated the ability of the CCAAF to yield reasonable outcomes given current data availabilities, the validity and reliability of those results can be substantially enhanced with a more thorough understanding of the interplay among risk dimensions, and thus how weighting can be used to improve culvert asset prioritization outcomes.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

This research study has sought to develop a nationally applicable, risk-based framework that will enable transportation agencies to assess and prioritize the network-level adaptation needs of highway culvert assets given the projected impacts of climate change. Specifically, this framework examines the impacts of projected increases in extreme precipitation to highway culvert assets and the potential for disruption to roadways due to the failure of those assets under increased flows. The outcome of this research objective has been the development of the Culvert Climate Adaptation Assessment Framework (CCAAF).

The CCAAF was then implemented in a series of case studies, using culvert inventory and attribute data provided by four state DOTs (Minnesota, New York State, Oregon, and Washington State), as well as national infrastructure datasets, to evaluate and assess the efficacy of the CCAAF's application as an infrastructure management and planning tool given current data availabilities and culvert management practices. The four case study DOTs represent transportation agencies with culvert management systems of varying maturity and sophistication. While all case study states are located in the northern United States, they present different climate and environmental conditions. In all four case studies, the same assessment framework was utilized, with some adjustments made to the vulnerability analysis methods due to differences in culvert management data from state to state.

The outcomes of these case studies demonstrate that despite differing culvert management practices among state DOTs, reasonable assessments of climate change-related impacts to culvert assets can be undertaken. This is facilitated by the use of nationally-available climate change datasets and infrastructure data, which enhances the replicability of the framework among state DOTs in all regions of the United States. However, the outcomes of the four case studies do also demonstrate that risk prioritization outcomes are highly dependent upon the types of culvert management data used to facilitate the vulnerability analysis component of the framework. Therefore, continued research is necessary to clarify the culvert management data needs and vulnerability analysis methods that would best promote a nationally-applicable assessment, thus enabling a more equitable competition for federal adaptation funding, should such funds become available in the future.

There are three important contributions of this research. The first, a methodological contribution, is the development and demonstration of the risk-based adaptation assessment framework itself. The CCAAF represents an initial effort to move away from climate change adaptation assessment practices that use the traditional definition of risk (the combination likelihood and consequence). This traditional definition of risk can be problematic in situations where probabilistic or qualitative likelihood cannot be easily determined. Instead, the CCAAF offers a new characterization of infrastructure asset risk due to climate change impacts as a function of three dimensions (climate impact exposure, asset vulnerability, and asset criticality), which can be examined across multiple scenarios that represent plausible characterizations of future conditions, to arrive at robust assessment outcomes. This contribution expands the current risk management toolkit available to transportation professionals (and potentially to other infrastructure professionals), and provides an alternative means by which to assess infrastructure and asset adaptation needs.

The second and third major contributions have to do with specific steps within the CCAAF that are more practice-oriented contributions rather than methodological. The first is the development of an extreme precipitation event projection method whereby projections of high-frequency heavy precipitation events (e.g., 10-year storm) are used as indicators of low-frequency extreme precipitation events. These indicators are used in a geospatial analysis to determine the spatial extent and qualitative changes in precipitation magnitudes of those events to facilitate system-wide comparison of exposure.

The next contribution is the development of two culvert vulnerability analysis methods that illustrate how culvert management data (i.e., condition and functional performance data) can be used to characterize the failure potential of highway culverts as a result of increased flow conditions. The two simplified methods proposed in this research provide a foundation for future research in culvert deterioration and vulnerability modeling as may be relevant to the emerging sub-discipline of ancillary asset management (which may be expected to expand substantially in the future given recent revelations in federal transportation legislation).

In addition to these contributions, this research helps to identify several assessment framework attributes that would be desirable in future assessments, and provides an outline of the types of data and information needed to perform such assessments. Such an outline may enable the identification and integration of additional data types into the assessment framework as it evolves in future implementations. For example, this research indicates the importance of inventory and inventory data completeness in conducting network-level assessments of climate change impact risks to infrastructure. Inventory and data completeness enables a more accurate characterization of how climate impact exposure, vulnerability, criticality and risk are distributed across network assets.

Second, this research indicates that current culvert management data may be useful in developing relative measures of culvert vulnerability, although much research is needed to further explore such measures, as well as the data needed to support them. For example, future research must investigate the calibration of the proposed vulnerability analysis methods to ensure that the qualitative measures of vulnerability in this study faithfully convey the quantitative information contained in the culvert management data items. More broadly, future research must also investigate whether the vulnerability measures proposed in this study provide reasonable approximations of culverts' true vulnerability in increased flow conditions, but also investigate new measures and data needs that may offer similar measures of vulnerability.

Lastly, this research demonstrates that the three dimensions of risk proposed in this study provide a practical alternative characterization of infrastructure climate change impact risks, but that the usefulness of that characterization can be enhanced through a better understanding of how those dimensions interact with one another and influence risk outcomes. These contributions of the CCAAF and attributes identified as desirable in future frameworks are discussed in greater detail in the following sections.

7.1 The Multi-Dimensional Characterization of Risk

The cascading effect of uncertainty in climate change modeling complicates the use of adaptation approaches based upon the traditional definition of risk (i.e., the combination of event likelihood and consequence). This is because climate change projections simply provide plausible characterizations of future conditions, but do not assign any likelihood to one projection over another. In response, this dissertation research suggests an alternative characterization of infrastructure climate impact risk as a function of three dimensions: (1) the exposure of an asset to climate change impacts, (2) the vulnerability of the asset to those impacts, and (3) the criticality of the asset as part of the system. The characterization of risk using these three dimensions provides a framework by which infrastructure adaptation assessments can then evaluate multiple plausible characterizations of the future (i.e., multiple climate projections), instead of responding to a single future scenario that has been probabilistically identified, to determine outcomes that are robust across a range of plausible scenarios.

The structure of the CCAAF and the alternative characterization of risk also enable the evaluation of other factors that may influence assessment outcomes. That is, the use of a multidimensional risk matrix could incorporate additional dimensions. This is particularly important as future research may identify other dimensions that are relevant to adaptation planning that were not considered here, nor in other previous assessment approaches. Furthermore, the structure of the CCAAF facilitates the systematic integration of data into the adaptation assessment, which may serve to facilitate greater replicability of the framework.

Another beneficial aspect of the three dimensional approach to risk is that differential weighting of the three dimensions (or additional dimensions may be identified in the future) could afford flexibility in aligning the assessment outcomes with agency-specific needs, goals, or priorities. For example, an agency with a mature culvert maintenance program, and a generally high network-wide state of good repair, may seek to apply greater weighting to the asset criticality dimension in an effort to further harden system resilience. Agencies may alternatively choose to adjust risk dimension weighting to align with other broad strategic priorities such as increasing a system's adaptive capacity. In any event, the implementation of variable weighting schemes that serve agency- or location-specific management requires further research to investigate the sensitivity of assessment outcomes to changes in the various risk dimension weights. This research need is discussed in greater detail in following sections.

The alternative characterization of risk proposed in this research expands the current risk management toolkit available to transportation professionals and provides practical and flexible means by which to examine multiple plausible future outcomes. Additionally, the structure of the framework and the asset prioritization afford the flexibility to integrate additional dimensions or considerations should they be identified in future implementations or research.

7.2 Developing Infrastructure-Relevant Climate Impact Projections

Developing climate change impact projections that are relevant to infrastructure planning and management activities is a significant challenge in adaptation planning, and much of the current practice relies on a combination of scenario analysis and expert opinion. The framework developed in this research uses scenarios (multiple analysis timeframes and emission scenarios) to develop robust conclusions about the exposure of culvert assets to climate change-related increases in extreme precipitation magnitude. However, in developing these projections, this research introduces a new, data-driven method to project the relative impacts of extreme precipitation events so as to be relevant to infrastructure planning and management.

This research study has proposed using projections of higher-frequency heavy precipitation events (e.g., the 10-year, 24-hour precipitation event) as indicators of the relative magnitude and geospatial extent of future lower-frequency extreme precipitation events. These projections, when used as indicators, provide infrastructure managers with a means to reasonably compare the relative impacts of climate change-related extreme precipitation across various regions within an agency's jurisdiction, facilitating network-level assessments. One limitation of this method is that it does not provide an actual measure or prediction of extreme precipitation event magnitudes, but rather a comparative measure. Therefore, this method is likely more useful in network-level management and planning activities than in infrastructure asset design or in project-level assessments.

7.3 Measures of Culvert Vulnerability to Increased Flows

The four state DOTs that participated in the research case studies constitute a limited sample of state DOTs and culvert management practices in the United States. Nonetheless, they do illustrate the substantial diversity in the types and detail of data collected for culvert management purposes. This diversity of data types and data recording practices across DOTs requires some degree of flexibility in methods used to determine culvert vulnerability. This flexibility is necessary in order to balance the overarching goal of national replicability with the need to recognize locally-relevant, or agency-specific conditions and design contexts.

The results of the four case studies (particularly MnDOT and NYSDOT) illustrate that incorporating some measure of vulnerability into the CCAAF (as opposed to only considering exposure and criticality) impacts the prioritization outcomes. However, the outcomes do suggest that there is also some value in assessing asset criticality and exposure of critical assets to projected future precipitation impacts when vulnerability information is not available.

It is unclear from the results whether more detailed information (i.e., based on condition and functional performance criteria, as in Method 3) yields any benefit over the use of a more generalized Overall Condition Rating (as in Method 2) in assessing vulnerability. Nonetheless, the findings suggest that culvert asset vulnerability is an important element in climate change adaptation assessment, which can have a strong bearing on the assessment outcomes.

Given the often sparse or incomplete nature of recorded culvert management data, any measure of culvert vulnerability to increased flows will likely rely on a limited number of condition and functional performance data items. This suggests that the use of a relative scale (e.g., Vulnerability Index) to rate culvert vulnerability is more appropriate than seeking any measure of vulnerability in absolute values, as a relative scale will enable greater confidence in analysis outcomes based on sparse data. The diversity in culvert data types among the four case study DOTs (which may provide a reasonable illustration of the broader diversity among state DOTs) further suggests that a one-size-fits-all approach to culvert vulnerability analysis is inappropriate. A reasonable course of action may be to seek the development of national guidelines for culvert vulnerability assessment instead of a national standardization of practice. Such guidelines could then be used by state DOTs to inform the development of locally- or regionally-relevant vulnerability analysis method that seek consistency in assessment outcomes, but that still enable greater flexibility in the methods used to generate those outcomes.

The broader significance of the vulnerability analysis results from the four case studies is that the differences in vulnerability assessment outcomes between the two methods indicate a need for greater understanding of the methods themselves as approximations of a culvert’s true vulnerability. Future research is required to validate whether these two methods provide an accurate measure of a culvert’s relative vulnerability to increases flows. One possible direction for this research would be to determine if the two methods could be combined to use functional performance-based criteria from Method 3 to supplement the overall condition ratings used in Method 2. One way that this could be done would be to divide the overall condition ratings currently assigned to culverts into two overall ratings: one for overall physical condition, and one for overall functional performance. Such a rating system may allow agencies to perform a network level screening to separate those culverts that require physical repairs but are not functionally deficient (i.e., flow capacity is not impeded) from those that require other actions (e.g., maintenance) to restore functional performance. In addition, future research should also explore other methods of determining the relative vulnerability of culverts to increased flow given current data availabilities, as well as propose additional data relevant to such analyses.

7.4 Criticality Assessment and Asset Prioritization

The method used to conduct the culvert asset criticality assessment in this research study, although simple, illustrates how such an assessment can be used to provide a relative measure for the consequence component of risk, as part of the overall evaluation framework. It also provides a framework under which additional criticality criteria could be integrated, or by which additional types of criticality analyses could be undertaken.

The criticality assessment in this study examined three categories of criticality (economic, operational, and health and safety), which were informed by criticality assessments conducted in the Gulf Coast 2 Study. However, it is recognized that there are myriad other aspects of criticality that could or should be considered. For example, as discussed in Section 5.5.1, the evaluation of economic criticality in these case studies explicitly excludes any social component (socioeconomic criticality was one of the Gulf Coast 2 categories). Certainly social criticality (e.g., access to hospitals, schools, grocery stores) is a very important dimension that should be a part of overall criticality assessments. The combined criticality assessment step of the CCAAF, through simple additive weighting (SAW), enables the inclusion of many more criticality dimensions than were demonstrated in this study. However, the necessary exclusion of social criticality due to data availability difficulties illustrates the need for further development of such criticality data (both social and others), at the national, state and federal levels.

The criticality assessment approach used in this study, while providing some measure of the relative importance of the culvert in isolation, fails to account for the importance of the culvert as one component of a larger network or system. For example, no network analyses were conducted to identify the time lost due to detour rerouting, or to identify the availability of evacuation routes. This is in part a limitation of the data collected in culvert asset management systems, but also arises out of the need to reasonably bound criticality analysis. One approach to recognizing the network-function aspects of culvert assets in future research would be to identify critical corridors, either to supplement or replace the current asset-specific criticality assessment. Another approach that could be pursued in future research would be to involve case-study stakeholders to fully realize the "system-critical" infrastructure identification mechanism that was built into the Combined Criticality Analysis, but not demonstrated in the case studies due to the need for local knowledge. Perhaps the most rigorous approach would be a complete network analysis that identifies detour routes, evaluates the accessibility of locations of importance (e.g., hospitals), and accounts for the impacts of increased congestion due to partial network disruption.

7.5 Matching Output Specificity with Input Uncertainty

It is important in climate change adaptation assessments to recognize the uncertainty inherent to the climate models and projections that are used as inputs. However, it is equally important to recognize the uncertainty that these inputs, as well as the framework itself, create in the assessment outcomes and then frame those outcomes appropriately. One way that this is addressed in the CCAAF is the use of risk scales and risk matrices to qualitatively assign risk using a limited number of classifications (e.g., high, medium, low). While the assessment could be altered to increase the number of classifications (e.g., 1 to 5), or to produce higher precision numerical risk scores, doing so may inadvertently convey greater certainty in the results than is supported by the assessment inputs. While the risk scales used in the CCAAF provide a reasonable foundation for assigning qualitative risk, their classification and calibration should be the subject of future research to ensure that the outcomes adequately reflect the level of uncertainty entrained in the analysis.

Another example from this study of matching input uncertainty to output detail is seen in the development of the precipitation exposure maps, where each of the grid squares were assigned to a qualitative Precipitation Exposure Index classification. This grid square assignment of range-based exposure indices is intended to generalize the magnitude and, to some degree, the geospatial distribution of projected precipitation. However, it is possible that the distinct definition of the grids used in the geospatial analysis and outcomes convey greater certainty in the results than is supported by the down-scaled climate model data. Future research could pursue ways to further generalize these results by dividing a state or region into several range-based precipitation exposure sub-regions, as opposed to several hundred distinct grid squares under the current approach. This generalization would likely require the input of regional experts (e.g., state climatologists and hydrologists) to define such regions.

7.6 Climate Change Adaptation in the Context of Infrastructure Management

Although this research study conducts a stand-alone assessment of culvert risks to increased extreme precipitation event magnitudes due to climate change, it is recognized that such an assessment, in practice, would most likely take place in the broader context of infrastructure asset management and decision making. In fact, the requirement for risk-based, performance-based asset management in recent federal transportation legislation (i.e., MAP-21) provides strong motivation for the greater consideration in future research of how adaptation assessments may interface with asset management programs.

The outcomes of the CCAAF evaluation could provide valuable input into transportation asset management decision making in the broader context of climate change adaptation. Not only could the final outcomes help agencies to identify high-risk culvert assets by placing climate change-related concerns alongside other relevant culvert management considerations, but the intermediate outcomes could prove synergistic with transportation asset management activities. For example, the precipitation exposure analysis outcomes could benefit transportation asset management programs by helping to identify future increased exposure of other transportation assets (e.g., bridges, earth retention structure, non-culvert drainage systems) to extreme precipitation.

Additionally, the CCAAF may also benefit in its methodological approach from integration with an asset management program. For example, the criticality assessment could likely build upon existing information and practices of identifying important corridors, routes, and network links. Also, two of the key dimensions of risk – criticality and vulnerability – are both factors that change with time. The systematic and periodic reevaluation of infrastructure as part of an institutionalized asset management program could enable culvert vulnerability (due to changes in the condition and functional performance of the assets) and criticality (due to changes in land use, traffic volumes, etc.) to be reassessed over time, thus updating climate change-related risks to culverts.

In addition, the institutionalized nature of transportation asset management programs could also help to address issues of data consistency and completeness, which were identified in the case study results as critical to the development of a representative risk distribution. The integration of culvert climate change assessments into institutionalized transportation asset management programs would likely increase the systematic collection of data items that are more directly relevant to the three dimensions of risk. This may lead to more completeness in data records, which would enable a more accurate characterization of the distribution of risk dimensions across the entire culvert inventory. As always, the costs of collecting and keeping data current will have to be weighed against the perceived risks of changing climate or extreme weather events.

7.7 Recommendations and Future Research

The previous sections of this chapter have thematically discussed several outcomes of this dissertation research, and in doing so, have identified several broad future research needs. This section briefly recommends several additional subjects for future research tied to the specific tasks within the CCAAF.

7.7.1 Future Research – Culvert Asset Data and Vulnerability Analysis

As discussed above, the analysis of culvert vulnerability based on culvert inventory and attribute data should be the subject of much future research. As the field of ancillary asset management expands, it will be increasingly valuable to better understand the physical and functional deterioration of culvert systems, and the resultant vulnerabilities, both for general asset management purposes and also climate change-related assessments. To that end, future research should refine the vulnerability analysis methods developed in this research study, and also investigate new measures of culvert vulnerability to increased flows, and other factors. It may be valuable to investigate not only the individual contributions of the culvert data items and inspection criteria (discussed in Chapter 4) to culvert vulnerability, but also the interaction and compounding effects of multiple criteria on vulnerability.

Two priorities for research in this area should be: the calibration of the two vulnerability analysis methods proposed in this research; and the investigation of those methods (and others) as characterizations of culverts' true vulnerability. Calibration should focus on translating the quantitative ratings scales used by DOTs for culvert inspection and management into qualitative measures. Particularly, it is important that qualitative classifications faithfully represent the quantitative information recorded by the state DOTs.

One important project for future research related to the efficacy of vulnerability analysis methods as characterizations of true vulnerability is the forensic analysis of culvert failures in states and jurisdictions with existing culvert asset management programs. This type of analysis would enable failure- and vulnerability-relevant condition and performance criteria to be identified, laying a foundation for further research in this area.

7.7.2 Future Research – Precipitation Exposure Analysis

The precipitation exposure projection method developed in this study uses the 10-year 24-hour precipitation event as an indicator of potential low-frequency/high-impact events. While the projection technique has its foundation in climatic and hydrologic theory, further research is necessary to investigate the validity of the approach. This research should focus on three areas. First, this research study has treated the statistically downscaled outputs of all climate models (AOGCMs) equally. In practice, it is likely that some models are superior to others in predicting regional precipitation, and that the ability of the various models may vary from region to region. Research should be conducted to identify climate models that are regionally relevant to the analysis areas.

Second, the precipitation exposure analysis employs the GEV distribution to project the magnitude of high-frequency extreme precipitation events. While the use of the GEV distribution has a foundation in the relevant literature, other distributions (e.g., Log-Pearson Type III) are also suggested. Further research should be conducted to investigate which distributions will provide the best outcomes.

Lastly, precipitation exposure was generalized with respect to relative magnitude (i.e., classification of quantitative projections into qualitative ranges), and to a limited extent, it was also generalized geospatially (as grid-squares). First, the classification of projected precipitation magnitudes into defined and calibrated ranges should be further investigated. This would ensure that relevant ranges, tied more directly to hydrologic theory and culvert impacts, are used in analyses. Second, the grid-based spatial arrangement of precipitation projections likely suggests greater certainty in the precipitation exposure analysis outcomes than is supported by the climate inputs. Future research should seek ways to geospatially generalized precipitation exposure outcomes by, for example, grouping gridded outcomes into several impact sub-regions.

7.7.3 Future Research – Calibration and Sensitivity Analyses

There are many places in the CCAAF where quantitative evaluation values were assigned to qualitative ranges (e.g., high/medium/low) based upon engineering judgment and suggestions from the literature. For example, engineering judgment informed the decision to discard from the R-CAP analysis any culverts with Certainty Ratings below 2 in NYSDOT, and below 3 in MnDOT. Each of these instances requires research to further calibrate the qualitative rating scales chosen, and to evaluate the bounding and threshold choices used in this analysis. Such research would serve to mitigate some of the uncertainty derived from the analysis itself, and ultimately strengthen the outcomes of the CCAAF.

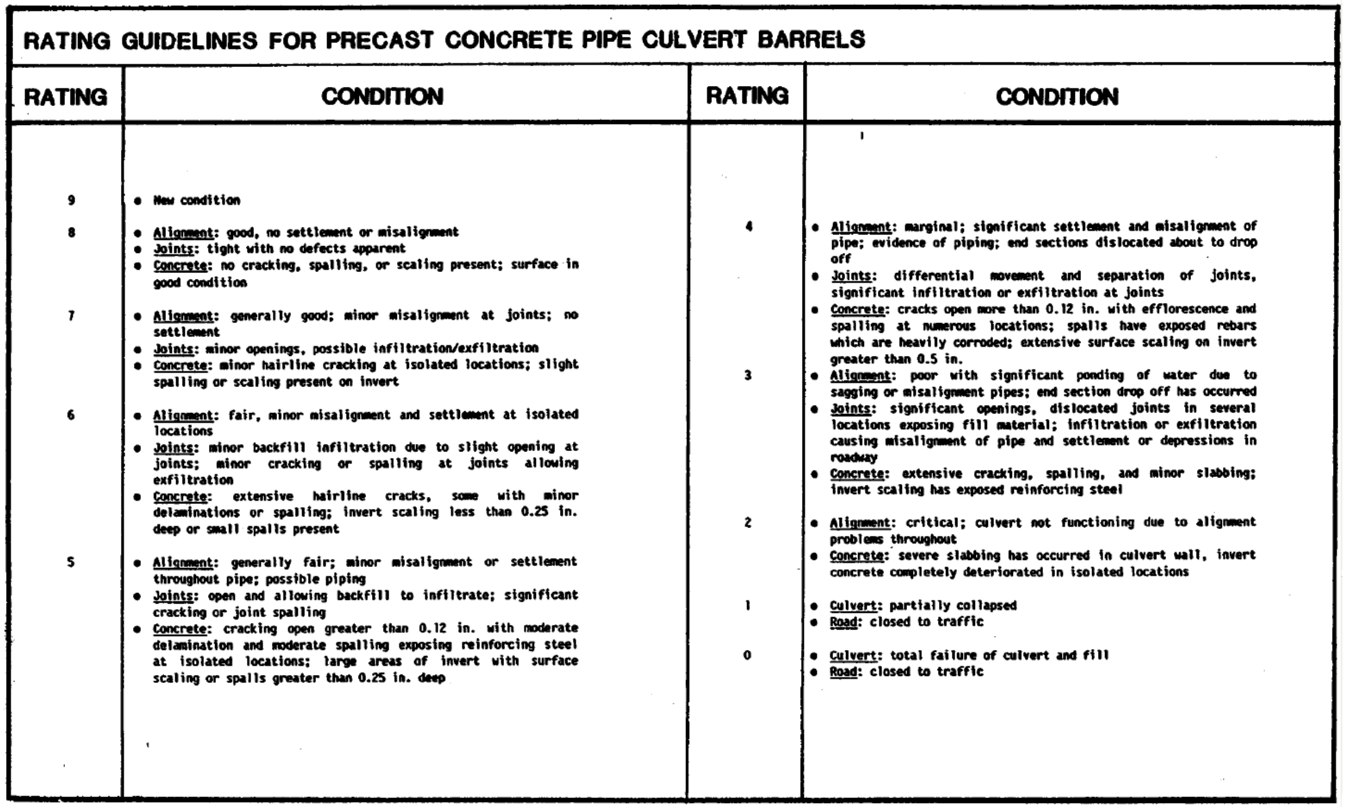
As discussed earlier in this chapter, it is imperative that the influence of the three dimensions of risk over the assessment outcomes be better understood. As the case study results indicate, equal weighting of the risk dimensions does not equate to equal influence in the outcomes. Therefore, it is important that future research pursue a better understanding of the relative influence of these dimensions through sensitivity analyses or other analytical approaches. It would be beneficial for this research to also investigate ways that variable weighting of risk dimensions could be used to better align the assessment framework outcomes with broader agency adaptation strategy goals (e.g., stronger focus on criticality, adaptive capacity, resiliency, etc.).

7.7.4 Future Research – Broader Applications and Framework Development

The assessment framework developed and demonstrated in this dissertation research has specifically focused on highway culvert assets. However, the general structure and approach of the framework may provide an appropriate means by which to assess the climate change-related risks associated with other types of assets. It is also possible that the qualitative approach to risk utilized in this study may have applications in other non-climate related infrastructure asset assessments. The application of the CCAAF structure to other asset types or in other non-climate infrastructure assessments may also be a reasonable area for future research.

Finally, this dissertation research constitutes an initial effort to develop a risk-based assessment framework for network-level evaluation of climate change impacts to infrastructure assets. It expands upon current methods in risk assessment and risk management, but as an initial effort, future work should seek to refine the structure of the framework and investigate additional relevant considerations that may lead to more robust assessments in the context of an uncertain future.

APPENDIX A: FHWA CULVERT INSPECTION MANUAL RATING SCALES[6]



RATING GUIDELINES FOR PRECAST CONCRETE PIPE CULVERT BARRELS

RATING	CONDITION
9	• New condition
8	• Alignment: good, no settlement or misalignment • Joints: tight with no defects apparent • Concrete: no cracking, spalling, or scaling present; surface in good condition
7	• Alignment: generally good; minor misalignment at joints; no settlement • Joints: minor openings, possible infiltration/exfiltration • Concrete: minor hairline cracking at isolated locations; slight spalling or scaling present on invert
6	• Alignment: fair, minor misalignment and settlement at isolated locations • Joints: minor backfill infiltration due to slight opening at joints; minor cracking or spalling at joints allowing exfiltration • Concrete: extensive hairline cracks, some with minor delaminations or spalling; invert scaling less than 0.25 in. deep or small spalls present
5	• Alignment: generally fair; minor misalignment or settlement throughout pipe; possible piping • Joints: open and allowing backfill to infiltrate; significant cracking or joint spalling • Concrete: cracking open greater than 0.12 in. with moderate delamination and moderate spalling exposing reinforcing steel at isolated locations; large areas of invert with surface scaling or spalls greater than 0.25 in. deep
4	• Alignment: marginal; significant settlement and misalignment of pipe; evidence of piping; end sections dislocated about to drop off • Joints: differential movement and separation of joints, significant infiltration or exfiltration at joints • Concrete: cracks open more than 0.12 in. with efflorescence and spalling at numerous locations; spalls have exposed rebars which are heavily corroded; extensive surface scaling on invert greater than 0.5 in.
3	• Alignment: poor with significant ponding of water due to sagging or misalignment pipes; end section drop off has occurred • Joints: significant openings, dislocated joints in several locations exposing fill material; infiltration or exfiltration causing misalignment of pipe and settlement or depressions in roadway • Concrete: extensive cracking, spalling, and minor slabbing; invert scaling has exposed reinforcing steel
2	• Alignment: critical; culvert not functioning due to alignment problems throughout • Concrete: severe slabbing has occurred in culvert wall, invert concrete completely deteriorated in isolated locations
1	• Culvert: partially collapsed • Road: closed to traffic
0	• Culvert: total failure of culvert and fill • Road: closed to traffic

Figure A.1 Condition Rating Scale - Precast Concrete Pipe Culverts

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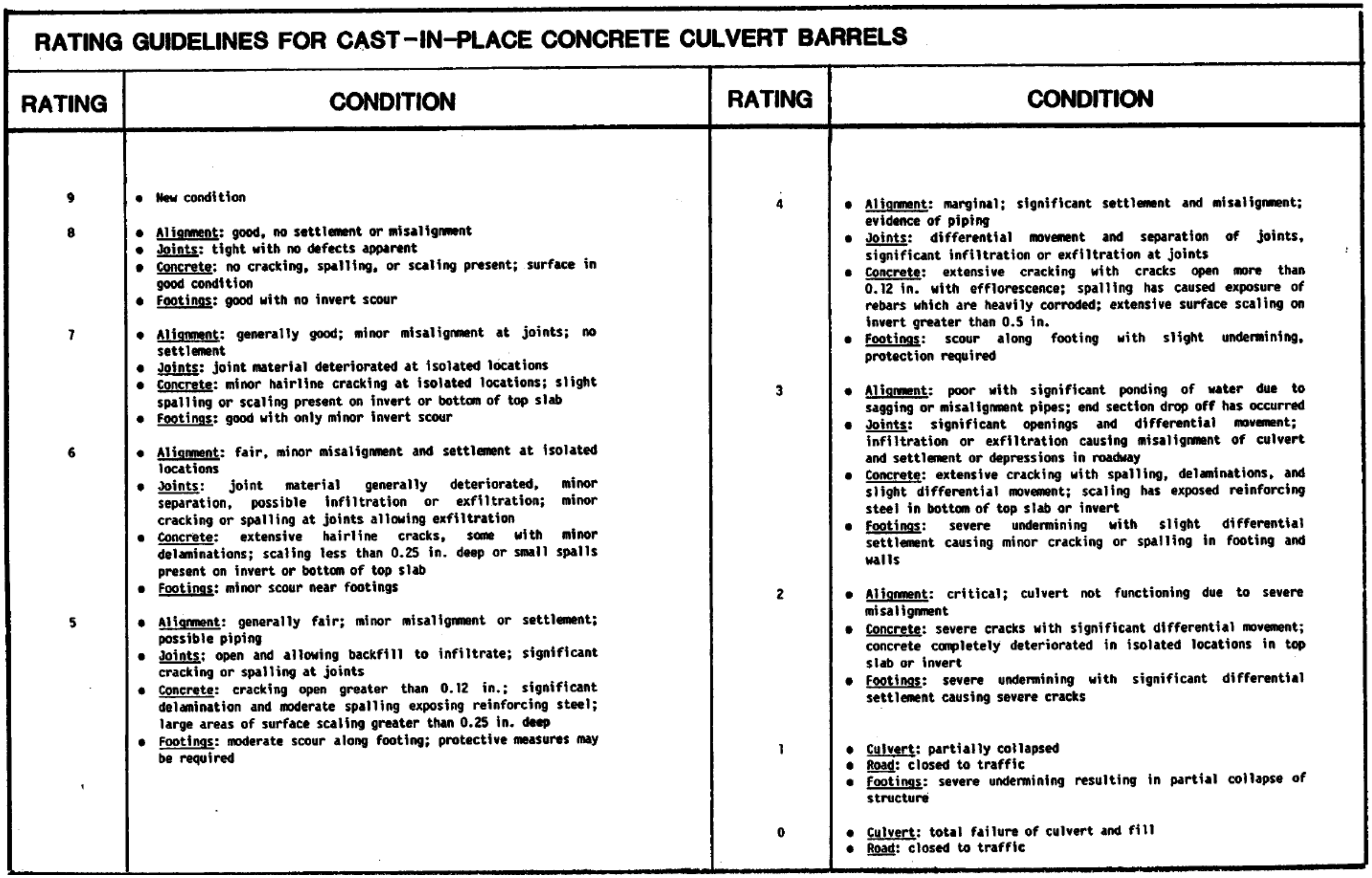
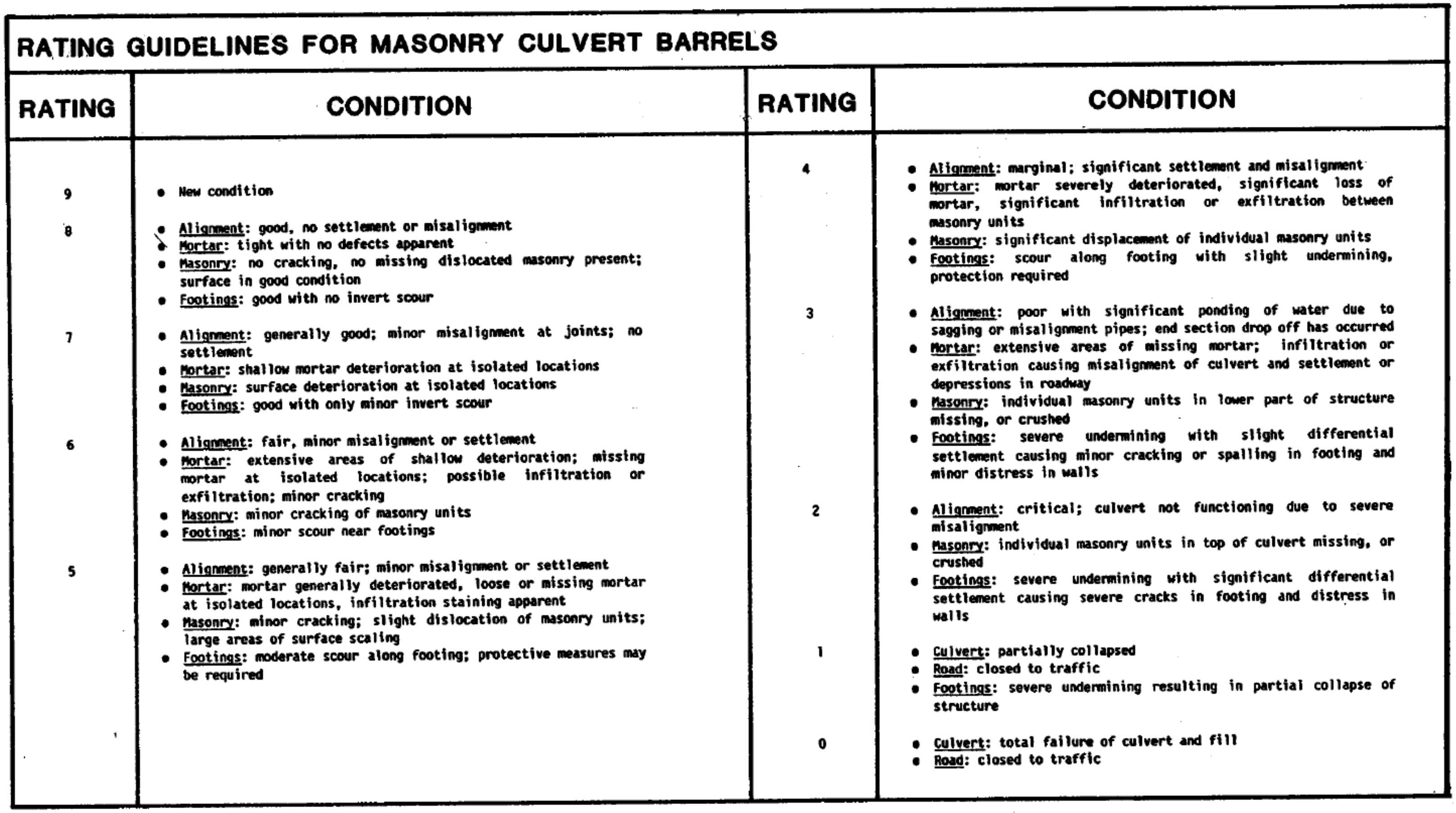
[6] The figures in Appendix A are from: Arnoult (1986)



RATING GUIDELINES FOR CAST-IN-PLACE CONCRETE CULVERT BARRELS

RATING	CONDITION
9	• New condition
8	• Alignment: good, no settlement or misalignment • Joints: tight with no defects apparent • Concrete: no cracking, spalling, or scaling present; surface in good condition • Footings: good with no invert scour
7	• Alignment: generally good; minor misalignment at joints; no settlement • Joints: joint material deteriorated at isolated locations • Concrete: minor hairline cracking at isolated locations; slight spalling or scaling present on invert or bottom of top slab • Footings: good with only minor invert scour
6	• Alignment: fair, minor misalignment and settlement at isolated locations • Joints: joint material generally deteriorated, minor separation, possible infiltration or exfiltration; minor cracking or spalling at joints allowing exfiltration • Concrete: extensive hairline cracks, some with minor delaminations; scaling less than 0.25 in. deep or small spalls present on invert or bottom of top slab • Footings: minor scour near footings
5	• Alignment: generally fair; minor misalignment or settlement; possible piping • Joints: open and allowing backfill to infiltrate; significant cracking or spalling at joints • Concrete: cracking open greater than 0.12 in.; significant delamination and moderate spalling exposing reinforcing steel; large areas of surface scaling greater than 0.25 in. deep • Footings: moderate scour along footing; protective measures may be required
4	• Alignment: marginal; significant settlement and misalignment; evidence of piping • Joints: differential movement and separation of joints, significant infiltration or exfiltration at joints • Concrete: extensive cracking with cracks open more than 0.12 in. with efflorescence; spalling has caused exposure of rebars which are heavily corroded; extensive surface scaling on invert greater than 0.5 in. • Footings: scour along footing with slight undermining, protection required
3	• Alignment: poor with significant ponding of water due to sagging or misalignment pipes; end section drop off has occurred • Joints: significant openings and differential movement; infiltration or exfiltration causing misalignment of culvert and settlement or depressions in roadway • Concrete: extensive cracking with spalling, delaminations, and slight differential movement; scaling has exposed reinforcing steel in bottom of top slab or invert • Footings: severe undermining with slight differential settlement causing minor cracking or spalling in footing and walls
2	• Alignment: critical; culvert not functioning due to severe misalignment • Concrete: severe cracks with significant differential movement; concrete completely deteriorated in isolated locations in top slab or invert • Footings: severe undermining with significant differential settlement causing severe cracks
1	• Culvert: partially collapsed • Road: closed to traffic • Footings: severe undermining resulting in partial collapse of structure
0	• Culvert: total failure of culvert and fill • Road: closed to traffic

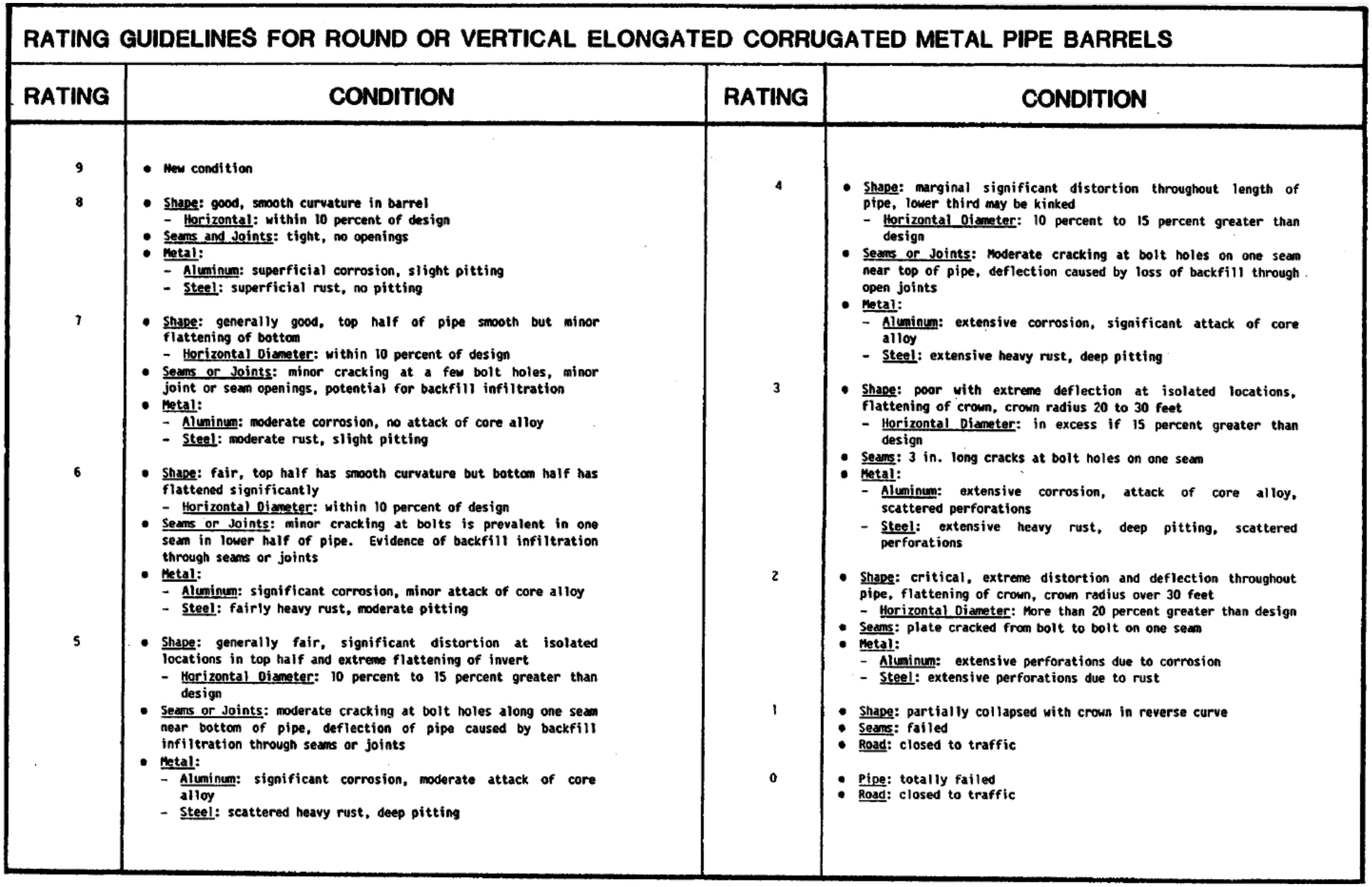
Figure A.2 Condition Rating Scale - Cast-in-Place Concrete Culverts



RATING GUIDELINES FOR MASONRY CULVERT BARRELS

RATING	CONDITION
9	• New condition
8	• Alignment: good, no settlement or misalignment • Mortar: tight with no defects apparent • Masonry: no cracking, no missing dislocated masonry present; surface in good condition • Footings: good with no invert scour
7	• Alignment: generally good; minor misalignment at joints; no settlement • Mortar: shallow mortar deterioration at isolated locations • Masonry: surface deterioration at isolated locations • Footings: good with only minor invert scour
6	• Alignment: fair, minor misalignment or settlement • Mortar: extensive areas of shallow deterioration; missing mortar at isolated locations; possible infiltration or exfiltration; minor cracking • Masonry: minor cracking of masonry units • Footings: minor scour near footings
5	• Alignment: generally fair; minor misalignment or settlement • Mortar: mortar generally deteriorated, loose or missing mortar at isolated locations, infiltration staining apparent • Masonry: minor cracking; slight dislocation of masonry units; large areas of surface scaling • Footings: moderate scour along footing; protective measures may be required
4	• Alignment: marginal; significant settlement and misalignment • Mortar: mortar severely deteriorated, significant loss of mortar, significant infiltration or exfiltration between masonry units • Masonry: significant displacement of individual masonry units • Footings: scour along footing with slight undermining, protection required
3	• Alignment: poor with significant ponding of water due to sagging or misalignment pipes; end section drop off has occurred • Mortar: extensive areas of missing mortar; infiltration or exfiltration causing misalignment of culvert and settlement or depressions in roadway • Masonry: individual masonry units in lower part of structure missing, or crushed • Footings: severe undermining with slight differential settlement causing minor cracking or spalling in footing and minor distress in walls
2	• Alignment: critical; culvert not functioning due to severe misalignment • Masonry: individual masonry units in top of culvert missing, or crushed • Footings: severe undermining with significant differential settlement causing severe cracks in footing and distress in walls
1	• Culvert: partially collapsed • Road: closed to traffic • Footings: severe undermining resulting in partial collapse of structure
0	• Culvert: total failure of culvert and fill • Road: closed to traffic

Figure A.3 Condition Rating Scale - Masonry Culverts



RATING GUIDELINES FOR ROUND OR VERTICAL ELONGATED CORRUGATED METAL PIPE BARRELS

RATING	CONDITION
9	• New condition
8	• Shape: good, smooth curvature in barrel - Horizontal: within 10 percent of design • Seams and Joints: tight, no openings • Metal: - Aluminum: superficial corrosion, slight pitting - Steel: superficial rust, no pitting
7	• Shape: generally good, top half of pipe smooth but minor flattening of bottom - Horizontal Diameter: within 10 percent of design • Seams or Joints: minor cracking at a few bolt holes, minor joint or seam openings, potential for backfill infiltration • Metal: - Aluminum: moderate corrosion, no attack of core alloy - Steel: moderate rust, slight pitting
6	• Shape: fair, top half has smooth curvature but bottom half has flattened significantly - Horizontal Diameter: within 10 percent of design • Seams or Joints: minor cracking at bolts is prevalent in one seam in lower half of pipe. Evidence of backfill infiltration through seams or joints • Metal: - Aluminum: significant corrosion, minor attack of core alloy - Steel: fairly heavy rust, moderate pitting
5	• Shape: generally fair, significant distortion at isolated locations in top half and extreme flattening of invert - Horizontal Diameter: 10 percent to 15 percent greater than design • Seams or Joints: moderate cracking at bolt holes along one seam near bottom of pipe, deflection of pipe caused by backfill infiltration through seams or joints • Metal: - Aluminum: significant corrosion, moderate attack of core alloy - Steel: scattered heavy rust, deep pitting
4	• Shape: marginal significant distortion throughout length of pipe, lower third may be kinked - Horizontal Diameter: 10 percent to 15 percent greater than design • Seams or Joints: Moderate cracking at bolt holes on one seam near top of pipe, deflection caused by loss of backfill through open joints • Metal: - Aluminum: extensive corrosion, significant attack of core alloy - Steel: extensive heavy rust, deep pitting
3	• Shape: poor with extreme deflection at isolated locations, flattening of crown, crown radius 20 to 30 feet - Horizontal Diameter: in excess if 15 percent greater than design • Seams: 3 in. long cracks at bolt holes on one seam • Metal: - Aluminum: extensive corrosion, attack of core alloy, scattered perforations - Steel: extensive heavy rust, deep pitting, scattered perforations
2	• Shape: critical, extreme distortion and deflection throughout pipe, flattening of crown, crown radius over 30 feet - Horizontal Diameter: More than 20 percent greater than design • Seams: plate cracked from bolt to bolt on one seam • Metal: - Aluminum: extensive perforations due to corrosion - Steel: extensive perforations due to rust
1	• Shape: partially collapsed with crown in reverse curve • Seams: failed • Road: closed to traffic
0	• Pipe: totally failed • Road: closed to traffic

Figure A.4 Condition Rating Scale - Found or Vertical Elongated Corrugated Metal Pipe Culverts

RATING GUIDELINES FOR CORRUGATED METAL PIPE-ARCH BARRELS

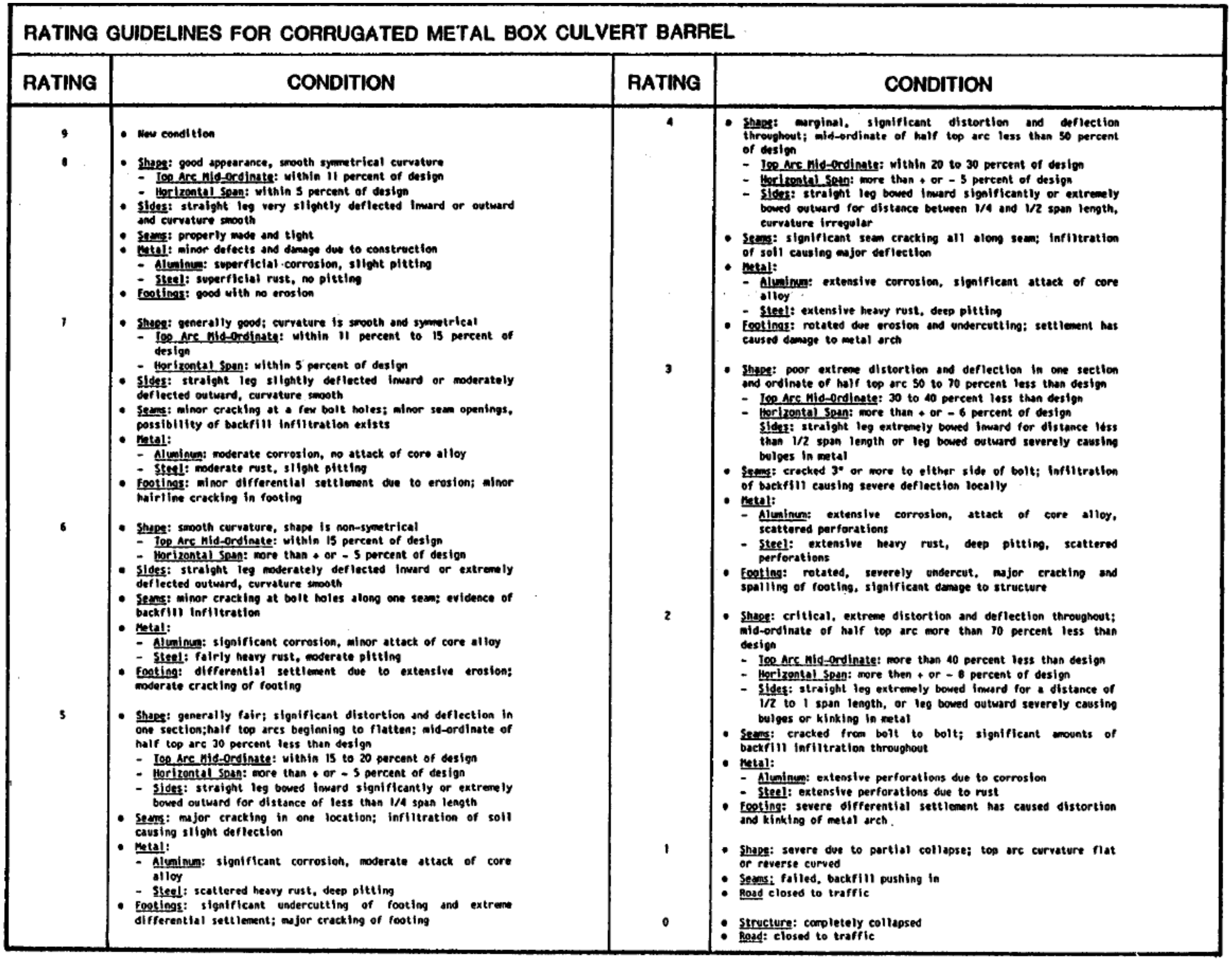
RATING	CONDITION
9	• New condition
8	• Shape: good with smooth curvature - Horizontal Span: less than 3 percent greater than design • Joints or Seams: good condition • Metal: minor construction defects, protective coatings intact - Aluminum: superficial corrosion, slight pitting - Steel: superficial rust, no pitting
7	• Shape: generally good, smooth curvature in top half, bottom flattened but still curved - Horizontal Span: within 3 to 5 percent greater than design • Joints or Seams: minor cracking at a few bolt holes; minor joint or seam openings, infiltration of backfill possible • Metal: protective coating ineffective - Aluminum: moderate corrosion, no attack of core alloy - Steel: moderate rust, slight pitting
6	• Shape: fair, smooth curvature in top half, bottom flat - Horizontal Span: 5 percent greater than design • Joints or Seams: minor cracking all along one seam; minor joint openings with evidence of infiltration • Metal: - Aluminum: significant corrosion, minor attack of core alloy - Steel: fairly heavy rust, moderate pitting
5	• Shape: generally fair, significant distortion in top in one location; bottom has slight reverse curvature in one location - Horizontal Span: within 5 to 7 percent greater than design • Joints and Seams: moderate cracking at bolt holes along a seam in one section, backfill being lost through seam or joint causing slight deflection • Metal: - Aluminum: significant corrosion, moderate attack of core alloy - Steel: scattered heavy rust, deep pitting
4	• Shape: marginal, significant distortion all along top of arch, bottom has reverse curve - Horizontal Span: more than 7 percent greater than design • Joints and Seams: moderate cracking all along one seam; backfill infiltration causing major deflection • Metal: - Aluminum: extensive corrosion, significant attack of core alloy - Steel: extensive heavy rust, deep pitting
3	• Shape: poor, extreme deflection in top arch in one section; bottom has reverse curvature throughout - Horizontal Span: more than 7 percent greater than design • Seams: seam cracked 3 in. on each side of bolt holes • Metal: - Aluminum: extensive corrosion, attack of core alloy, scattered perforations - Steel: extensive heavy rust, deep pitting, scattered perforations
2	• Shape: critical, extreme deflection along top of pipe - Horizontal Span: more than 7 percent greater than design • Seams: seam cracked from bolt to bolt down one seam • Metal: - Aluminum: extensive perforations due to corrosion - Steel: extensive perforations due to rust
1	• Shape: structure partially collapsed • Seams: seam failed • Road: closed to traffic
0	• Shape: structure collapsed • Road: closed to traffic

Figure A.5 Condition Rating Scale - Corrugated Metal Pipe-Arch Culverts

RATING GUIDELINES FOR STRUCTURAL PLATE ARCH BARREL

RATING	CONDITION
9	• New condition
8	• Shape: good, smooth symmetrical curvature • Rise: within ± 3 percent of design • Seams: properly made and tight • Metal: minor defects and damage due to contraction - Aluminum: superficial corrosion, slight pitting - Steel: superficial rust, no pitting • Footings: good with no erosion
7	• Shape: generally good with smooth curvature, symmetrical; slight flattening of top or sides in one section • Rise: within 3 to 4 percent of design • Seams: minor cracking at a few bolt holes; minor seam opening, possibility of soil infiltration • Metal: - Aluminum: moderate corrosion, no attack of core alloy - Steel: moderate rust, slight pitting • Footings: moderate erosion causing differential settlement and minor cracking in footing
6	• Shape: fair, smooth curvature but non-symetrical; slight flattening of top and sides throughout • Rise: within 4 to 5 percent of design • Seams: minor cracking of bolt holes along one or more seams; evidence of backfill infiltration • Metal: - Aluminum: significant corrosion, minor attack of core alloy - Steel: fairly heavy rust, moderate pitting • Footings: moderate cracking and differential settlement of footing due to extensive erosion
5	• Shape: generally fair, significant distortion and deflection in one section; sides beginning to flattend; non-symetrical • Rise: within 5 to 7 percent of design • Seams: moderate cracking of one seam near footing; infiltration of soil causing slight deflection • Metal: - Aluminum: significant corrosion, moderate attack of core alloy - Steel: scattered heavy rust, deep pitting • Footings: significant undercutting of footing and extreme differential settlement; major cracking in footing
4	• Shape: marginal, significant distortion and deflection throughout; sides flattened with radius 100 percent greater than design • Rise: within 7 to 8 percent of design • Seams: major cracking of seam near crown; infiltration of soil causing major deflection • Metal: - Aluminum: extensive corrosion, significant attack of core alloy - Steel: extensive heavy rust, deep pitting • Footings: rotated due to erosion and undercutting; settlement has caused damage to metal arch
3	• Shape: poor, extreme distortion and deflection in one section; sides virtually flattened; extremely non-symetrical • Rise: within 8 to 10 percent of design • Seams: cracked 3" to either side of bolts • Metal: - Aluminum: extensive corrosion, attack of core alloy, scattered perforations - Steel: extensive heavy rust, deep pitting, scattered perforations • Footing: rotated, severely undercut; major cracking and spalling
2	• Shape: critical, extreme deflection, throughout; sides flattened; extremely non-symetrical • Rise: greater than 10 percent of design • Seams: cracked from bolt to bolt; significant amounts of backfill infiltration • Metal: - Aluminum: extensive perforations due to corrosion - Steel: extensive perforations due to rust • Footing: severe differential settlement has caused distortion and kinking of metal arch
1	• Shape: severe due to partial collapse; local reverse curve of crown and sides • Seams: failed, backfill pushing in • Road: closed to traffic
0	• Structure: completely collapsed • Road: closed to traffic

Figure A.6 Condition Rating Scale - Structural Plate Arch Culverts



RATING GUIDELINES FOR CORRUGATED METAL BOX CULVERT BARREL

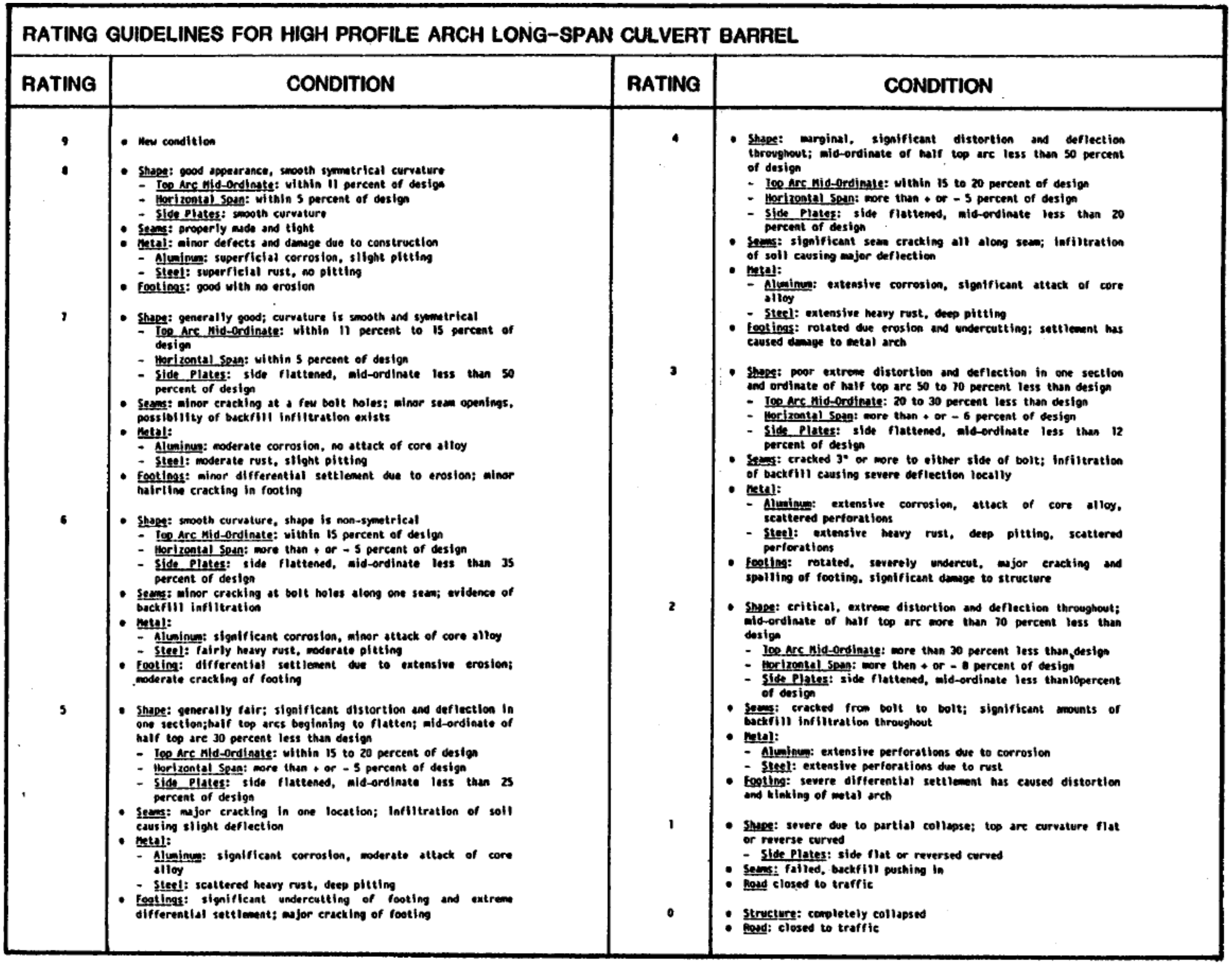
RATING	CONDITION
9	• New condition
8	• Shape: good appearance, smooth symmetrical curvature - Top Arc Mid-Ordinate: within 11 percent of design - Horizontal Span: within 5 percent of design • Sides: straight leg very slightly deflected inward or outward and curvature smooth • Seams: properly made and tight • Metal: minor defects and damage due to construction - Aluminum: superficial corrosion, slight pitting - Steel: superficial rust, no pitting • Footings: good with no erosion
7	• Shape: generally good; curvature is smooth and symmetrical - Top Arc Mid-Ordinate: within 11 percent to 15 percent of design - Horizontal Span: within 5 percent of design • Sides: straight leg slightly deflected inward or moderately deflected outward, curvature smooth • Seams: minor cracking at a few bolt holes; minor seam openings, possibility of backfill infiltration exists • Metal: - Aluminum: moderate corrosion, no attack of core alloy - Steel: moderate rust, slight pitting • Footings: minor differential settlement due to erosion; minor hairline cracking in footing
6	• Shape: smooth curvature, shape is non-symetrical - Top Arc Mid-Ordinate: within 15 percent of design - Horizontal Span: more than + or - 5 percent of design • Sides: straight leg moderately deflected inward or extremely deflected outward, curvature smooth • Seams: minor cracking at bolt holes along one seam; evidence of backfill infiltration • Metal: - Aluminum: significant corrosion, minor attack of core alloy - Steel: fairly heavy rust, moderate pitting • Footing: differential settlement due to extensive erosion; moderate cracking of footing
5	• Shape: generally fair; significant distortion and deflection in one section;half top arcs beginning to flatten; mid-ordinate of half top arc 30 percent less than design - Top Arc Mid-Ordinate: within 15 to 20 percent of design - Horizontal Span: more than + or - 5 percent of design - Sides: straight leg bowed inward significantly or extremely bowed outward for distance of less than 1/4 span length • Seams: major cracking in one location; infiltration of soil causing slight deflection • Metal: - Aluminum: significant corrosioh, moderate attack of core alloy - Steel: scattered heavy rust, deep pitting • Footings: significant undercutting of footing and extreme differential settlement; major cracking of footing
4	• Shape: marginal, significant distortion and deflection throughout; mid-ordinate of half top arc less than 50 percent of design - Top Arc Mid-Ordinate: within 20 to 30 percent of design - Horizontal Span: more than + or - 5 percent of design - Sides: straight leg bowed inward significantly or extremely bowed outward for distance between 1/4 and 1/2 span length, curvature irregular • Seams: significant seam cracking all along seam; infiltration of soil causing major deflection • Metal: - Aluminum: extensive corrosion, significant attack of core alloy - Steel: extensive heavy rust, deep pitting • Footings: rotated due erosion and undercutting; settlement has caused damage to metal arch
3	• Shape: poor extreme distortion and deflection in one section and ordinate of half top arc 50 to 70 percent less than design - Top Arc Mid-Ordinate: 30 to 40 percent less than design - Horizontal Span: more than + or - 6 percent of design Sides: straight leg extremely bowed inward for distance less than 1/2 span length or leg bowed outward severely causing bulges in metal • Seams: cracked 3" or more to either side of bolt; infiltration of backfill causing severe deflection locally • Metal: - Aluminum: extensive corrosion, attack of core alloy, scattered perforations - Steel: extensive heavy rust, deep pitting, scattered perforations • Footing: rotated, severely undercut, major cracking and spalling of footing, significant damage to structure
2	• Shape: critical, extreme distortion and deflection throughout; mid-ordinate of half top arc more than 70 percent less than design - Top Arc Mid-Ordinate: more than 40 percent less than design - Horizontal Span: more then + or - 8 percent of design - Sides: straight leg extremely bowed inward for a distance of 1/2 to 1 span length, or leg bowed outward severely causing bulges or kinking in metal • Seams: cracked from bolt to bolt; significant amounts of backfill infiltration throughout • Metal: - Aluminum: extensive perforations due to corrosion - Steel: extensive perforations due to rust • Footing: severe differential settlement has caused distortion and kinking of metal arch
1	• Shape: severe due to partial collapse; top arc curvature flat or reverse curved • Seams: failed, backfill pushing in • Road closed to traffic
0	• Structure: completely collapsed • Road: closed to traffic

Figure A.7 Condition Rating Scale - Corrugated Metal Box Culverts

RATING GUIDELINES FOR LOW PROFILE ARCH LONG-SPAN CULVERT BARREL

RATING	CONDITION
9	• New condition
8	• Shape: good appearance, smooth symmetrical curvature - Top Arc Mid-Ordinate: within 11 percent of design - Horizontal Span: within 5 percent of design • Seams: properly made and tight • Metal: minor defects and damage due to construction - Aluminum: superficial corrosin, slight pitting - Steel: superficial rust, no pitting • Footings: good with no erosion
7	• Shape: generally good; curvature is smooth and symmetrical - Top Arc Mid-Ordinate: within 11 percent to 15 percent of design - Horizontal Span: within 5 percent of design • Seams: minor cracking at a few bolt holes; minor seam openings, possibility of backfill infiltration exists. • Metal: - Aluminum: moderate corrosion, no attack of core alloy - Steel: moderate rust, slight pitting • Footings: minor differential settlement due to erosion; minor hairline cracking in footing
6	• Shape: smooth curvature, shape is non-symetrical - Top Arc Mid-Ordinate: within 15 percent of design - Horizontal Span: more than + or - 5 percent of design • Seams: minor cracking at bolt holes along one seam; evidence of backfill infiltration • Metal: - Aluminum: significant corrosion, minor attack of core allow - Steel: fairly heavy rust, moderate pitting • Footing: differential settlement due to extensive erosion; moderate cracking of footing
5	• Shape: generally fair; significant distortion and deflection in one section;half top arcs beginning to flatten; mid-ordinate of half top arc 30 percent less than design - Top Arc Mid-Ordinate: within 15 to 20 percent of design - Horizontal Span: more than + or - 5 percent of design • Seams: major cracking in one location; infiltration of soil causing slight deflection • Metal: - Aluminum: significant corrosion, moderate attack of core alloy - Steel: scattered heavy rust, deep pitting • Footings: significant undercutting of footing and extreme differential settlement; major cracking of footing
4	• Shape: marginal, significant distortion and deflection throughout; mid-ordinate of half top arc less than 50 percent of design - Top Arc Mid-Ordinate: within 15 to 20 percent of design - Horizontal Span: more than + or - 5 percent of design • Seams: significant seam cracking all along seam; infiltration of soil causing major deflection • Metal: - Aluminum: extensive corrosion, significant attack of core alloy, - Steel: extensive heavy rust, deep pitting • Footings: rotated due erosion and undercutting; settlement has caused damage to metal arch
3	• Shape: poor extreme distortion and deflection in one section and ordinate of half top arc 50 to 70 percent less than design - Top Arc Mid-Ordinate: 20 to 30 percent less than design - Horizontal Span: more than + or - 6 percent of design • Seams: cracked 3" or more to either side of bolt; infiltration of backfill causing severe deflection locally • Metal: - Aluminum: extensive corrosion, attack of core alloy, scattered perforations - Steel: extensive heavy rust, deep pitting, scattered perforations • Footing: rotated, severely undercut, major cracking and spalling of footing, significant damage to structure
2	• Shape: critical, extreme distortion and deflection throughout; mid-ordinate of half top arc more than 70 percent less than design - Top Arc Mid-Ordinate: more than 30 percent less than design - Horizontal Span: more then + or - 8 percent of design • Seams: cracked from bolt to bolt; significant amounts of backfill infiltration throughout • Metal: - Aluminum: extensive perforations due to corrosion - Steel: extensive perforations due to rust • Footing: severe differential settlement has caused distortion and kinking of metal arch
1	• Shape: severe due to partial collapse: top arc curvature flat or reverse curved • Seams: failed, backfill pushing in • Road closed to traffic
0	• Structure: completely collapsed • Road: closed to traffic

Figure A.8 Condition Rating Scale - Low-Profile Arch Long-Span Culverts



RATING GUIDELINES FOR HIGH PROFILE ARCH LONG-SPAN CULVERT BARREL

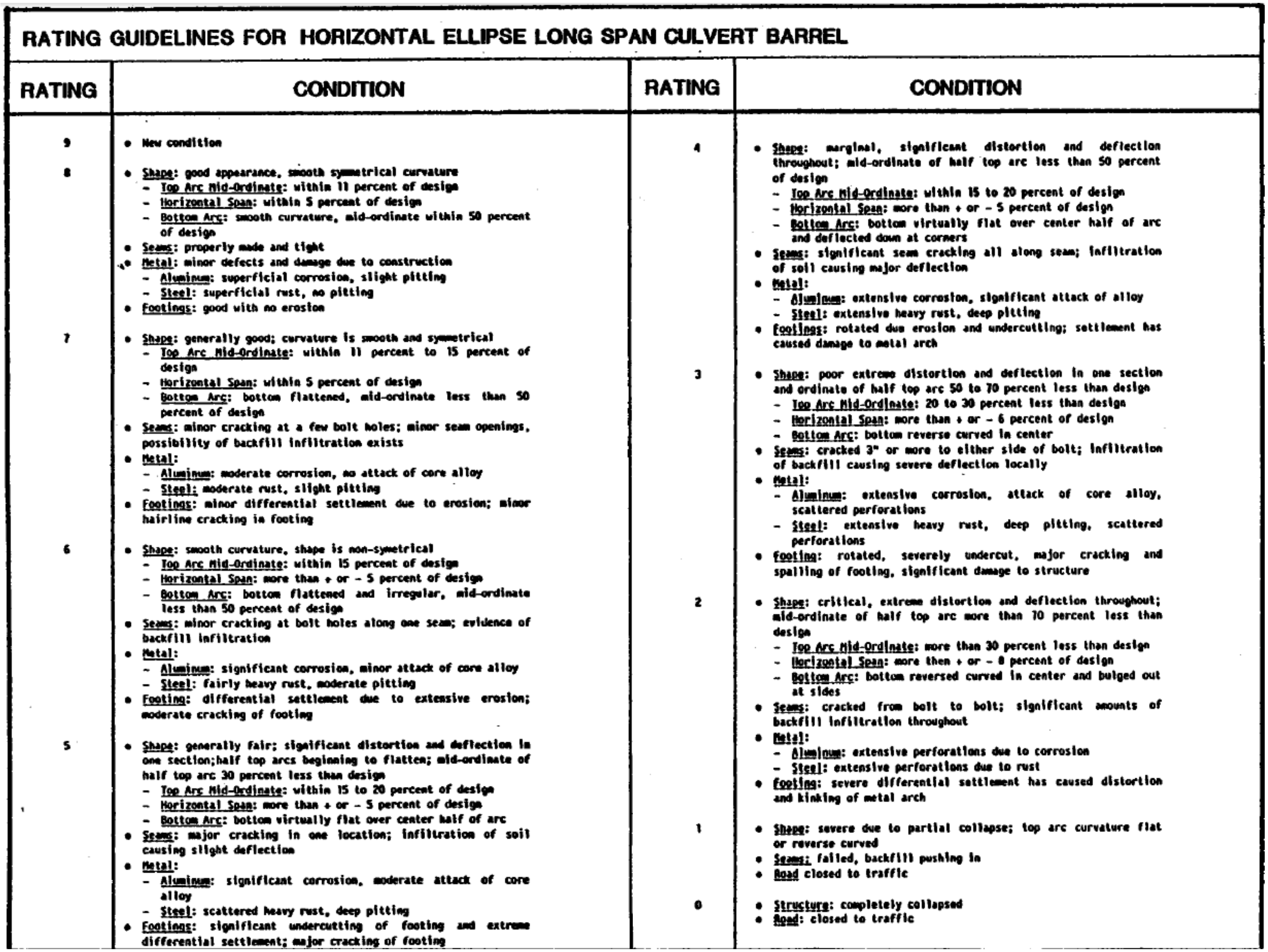
RATING	CONDITION
9	• New condition
8	• Shape: good appearance, smooth symmetrical curvature - Top Arc Mid-Ordinate: within 11 percent of design - Horizontal Span: within 5 percent of design - Side Plates: smooth curvature • Seams: properly made and tight • Metal: minor defects and damage due to construction - Aluminum: superficial corrosion, slight pitting - Steel: superficial rust, no pitting • Footings: good with no erosion
7	• Shape: generally good; curvature is smooth and symmetrical - Top Arc Mid-Ordinate: within 11 percent to 15 percent of design - Horizontal Span: within 5 percent of design - Side Plates: side flattened, mid-ordinate less than 50 percent of design • Seams: minor cracking at a few bolt holes; minor seam openings, possibility of backfill infiltration exists • Metal: - Aluminum: moderate corrosion, no attack of core alloy - Steel: moderate rust, slight pitting • Footings: minor differential settlement due to erosion; minor hairline cracking in footing
6	• Shape: smooth curvature, shape is non-symetrical - Top Arc Mid-Ordinate: within 15 percent of design - Horizontal Span: more than + or - 5 percent of design - Side Plates: side flattened, mid-ordinate less than 35 percent of design • Seams: minor cracking at bolt holes along one seam; evidence of backfill infiltration • Metal: - Aluminum: significant corrosion, minor attack of core alloy - Steel: fairly heavy rust, moderate pitting • Footing: differential settlement due to extensive erosion; moderate cracking of footing
5	• Shape: generally fair; significant distortion and deflection in one section;half top arcs beginning to flatten; mid-ordinate of half top arc 30 percent less than design - Top Arc Mid-Ordinate: within 15 to 20 percent of design - Horizontal Span: more than + or - 5 percent of design - Side Plates: side flattened, mid-ordinate less than 25 percent of design • Seams: major cracking in one location; infiltration of soil causing slight deflection • Metal: - Aluminum: significant corrosion, moderate attack of core alloy - Steel: scattered heavy rust, deep pitting • Footings: significant undercutting of footing and extreme differential settlement; major cracking of footing
4	• Shape: marginal, significant distortion and deflection throughout; mid-ordinate of half top arc less than 50 percent of design - Top Arc Mid-Ordinate: within 15 to 20 percent of design - Horizontal Span: more than + or - 5 percent of design - Side Plates: side flattened, mid-ordinate less than 20 percent of design • Seams: significant seam cracking all along seam; infiltration of soil causing major deflection • Metal: - Aluminum: extensive corrosion, significant attack of core alloy - Steel: extensive heavy rust, deep pitting • Footings: rotated due erosion and undercutting; settlement has caused damage to metal arch
3	• Shape: poor extreme distortion and deflection in one section and ordinate of half top arc 50 to 70 percent less than design - Top Arc Mid-Ordinate: 20 to 30 percent less than design - Horizontal Span: more than + or - 6 percent of design - Side Plates: side flattened, mid-ordinate less than 12 percent of design • Seams: cracked 3" or more to either side of bolt; infiltration of backfill causing severe deflection locally • Metal: - Aluminum: extensive corrosion, attack of core alloy, scattered perforations - Steel: extensive heavy rust, deep pitting, scattered perforations • Footing: rotated, severely undercut, major cracking and spalling of footing, significant damage to structure
2	• Shape: critical, extreme distortion and deflection throughout; mid-ordinate of half top arc more than 70 percent less than design - Top Arc Mid-Ordinate: more than 30 percent less than design - Horizontal Span: more then + or - 8 percent of design - Side Plates: side flattened, mid-ordinate less than10percent of design • Seams: cracked from bolt to bolt; significant amounts of backfill infiltration throughout • Metal: - Aluminum: extensive perforations due to corrosion - Steel: extensive perforations due to rust • Footing: severe differential settlement has caused distortion and kinking of metal arch
1	• Shape: severe due to partial collapse; top arc curvature flat or reverse curved - Side Plates: side flat or reversed curved • Seams: failed, backfill pushing in • Road closed to traffic
0	• Structure: completely collapsed • Road: closed to traffic

Figure A.9 Condition Rating Scale - High Profile Arch Long-Span Culverts

RATING GUIDELINES FOR PEAR SHAPED LONG-SPAN CULVERT BARREL

RATING	CONDITION
9	• New condition
8	• Shape: good appearance, smooth symmetrical curvature - Top Arc Mid-Ordinate: within 11 percent of design - Horizontal Span: within 5 percent of design - Side Plates: smooth curvature • Seams: properly made and tight • Metal: minor defects and damage due to construction; superficial corrosion with no pitting - Aluminum: superficial corrosion, slight pitting - Steel: superficial rust, no pitting
7	• Shape: generally good; curvature is smooth and symmetrical - Top Arc Mid-Ordinate: within 11 percent to 15 percent of design - Horizontal Span: within 5 percent of design - Side Plates: side flattened, mid-ordinate less than 50 percent of design • Seams: minor cracking at a few bolt holes; minor seam openings, possibility of backfill infiltration exists • Metal: - Aluminum: moderate corrosion, no attack of core alloy - Steel: moderate rust, slight pitting
6	• Shape: smooth curvature, shape is non-symmetrical - Top Arc Mid-Ordinate: within 15 percent of design - Horizontal Span: more than + or - 5 percent of design - Side Plates: side flattened, mid-ordinate less than 35 percent of design • Seams: minor cracking at bolt holes along one seam; evidence of backfill infiltration • Metal: - Aluminum: significant corrosion, minor attack of core alloy - Steel: fairly heavy rust, moderate pitting
5	• Shape: generally fair; significant distortion and deflection in one section;half top arcs beginning to flatten; mid-ordinate of half top arc 30 percent less than design - Top Arc Mid-Ordinate: within 15 to 20 percent of design - Horizontal Span: more than + or - 5 percent of design - Side Plates: side flattened, mid-ordinate less than 25 percent of design • Seams: major cracking in one location; infiltration of soil causing slight deflection • Metal: corroded locally - Aluminum: significant corrosion, moderate attack of core alloy - Steel: scattered heavy rust, deep pitting
4	• Shape: marginal, significant distortion and deflection throughout; mid-ordinate of half top arc less than 50 percent of design - Top Arc Mid-Ordinate: within 15 to 20 percent of design - Horizontal Span: more than + or - 5 percent of design - Side Plates: side flattened, mid-ordinate less than 20 percent of design • Seams: significant seam cracking all along seam; infiltration of soil causing major deflection • Metal: - Aluminum: extensive corrosion, significant attack of alloy - Steel: extensive heavy rust, deep pitting
3	• Shape: poor extreme distortion and deflection in one section and ordinate of half top arc 50 to 70 percent less than design - Top Arc Mid-Ordinate: 20 to 30 percent less than design - Horizontal Span: more than + or - 6 percent of design - Side Plates: side flattened, mid-ordinate less than 12 percent of design • Seams: cracked 3" or more to either side of bolt; infiltration of backfill causing severe deflection locally • Metal: - Aluminum: extensive corrosion, attack of core alloy, scattered perforations - Steel: extensive heavy rust, deep pitting, scattered perforations
2	• Shape: critical, extreme distortion and deflection throughout; mid-ordinate of half top arc more than 70 percent less than design - Top Arc Mid-Ordinate: more than 30 percent less than design - Horizontal Span: more then + or - 8 percent of design - Side Plates: side flattened, mid-ordinate less than10percent of design • Seams: cracked from bolt to bolt; significant amounts of backfill infiltration throughout • Metal: - Aluminum: extensive perforations due to corrosion - Steel: extensive perforations due to rust
1	• Shape: severe due to partial collapse; top arc curvature flat or reverse curved - Side Plates: side flat or reversed curved - Seams: failed, backfill pushing in • Road closed to traffic
0	• Structure: completely collapsed • Road: closed to traffic

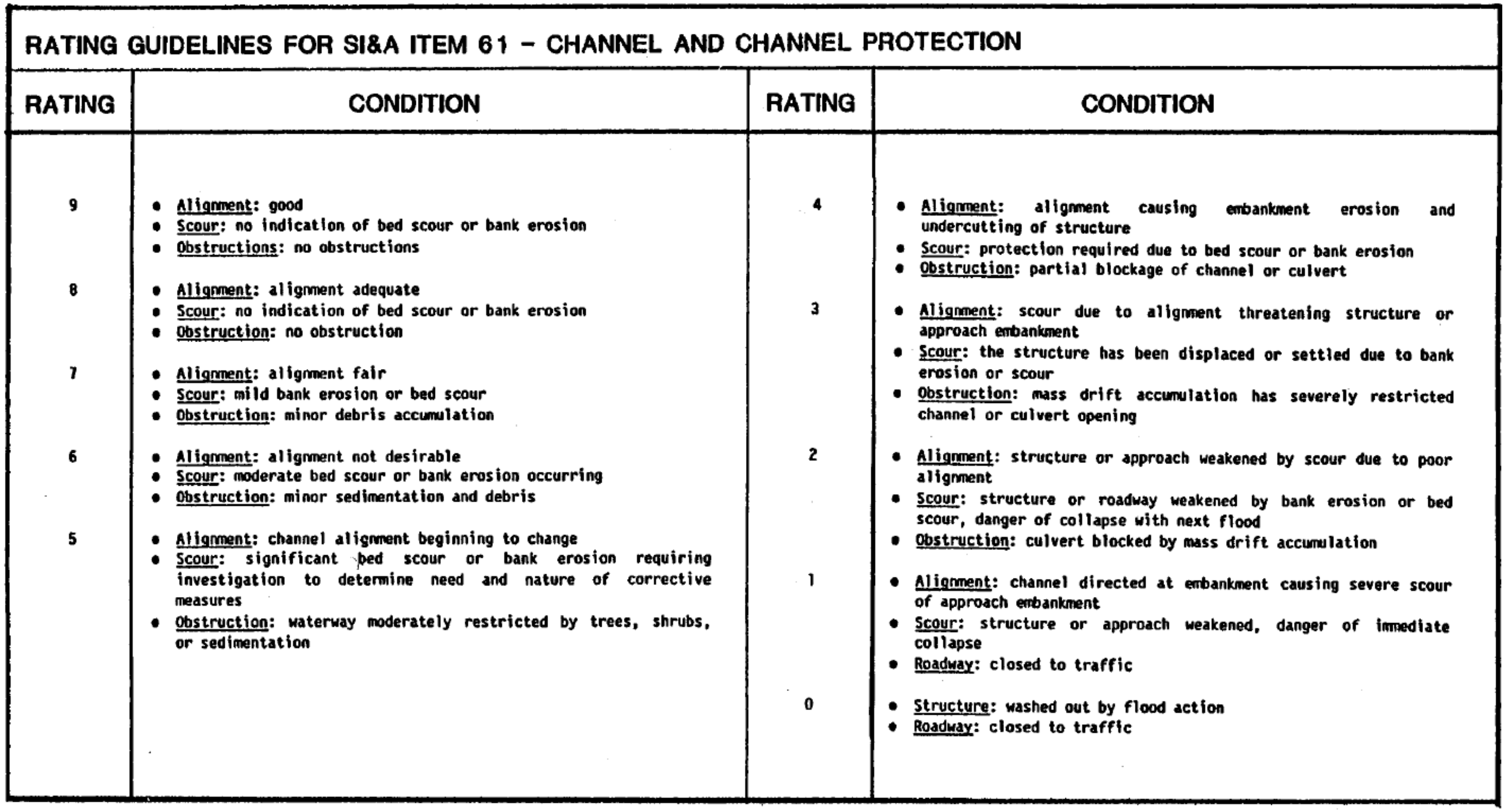
Figure A.10 Condition Rating Scale - Pear Shaped Long-Span Culverts



RATING GUIDELINES FOR HORIZONTAL ELLIPSE LONG SPAN CULVERT BARREL

RATING	CONDITION
9	• New condition
8	• Shape: good appearance, smooth symmetrical curvature – Top Arc Mid-Ordinate: within 11 percent of design – Horizontal Span: within 5 percent of design – Bottom Arc: smooth curvature, mid-ordinate within 50 percent of design • Seams: properly made and tight • Metal: minor defects and damage due to construction – Aluminum: superficial corrosion, slight pitting – Steel: superficial rust, no pitting • Footings: good with no erosion
7	• Shape: generally good; curvature is smooth and symmetrical – Top Arc Mid-Ordinate: within 11 percent to 15 percent of design – Horizontal Span: within 5 percent of design – Bottom Arc: bottom flattened, mid-ordinate less than 50 percent of design • Seams: minor cracking at a few bolt holes; minor seam openings, possibility of backfill infiltration exists • Metal: – Aluminum: moderate corrosion, no attack of core alloy – Steel: moderate rust, slight pitting • Footings: minor differential settlement due to erosion; minor hairline cracking in footing
6	• Shape: smooth curvature, shape is non-symetrical – Top Arc Mid-Ordinate: within 15 percent of design – Horizontal Span: more than + or – 5 percent of design – Bottom Arc: bottom flattened and irregular, mid-ordinate less than 50 percent of design • Seams: minor cracking at bolt holes along one seam; evidence of backfill infiltration • Metal: – Aluminum: significant corrosion, minor attack of core alloy – Steel: fairly heavy rust, moderate pitting • Footing: differential settlement due to extensive erosion; moderate cracking of footing
5	• Shape: generally fair; significant distortion and deflection in one section;half top arcs beginning to flatten; mid-ordinate of half top arc 30 percent less than design – Top Arc Mid-Ordinate: within 15 to 20 percent of design – Horizontal Span: more than + or – 5 percent of design – Bottom Arc: bottom virtually flat over center half of arc • Seams: major cracking in one location; infiltration of soil causing slight deflection • Metal: – Aluminum: significant corrosion, moderate attack of core alloy – Steel: scattered heavy rust, deep pitting • Footings: significant undercutting of footing and extreme differential settlement; major cracking of footing
4	• Shape: marginal, significant distortion and deflection throughout; mid-ordinate of half top arc less than 50 percent of design – Top Arc Mid-Ordinate: within 15 to 20 percent of design – Horizontal Span: more than + or – 5 percent of design – Bottom Arc: bottom virtually flat over center half of arc and deflected down at corners • Seams: significant seam cracking all along seam; infiltration of soil causing major deflection • Metal: – Aluminum: extensive corrosion, significant attack of alloy – Steel: extensive heavy rust, deep pitting • Footings: rotated due erosion and undercutting; settlement has caused damage to metal arch
3	• Shape: poor extreme distortion and deflection in one section and ordinate of half top arc 50 to 70 percent less than design – Top Arc Mid-Ordinate: 20 to 30 percent less than design – Horizontal Span: more than + or – 6 percent of design – Bottom Arc: bottom reverse curved in center • Seams: cracked 3" or more to either side of bolt; infiltration of backfill causing severe deflection locally • Metal: – Aluminum: extensive corrosion, attack of core alloy, scattered perforations – Steel: extensive heavy rust, deep pitting, scattered perforations • Footing: rotated, severely undercut, major cracking and spalling of footing, significant damage to structure
2	• Shape: critical, extreme distortion and deflection throughout; mid-ordinate of half top arc more than 70 percent less than design – Top Arc Mid-Ordinate: more than 30 percent less than design – Horizontal Span: more then + or – 8 percent of design – Bottom Arc: bottom reversed curved in center and bulged out at sides • Seams: cracked from bolt to bolt; significant amounts of backfill infiltration throughout • Metal: – Aluminum: extensive perforations due to corrosion – Steel: extensive perforations due to rust • Footing: severe differential settlement has caused distortion and kinking of metal arch
1	• Shape: severe due to partial collapse; top arc curvature flat or reverse curved • Seams: failed, backfill pushing in • Road closed to traffic
0	• Structure: completely collapsed • Road: closed to traffic

Figure A.11 Condition Rating Scale - Horizontal Elipse Long Span Culverts



RATING GUIDELINES FOR SI&A ITEM 61 – CHANNEL AND CHANNEL PROTECTION

RATING	CONDITION	RATING	CONDITION
9	• Alignment: good • Scour: no indication of bed scour or bank erosion • Obstructions: no obstructions	4	• Alignment: alignment causing embankment erosion and undercutting of structure • Scour: protection required due to bed scour or bank erosion • Obstruction: partial blockage of channel or culvert
8	• Alignment: alignment adequate • Scour: no indication of bed scour or bank erosion • Obstruction: no obstruction	3	• Alignment: scour due to alignment threatening structure or approach embankment • Scour: the structure has been displaced or settled due to bank erosion or scour • Obstruction: mass drift accumulation has severely restricted channel or culvert opening
7	• Alignment: alignment fair • Scour: mild bank erosion or bed scour • Obstruction: minor debris accumulation		
6	• Alignment: alignment not desirable • Scour: moderate bed scour or bank erosion occurring • Obstruction: minor sedimentation and debris	2	• Alignment: structure or approach weakened by scour due to poor alignment • Scour: structure or roadway weakened by bank erosion or bed scour, danger of collapse with next flood • Obstruction: culvert blocked by mass drift accumulation
5	• Alignment: channel alignment beginning to change • Scour: significant bed scour or bank erosion requiring investigation to determine need and nature of corrective measures • Obstruction: waterway moderately restricted by trees, shrubs, or sedimentation	1	• Alignment: channel directed at embankment causing severe scour of approach embankment • Scour: structure or approach weakened, danger of immediate collapse • Roadway: closed to traffic
		0	• Structure: washed out by flood action • Roadway: closed to traffic

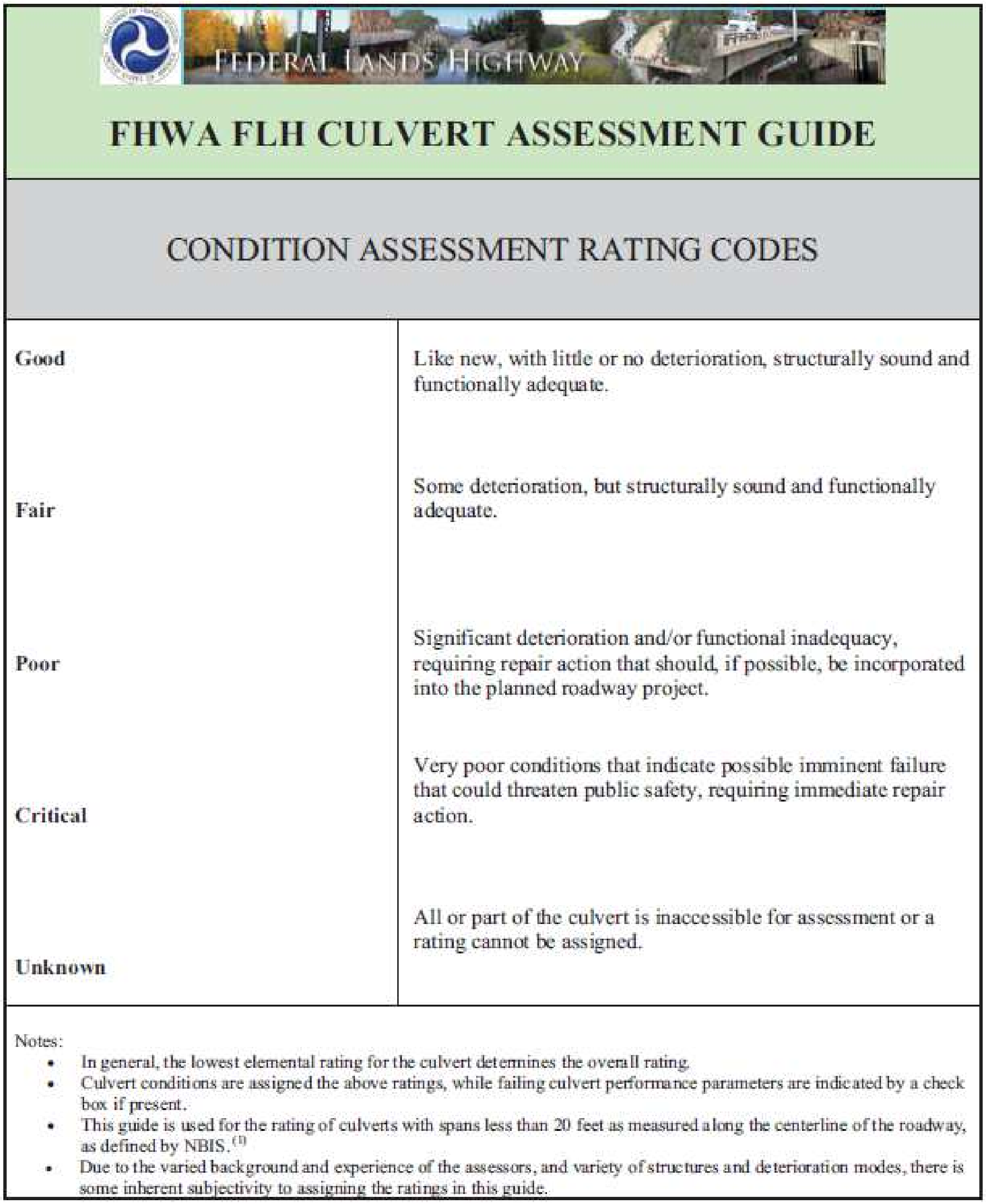
Figure A.12 Condition Rating Scale - Channel and Channel Protection Items

RATING GUIDELINES FOR SI&A ITEM 71 – WATERWAY ADEQUACY

RATING	CONDITION
9	• Opening and Alignment: good • Scour: no indication of bed scour or bank erosion
8	• Opening: waterway opening is adequate • Alignment: stream aligned with culvert centerline • Scour: no indication of bed scour or bank erosion
7	• Opening: opening is adequate • Alignment: stream at slight angle to culvert centerline • Scour: mild bank erosion or bed scour
6	• Opening: occasional drift or sediment removal required • Alignment: stream enters or exits at moderate angle • Scour: moderate bed scour or bed erosion occurring
5	• Opening: evidence of extensive ponding due to inadequate size opening, partial blockage or poor alignment • Alignment: alignment causing ponding or erosion • Scour: significant bed scour or bank erosion requiring investigation to determine need and nature of corrective measures
4	• Opening: marginally adequate, allowable headwater, depths may be exceeded during peak flows due to inadequate size opening, partial blockage or poor alignment • Alignment: misalignment causing erosion of embankment, or undercutting structure • Scour: protection required due to bed scour or bank erosion
3	• Opening: evidence that roadway is topped during high flows, or that ponding area is excessive due to inadequate size opening, partial blockage or poor alignment • Alignment: stream approaches or exits on small angle, channel is in the process of changing • Scour: the structure has been displaced or settled due to bank erosion or scour
2	• Opening: road/or adjacent properties frequently flooded due to inadequate size opening, partial blockage or poor alignment • Alignment: channel directed at embankment, collapse possible with next storm • Scour: structure or roadway weakened by bank erosion or bed scour, danger of collapse with next flood
1	• Opening: flood action has closed structure • Alignment: channel directed at embankment with threat of immediate collapse • Scour: structure weakened with threat of collapse • Roadway: closed to traffic
0	• Opening: structure collapsed or washed out • Roadway: closed to traffic

Figure A.13 Condition Rating Scale - Waterway Adequacy Items

APPENDIX B: FEDERAL LANDS HIGHWAY CULVERT ASSESSMENT TOOL CRITERIA RATING TABLES[7]



FEDERAL LANDS HIGHWAY

FHWA FLH CULVERT ASSESSMENT GUIDE

CONDITION ASSESSMENT RATING CODES

Good	Like new, with little or no deterioration, structurally sound and functionally adequate.
Fair	Some deterioration, but structurally sound and functionally adequate.
Poor	Significant deterioration and/or functional inadequacy, requiring repair action that should, if possible, be incorporated into the planned roadway project.
Critical	Very poor conditions that indicate possible imminent failure that could threaten public safety, requiring immediate repair action.
Unknown	All or part of the culvert is inaccessible for assessment or a rating cannot be assigned.

Notes:

- In general, the lowest elemental rating for the culvert determines the overall rating.
- Culvert conditions are assigned the above ratings, while failing culvert performance parameters are indicated by a check box if present.
- This guide is used for the rating of culverts with spans less than 20 feet as measured along the centerline of the roadway, as defined by NBIS.(1)
- Due to the varied background and experience of the assessors, and variety of structures and deterioration modes, there is some inherent subjectivity to assigning the ratings in this guide.

Figure B.1 Culvert Condition Rating Codes

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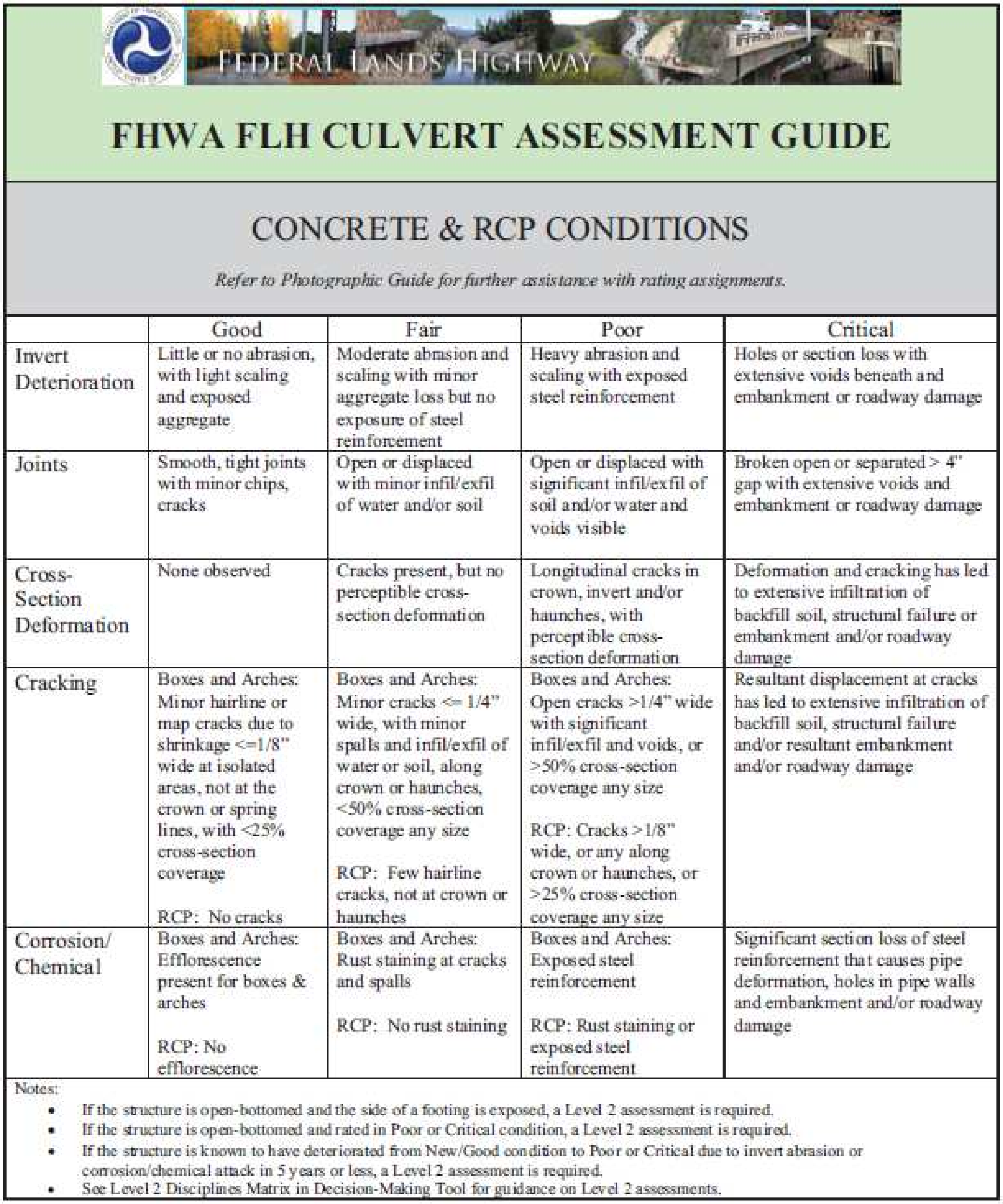
[7] The figures in Appendix B are from: Hunt et al. (2010)



FHWA FLH CULVERT ASSESSMENT GUIDE

CONCRETE & RCP CONDITIONS

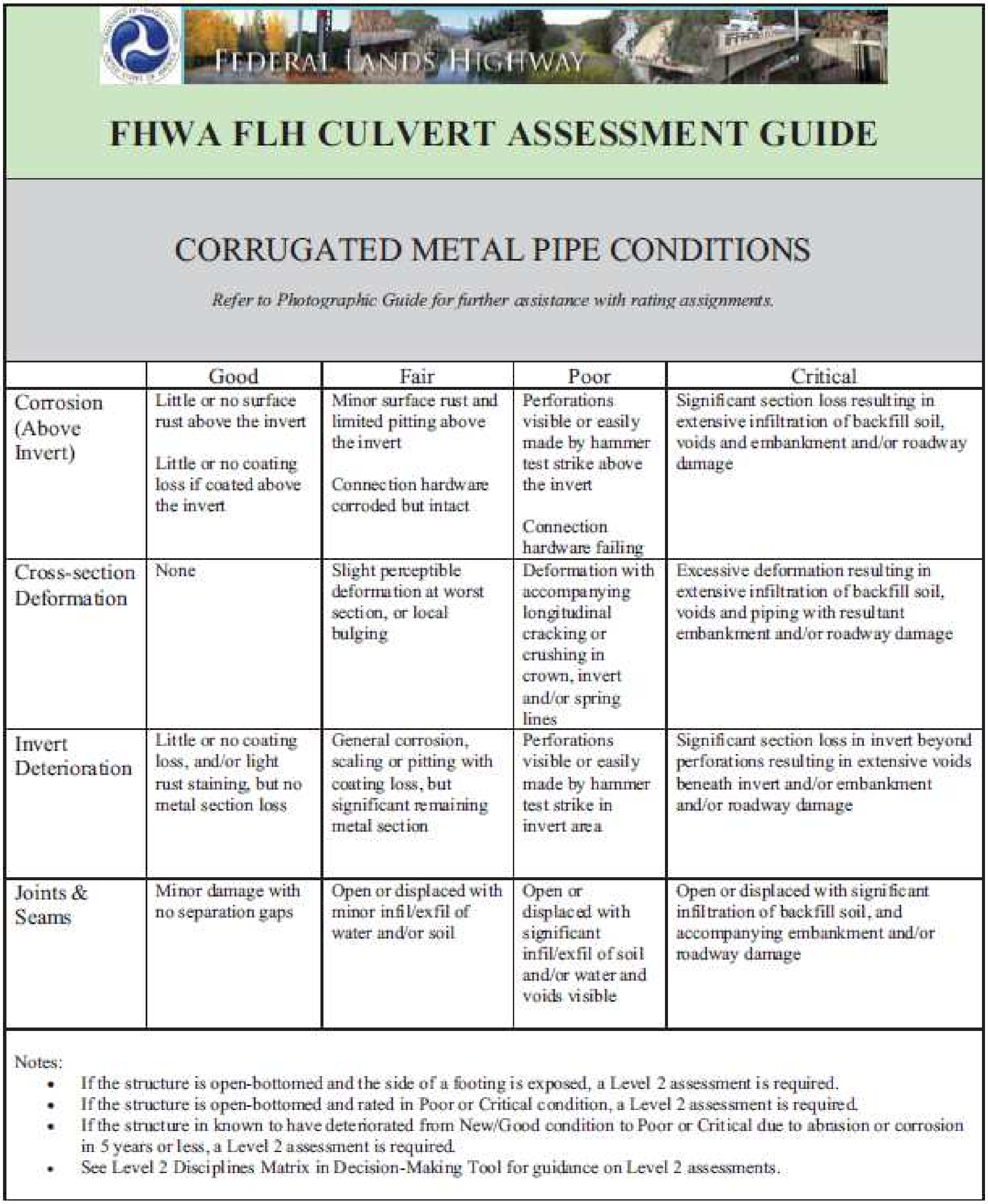
Refer to Photographic Guide for further assistance with rating assignments.

	Good	Fair	Poor	Critical
Invert Deterioration	Little or no abrasion, with light scaling and exposed aggregate	Moderate abrasion and scaling with minor aggregate loss but no exposure of steel reinforcement	Heavy abrasion and scaling with exposed steel reinforcement	Holes or section loss with extensive voids beneath and embankment or roadway damage
Joints	Smooth, tight joints with minor chips, cracks	Open or displaced with minor infil/exfil of water and/or soil	Open or displaced with significant infil/exfil of soil and/or water and voids visible	Broken open or separated > 4" gap with extensive voids and embankment or roadway damage
Cross-Section Deformation	None observed	Cracks present, but no perceptible cross-section deformation	Longitudinal cracks in crown, invert and/or haunches, with perceptible cross-section deformation	Deformation and cracking has led to extensive infiltration of backfill soil, structural failure or embankment and/or roadway damage
Cracking	Boxes and Arches: Minor hairline or map cracks due to shrinkage <=1/8" wide at isolated areas, not at the crown or spring lines, with <25% cross-section coverage RCP: No cracks	Boxes and Arches: Minor cracks <= 1/4" wide, with minor spalls and infil/exfil of water or soil, along crown or haunches, <50% cross-section coverage any size RCP: Few hairline cracks, not at crown or haunches	Boxes and Arches: Open cracks >1/4" wide with significant infil/exfil and voids, or >50% cross-section coverage any size RCP: Cracks >1/8" wide, or any along crown or haunches, or >25% cross-section coverage any size	Resultant displacement at cracks has led to extensive infiltration of backfill soil, structural failure and/or resultant embankment and/or roadway damage
Corrosion/ Chemical	Boxes and Arches: Efflorescence present for boxes & arches RCP: No efflorescence	Boxes and Arches: Rust staining at cracks and spalls RCP: No rust staining	Boxes and Arches: Exposed steel reinforcement RCP: Rust staining or exposed steel reinforcement	Significant section loss of steel reinforcement that causes pipe deformation, holes in pipe walls and embankment and/or roadway damage

Notes:

- If the structure is open-bottomed and the side of a footing is exposed, a Level 2 assessment is required.
- If the structure is open-bottomed and rated in Poor or Critical condition, a Level 2 assessment is required.
- If the structure is known to have deteriorated from New/Good condition to Poor or Critical due to invert abrasion or corrosion/chemical attack in 5 years or less, a Level 2 assessment is required.
- See Level 2 Disciplines Matrix in Decision-Making Tool for guidance on Level 2 assessments.

Figure B.2 Condition Rating Items - Concrete and Reinforced Concrete Pipes



FEDERAL LANDS HIGHWAY

FHWA FLH CULVERT ASSESSMENT GUIDE

CORRUGATED METAL PIPE CONDITIONS

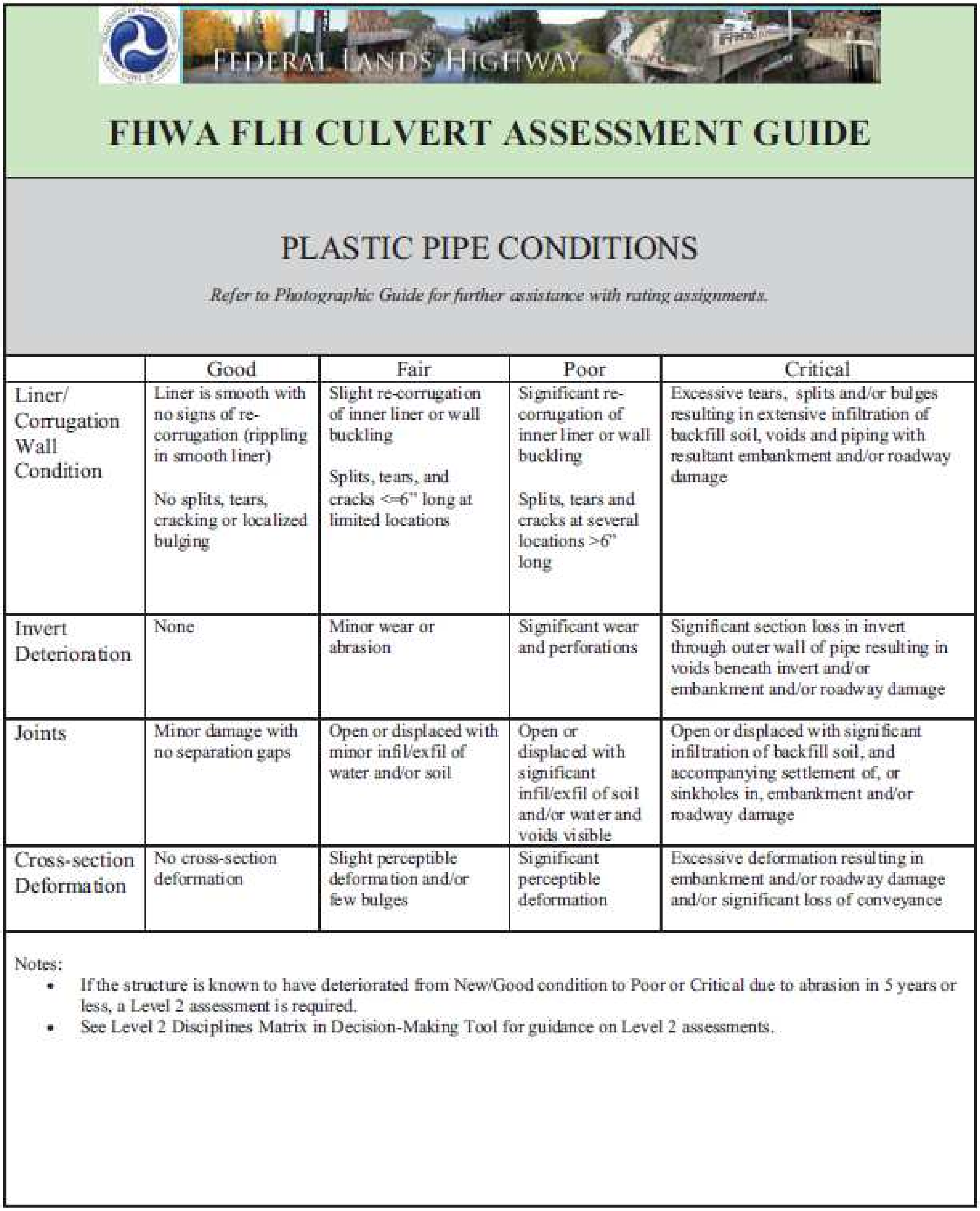
Refer to Photographic Guide for further assistance with rating assignments.

	Good	Fair	Poor	Critical
Corrosion (Above Invert)	Little or no surface rust above the invert Little or no coating loss if coated above the invert	Minor surface rust and limited pitting above the invert Connection hardware corroded but intact	Perforations visible or easily made by hammer test strike above the invert Connection hardware failing	Significant section loss resulting in extensive infiltration of backfill soil, voids and embankment and/or roadway damage
Cross-section Deformation	None	Slight perceptible deformation at worst section, or local bulging	Deformation with accompanying longitudinal cracking or crushing in crown, invert and/or spring lines	Excessive deformation resulting in extensive infiltration of backfill soil, voids and piping with resultant embankment and/or roadway damage
Invert Deterioration	Little or no coating loss, and/or light rust staining, but no metal section loss	General corrosion, scaling or pitting with coating loss, but significant remaining metal section	Perforations visible or easily made by hammer test strike in invert area	Significant section loss in invert beyond perforations resulting in extensive voids beneath invert and/or embankment and/or roadway damage
Joints & Seams	Minor damage with no separation gaps	Open or displaced with minor infil/exfil of water and/or soil	Open or displaced with significant infil/exfil of soil and/or water and voids visible	Open or displaced with significant infiltration of backfill soil, and accompanying embankment and/or roadway damage

Notes:

- If the structure is open-bottomed and the side of a footing is exposed, a Level 2 assessment is required.
- If the structure is open-bottomed and rated in Poor or Critical condition, a Level 2 assessment is required.
- If the structure in known to have deteriorated from New/Good condition to Poor or Critical due to abrasion or corrosion in 5 years or less, a Level 2 assessment is required.
- See Level 2 Disciplines Matrix in Decision-Making Tool for guidance on Level 2 assessments.

Figure B.3 Condition Rating Items - Corrugated Metal Pipes



FEDERAL LANDS HIGHWAY

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PLASTIC PIPE CONDITIONS

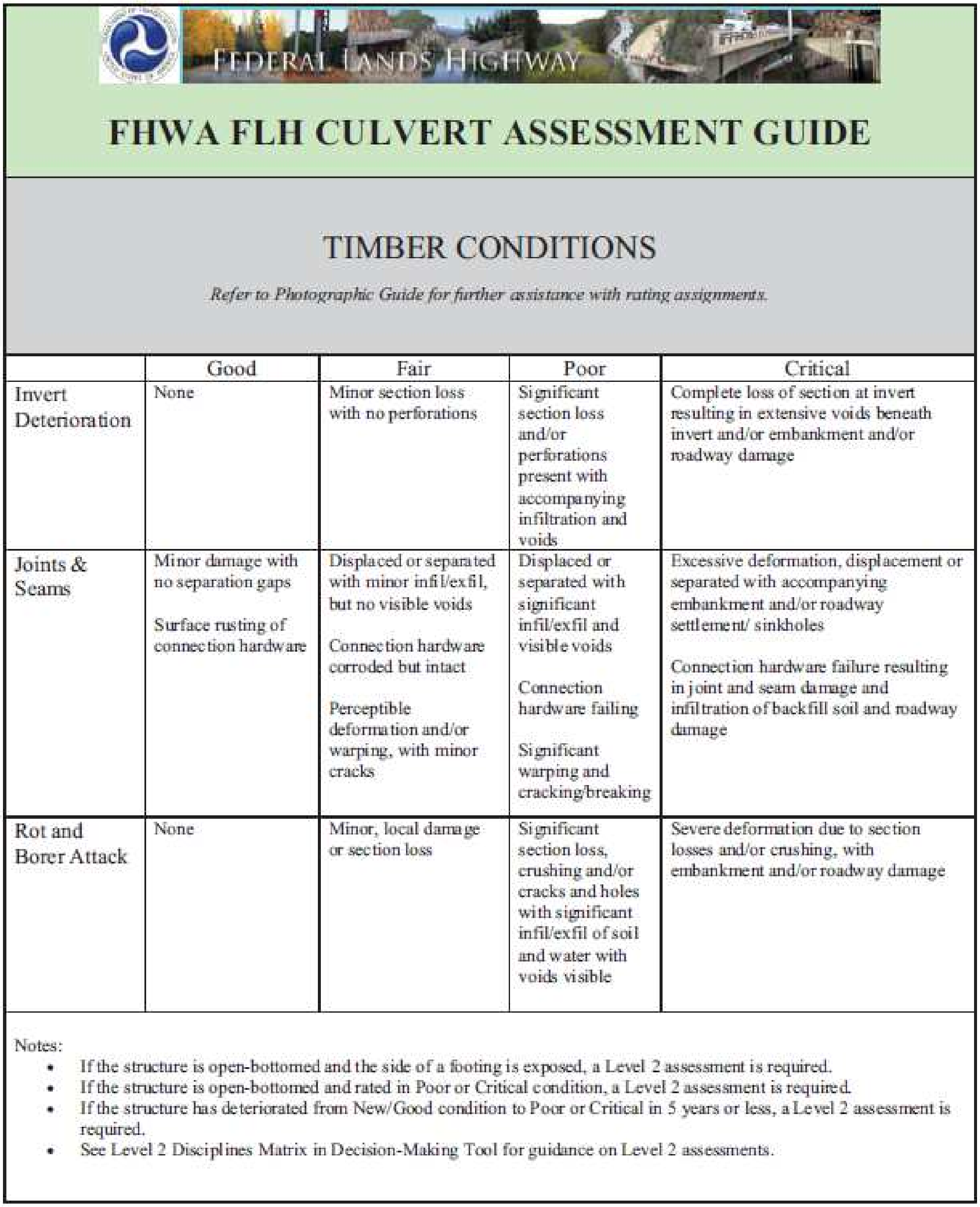
Refer to Photographic Guide for further assistance with rating assignments.

	Good	Fair	Poor	Critical
Liner/ Corrugation Wall Condition	Liner is smooth with no signs of re-corrugation (rippling in smooth liner) No splits, tears, cracking or localized bulging	Slight re-corrugation of inner liner or wall buckling Splits, tears, and cracks <=6" long at limited locations	Significant re-corrugation of inner liner or wall buckling Splits, tears and cracks at several locations >6" long	Excessive tears, splits and/or bulges resulting in extensive infiltration of backfill soil, voids and piping with resultant embankment and/or roadway damage
Invert Deterioration	None	Minor wear or abrasion	Significant wear and perforations	Significant section loss in invert through outer wall of pipe resulting in voids beneath invert and/or embankment and/or roadway damage
Joints	Minor damage with no separation gaps	Open or displaced with minor infil/exfil of water and/or soil	Open or displaced with significant infil/exfil of soil and/or water and voids visible	Open or displaced with significant infiltration of backfill soil, and accompanying settlement of, or sinkholes in, embankment and/or roadway damage
Cross-section Deformation	No cross-section deformation	Slight perceptible deformation and/or few bulges	Significant perceptible deformation	Excessive deformation resulting in embankment and/or roadway damage and/or significant loss of conveyance

Notes:

- If the structure is known to have deteriorated from New/Good condition to Poor or Critical due to abrasion in 5 years or less, a Level 2 assessment is required.
- See Level 2 Disciplines Matrix in Decision-Making Tool for guidance on Level 2 assessments.

Figure B.4 Condition Rating Items - Plastic Pipes



FHWA FLH CULVERT ASSESSMENT GUIDE

TIMBER CONDITIONS

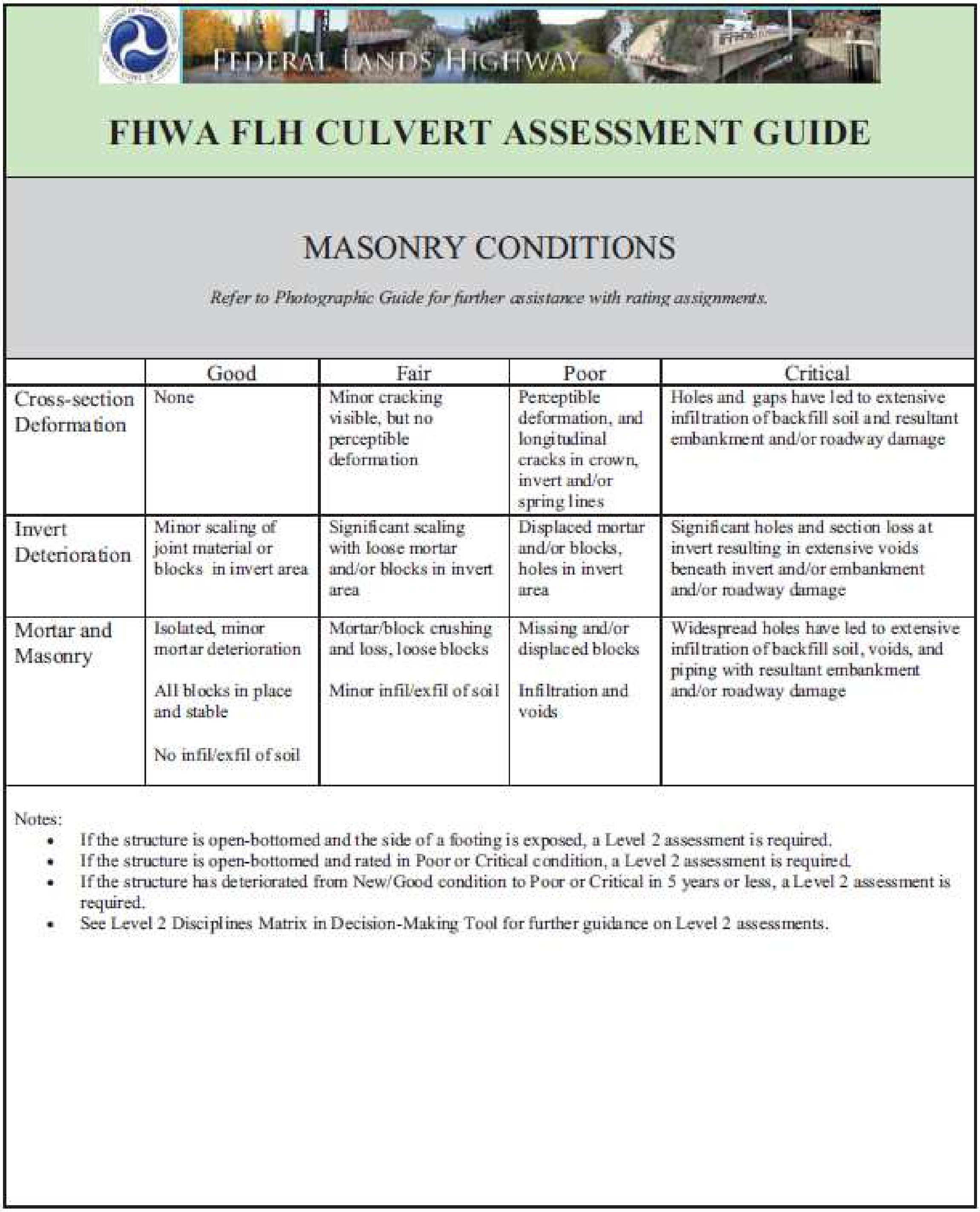
Refer to Photographic Guide for further assistance with rating assignments.

	Good	Fair	Poor	Critical
Invert Deterioration	None	Minor section loss with no perforations	Significant section loss and/or perforations present with accompanying infiltration and voids	Complete loss of section at invert resulting in extensive voids beneath invert and/or embankment and/or roadway damage
Joints & Seams	Minor damage with no separation gaps Surface rusting of connection hardware	Displaced or separated with minor infil/exfil, but no visible voids Connection hardware corroded but intact Perceptible deformation and/or warping, with minor cracks	Displaced or separated with significant infil/exfil and visible voids Connection hardware failing Significant warping and cracking/breaking	Excessive deformation, displacement or separated with accompanying embankment and/or roadway settlement/ sinkholes Connection hardware failure resulting in joint and seam damage and infiltration of backfill soil and roadway damage
Rot and Borer Attack	None	Minor, local damage or section loss	Significant section loss, crushing and/or cracks and holes with significant infil/exfil of soil and water with voids visible	Severe deformation due to section losses and/or crushing, with embankment and/or roadway damage

Notes:

- If the structure is open-bottomed and the side of a footing is exposed, a Level 2 assessment is required.
- If the structure is open-bottomed and rated in Poor or Critical condition, a Level 2 assessment is required.
- If the structure has deteriorated from New/Good condition to Poor or Critical in 5 years or less, a Level 2 assessment is required.
- See Level 2 Disciplines Matrix in Decision-Making Tool for guidance on Level 2 assessments.

Figure B.5 Condition Rating Items - Timber Culverts



FEDERAL LANDS HIGHWAY

FHWA FLH CULVERT ASSESSMENT GUIDE

MASONRY CONDITIONS

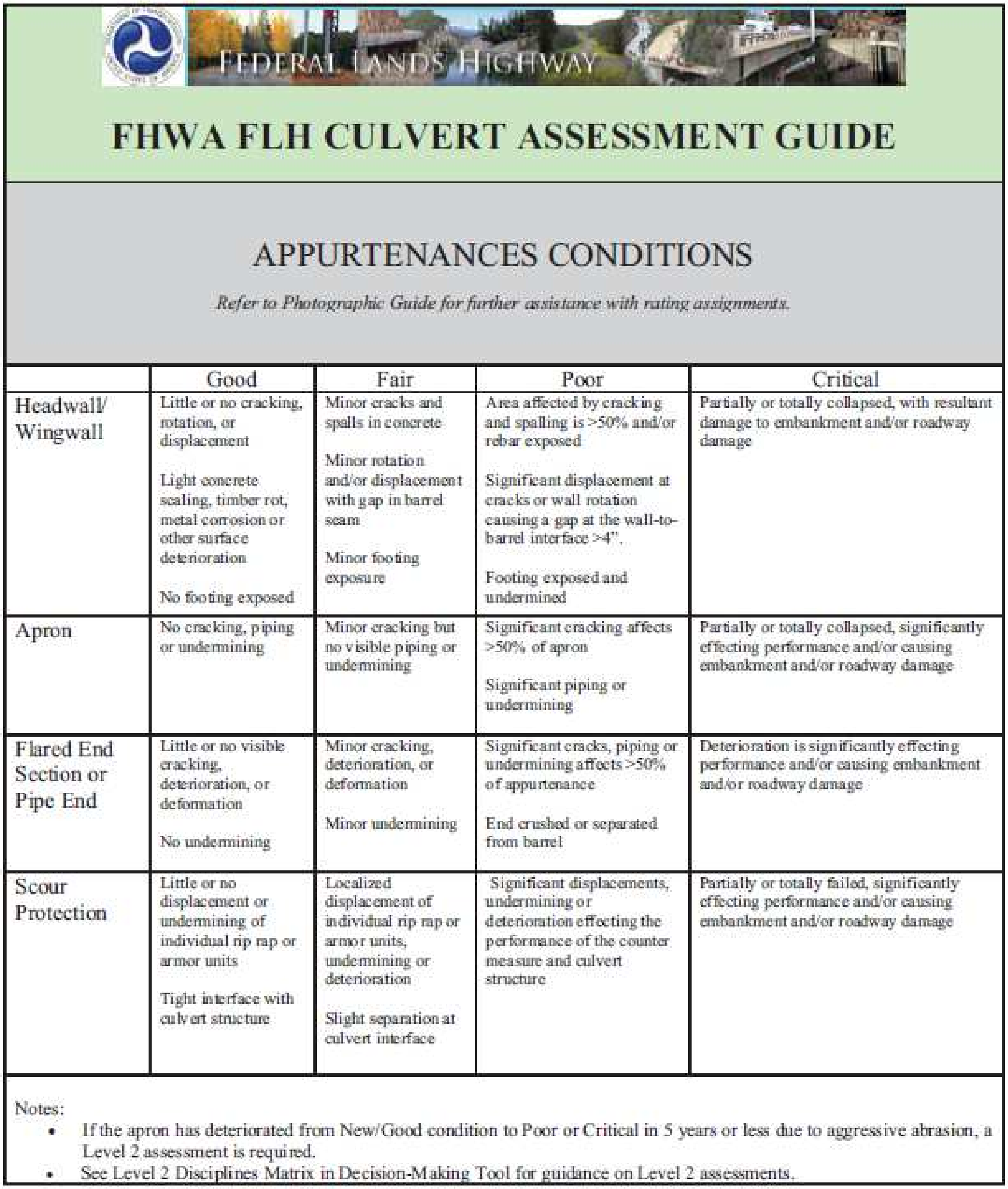
Refer to Photographic Guide for further assistance with rating assignments.

	Good	Fair	Poor	Critical
Cross-section Deformation	None	Minor cracking visible, but no perceptible deformation	Perceptible deformation, and longitudinal cracks in crown, invert and/or spring lines	Holes and gaps have led to extensive infiltration of backfill soil and resultant embankment and/or roadway damage
Invert Deterioration	Minor scaling of joint material or blocks in invert area	Significant scaling with loose mortar and/or blocks in invert area	Displaced mortar and/or blocks, holes in invert area	Significant holes and section loss at invert resulting in extensive voids beneath invert and/or embankment and/or roadway damage
Mortar and Masonry	Isolated, minor mortar deterioration All blocks in place and stable No infil/exfil of soil	Mortar/block crushing and loss, loose blocks Minor infil/exfil of soil	Missing and/or displaced blocks Infiltration and voids	Widespread holes have led to extensive infiltration of backfill soil, voids, and piping with resultant embankment and/or roadway damage

Notes:

- If the structure is open-bottomed and the side of a footing is exposed, a Level 2 assessment is required.
- If the structure is open-bottomed and rated in Poor or Critical condition, a Level 2 assessment is required.
- If the structure has deteriorated from New/Good condition to Poor or Critical in 5 years or less, a Level 2 assessment is required.
- See Level 2 Disciplines Matrix in Decision-Making Tool for further guidance on Level 2 assessments.

Figure B.7 Condition Rating Items - Masonry Culverts



FEDERAL LANDS HIGHWAY

FHWA FLH CULVERT ASSESSMENT GUIDE

APPURTENANCES CONDITIONS

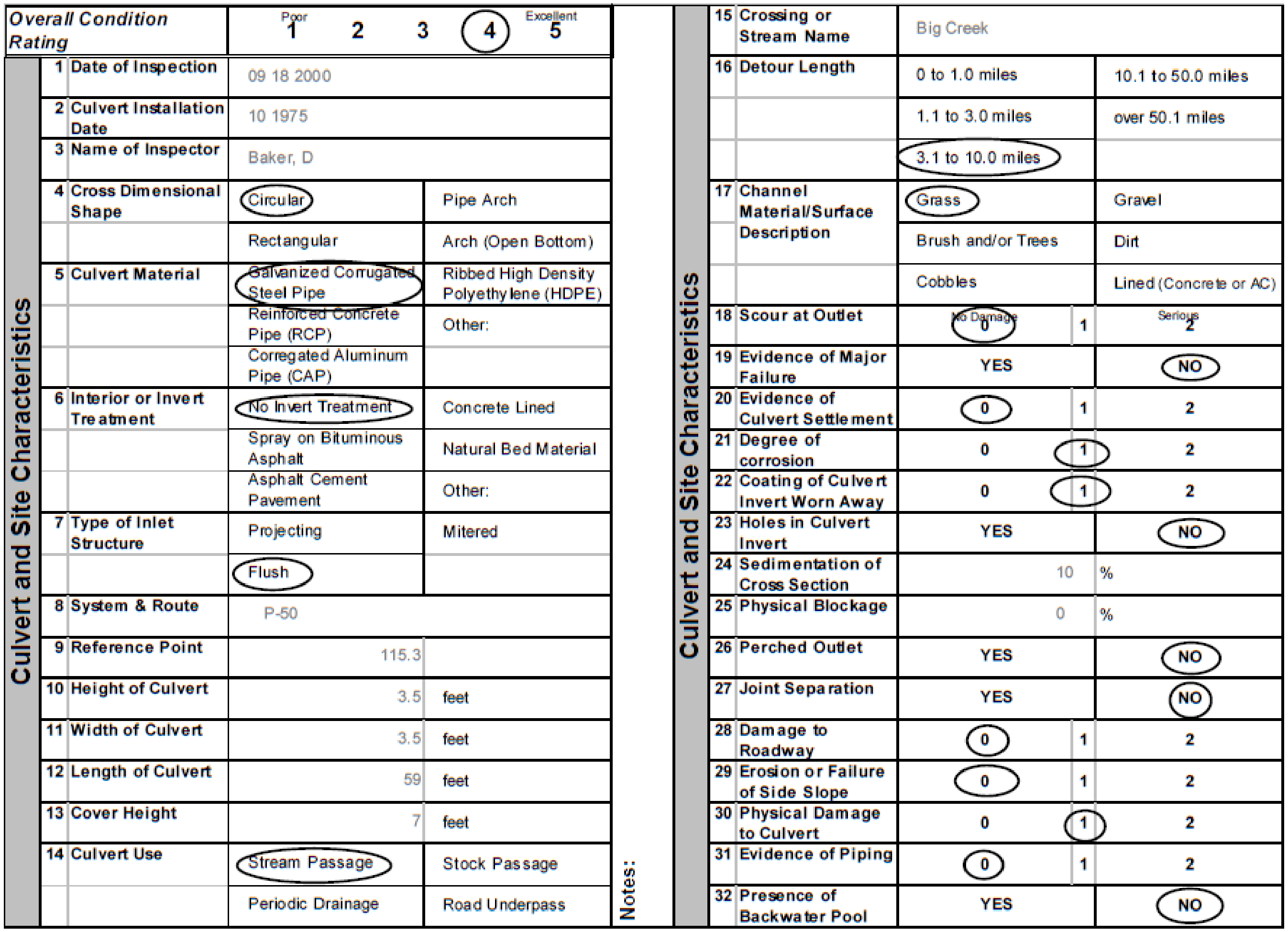
Refer to Photographic Guide for further assistance with rating assignments.

	Good	Fair	Poor	Critical
Headwall/ Wingwall	Little or no cracking, rotation, or displacement Light concrete scaling, timber rot, metal corrosion or other surface deterioration No footing exposed	Minor cracks and spalls in concrete Minor rotation and/or displacement with gap in barrel seam Minor footing exposure	Area affected by cracking and spalling is >50% and/or rebar exposed Significant displacement at cracks or wall rotation causing a gap at the wall-to-barrel interface >4". Footing exposed and undermined	Partially or totally collapsed, with resultant damage to embankment and/or roadway damage
Apron	No cracking, piping or undermining	Minor cracking but no visible piping or undermining	Significant cracking affects >50% of apron Significant piping or undermining	Partially or totally collapsed, significantly effecting performance and/or causing embankment and/or roadway damage
Flared End Section or Pipe End	Little or no visible cracking, deterioration, or deformation No undermining	Minor cracking, deterioration, or deformation Minor undermining	Significant cracks, piping or undermining affects >50% of appurtenance End crushed or separated from barrel	Deterioration is significantly effecting performance and/or causing embankment and/or roadway damage
Scour Protection	Little or no displacement or undermining of individual rip rap or armor units Tight interface with culvert structure	Localized displacement of individual rip rap or armor units, undermining or deterioration Slight separation at culvert interface	Significant displacements, undermining or deterioration effecting the performance of the counter measure and culvert structure	Partially or totally failed, significantly effecting performance and/or causing embankment and/or roadway damage

Notes:
- If the apron has deteriorated from New/Good condition to Poor or Critical in 5 years or less due to aggressive abrasion, a Level 2 assessment is required.
- See Level 2 Disciplines Matrix in Decision-Making Tool for guidance on Level 2 assessments.

Figure B.8 Condition Rating Items - Appurtenances

APPENDIX C: WTI Culvert Rating Data Collection Form[8]



Overall Condition Rating: Poor 1 2 3 [✓ 4] 5 Excellent

Culvert and Site Characteristics

1	Date of Inspection	09 18 2000	
2	Culvert Installation Date	10 1975	
3	Name of Inspector	Baker, D	
4	Cross Dimensional Shape	[✓ Circular]	Pipe Arch
		Rectangular	Arch (Open Bottom)
5	Culvert Material	[✓ Galvanized Corrugated Steel Pipe]	Ribbed High Density Polyethylene (HDPE)
		Reinforced Concrete Pipe (RCP)	Other:
		Corregated Aluminum Pipe (CAP)	
6	Interior or Invert Treatment	[✓ No Invert Treatment]	Concrete Lined
		Spray on Bituminous Asphalt	Natural Bed Material
		Asphalt Cement Pavement	Other:
7	Type of Inlet Structure	Projecting	Mitered
		[✓ Flush]	
8	System & Route	P-50	
9	Reference Point	115.3	
10	Height of Culvert	3.5	feet
11	Width of Culvert	3.5	feet
12	Length of Culvert	59	feet
13	Cover Height	7	feet
14	Culvert Use	[✓ Stream Passage]	Stock Passage
		Periodic Drainage	Road Underpass

Notes:

Culvert and Site Characteristics

15	Crossing or Stream Name	Big Creek		
16	Detour Length	0 to 1.0 miles		10.1 to 50.0 miles
		1.1 to 3.0 miles		over 50.1 miles
		[✓ 3.1 to 10.0 miles]		
17	Channel Material/Surface Description	[✓ Grass]		Gravel
		Brush and/or Trees		Dirt
		Cobbles		Lined (Concrete or AC)
18	Scour at Outlet	No Damage [✓ 0]	1	Serious 2
19	Evidence of Major Failure	YES		[✓ NO]
20	Evidence of Culvert Settlement	[✓ 0]	1	2
21	Degree of corrosion	0	[✓ 1]	2
22	Coating of Culvert Invert Worn Away	0	[✓ 1]	2
23	Holes in Culvert Invert	YES		[✓ NO]
24	Sedimentation of Cross Section	10	%	
25	Physical Blockage	0	%	
26	Perched Outlet	YES		[✓ NO]
27	Joint Separation	YES		[✓ NO]
28	Damage to Roadway	[✓ 0]	1	2
29	Erosion or Failure of Side Slope	[✓ 0]	1	2
30	Physical Damage to Culvert	0	[✓ 1]	2
31	Evidence of Piping	[✓ 0]	1	2
32	Presence of Backwater Pool	YES		[✓ NO]

Figure C.1 WTI Culvert Rating Example Data Collection Form

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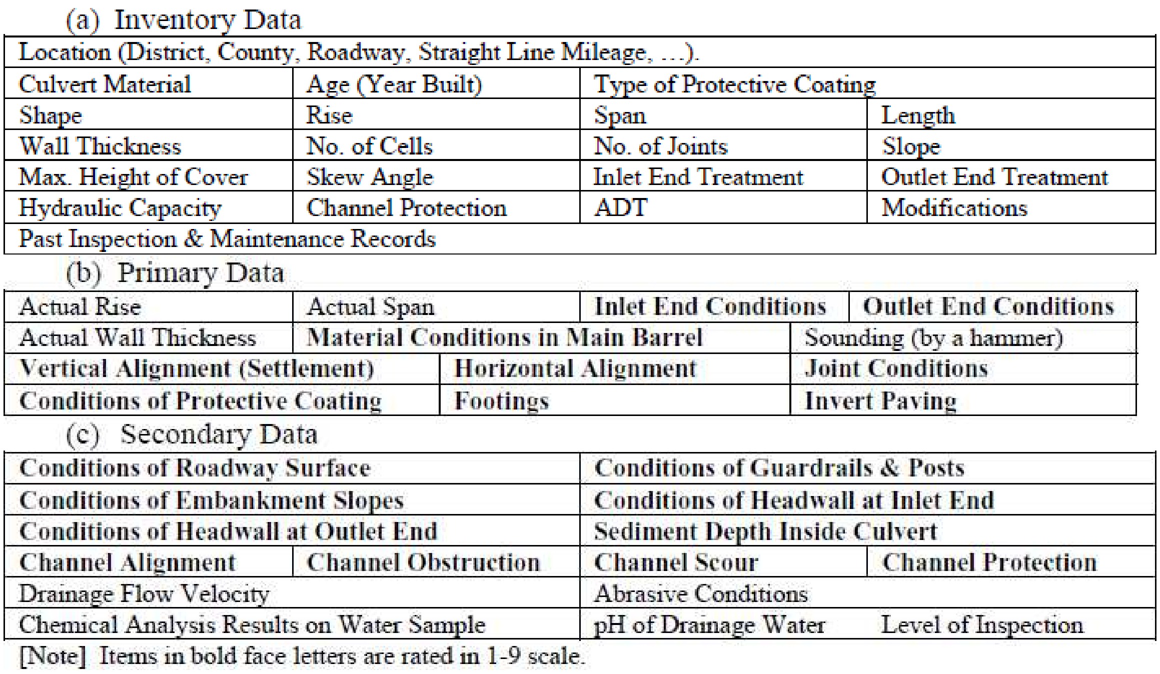
[8] The figures in Appendix C are from: Baker et al. (2001)

APPENDIX D: ORITE CULVERT RATING ITEMS AND SCALES[9]



(a) Inventory Data

Location (District, County, Roadway, Straight Line Mileage, …).			
Culvert Material	Age (Year Built)	Type of Protective Coating	
Shape	Rise	Span	Length
Wall Thickness	No. of Cells	No. of Joints	Slope
Max. Height of Cover	Skew Angle	Inlet End Treatment	Outlet End Treatment
Hydraulic Capacity	Channel Protection	ADT	Modifications
Past Inspection & Maintenance Records			

(b) Primary Data

Actual Rise	Actual Span	**Inlet End Conditions**	**Outlet End Conditions**
Actual Wall Thickness	**Material Conditions in Main Barrel**	Sounding (by a hammer)	
Vertical Alignment (Settlement)	**Horizontal Alignment**	**Joint Conditions**	
Conditions of Protective Coating	**Footings**	**Invert Paving**	

(c) Secondary Data

Conditions of Roadway Surface		**Conditions of Guardrails & Posts**	
Conditions of Embankment Slopes		**Conditions of Headwall at Inlet End**	
Conditions of Headwall at Outlet End		**Sediment Depth Inside Culvert**	
Channel Alignment	**Channel Obstruction**	**Channel Scour**	**Channel Protection**
Drainage Flow Velocity		Abrasive Conditions	
Chemical Analysis Results on Water Sample		pH of Drainage Water	Level of Inspection

[Note] Items in bold face letters are rated in 1-9 scale.

Figure D.1 Concrete Culvert Data Items

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[9] The figures in Appendix D are from: Mitchell et al. (2005)

(a) Inventory Data

Location (District, County, Roadway, Straight Line Mileage, …).			
Culvert Material	Age (Year Built)	Type of Protective Coating	
Shape	Rise	Span	Length
Wall Thickness	No. of Cells	Slope	Skew Angle
Max. Height of Cover	Inlet End Treatment	Outlet End Treatment	Hydraulic Capacity
Channel Protection	ADT	Modifications	Data on Invert Paving
Data on Backfill Soil	Trench Dimensions	Past Inspection & Maintenance Records	

(b) Primary Data

Actual Rise & Span	Other Cross-Sectional Dimensions		**Deflections**
Shape Evaluation	**Inlet End Conditions**	**Outlet End Conditions**	Actual Wall Thickness
Material Conditions	**Horizontal Alignment**	**Vertical Alignment (Settlement)**	
Conditions of Seams	**Conditions of Protective Coating**	**Conditions of Invert Paving**	
Conditions of Footings			

(c) Secondary Data

Conditions of Roadway Surface		**Conditions of Guardrails & Posts**	
Conditions of Embankment Slopes		**Conditions of Headwall at Inlet End**	
Conditions of Headwall at Outlet End		**Sediment Depth Inside Culvert**	
Channel Alignment	**Channel Blockage**	**Channel Scour**	**Channel Protection**
Drainage Flow Velocity		Abrasive Conditions	
Chemical Analysis Results on Water Sample		pH of Drainage Water	Level of Inspection

[Note] Items in bold face letters are rated in 1-9 scale.

Figure D.2 Metal Culvert Data Items

(a) Inventory Data

Location (District, County, Roadway, Straight Line Mileage, …).			
Culvert Material	Age (Year Built)	Manufacturer	Product Name
Diameter	Length	No. of Cells	Wall Thickness
Type of Joint	No. of Joints	Slope	Max. Height of Cover
Skew Angle	Inlet End Treatment	Outlet End Treatment	Hydraulic Capacity
Channel Protection	ADT	Past Inspection & Maintenance Records	

(b) Primary Data

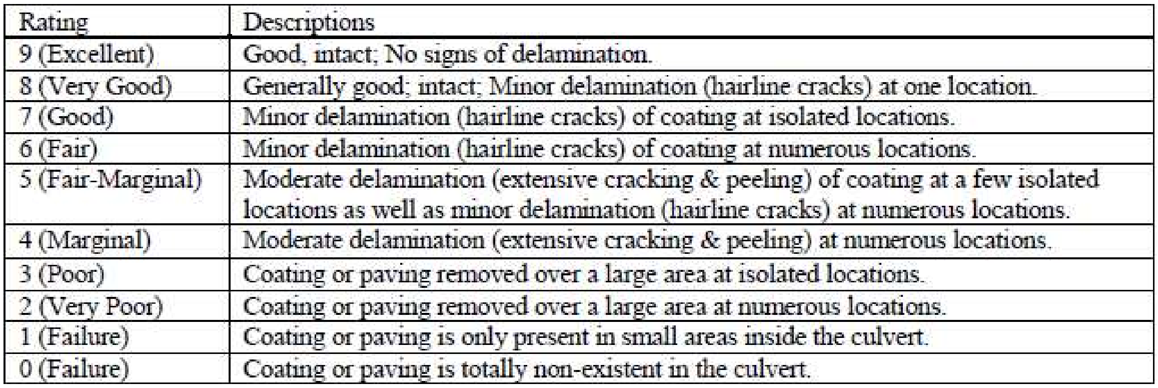
Actual Rise & Span	Other Cross-Sectional Dimensions		**Deflections**
Shape Evaluation	**Inlet End Conditions**	**Outlet End Conditions**	Actual Wall Thickness
Material Conditions	**Horizontal Alignment**	**Vertical Alignment (Settlement)**	
Conditions of Joints			

(c) Secondary Data

Conditions of Roadway Surface		**Conditions of Guardrails & Posts**	
Conditions of Embankment Slopes		**Conditions of Headwall at Inlet End**	
Conditions of Headwall at Outlet End		**Sediment Depth Inside Culvert**	
Channel Alignment	**Channel Blockage**	**Channel Scour**	**Channel Protection**
Drainage Flow Velocity		Abrasive Conditions	
Chemical Analysis Results on Water Sample		pH of Drainage Water	Level of Inspection

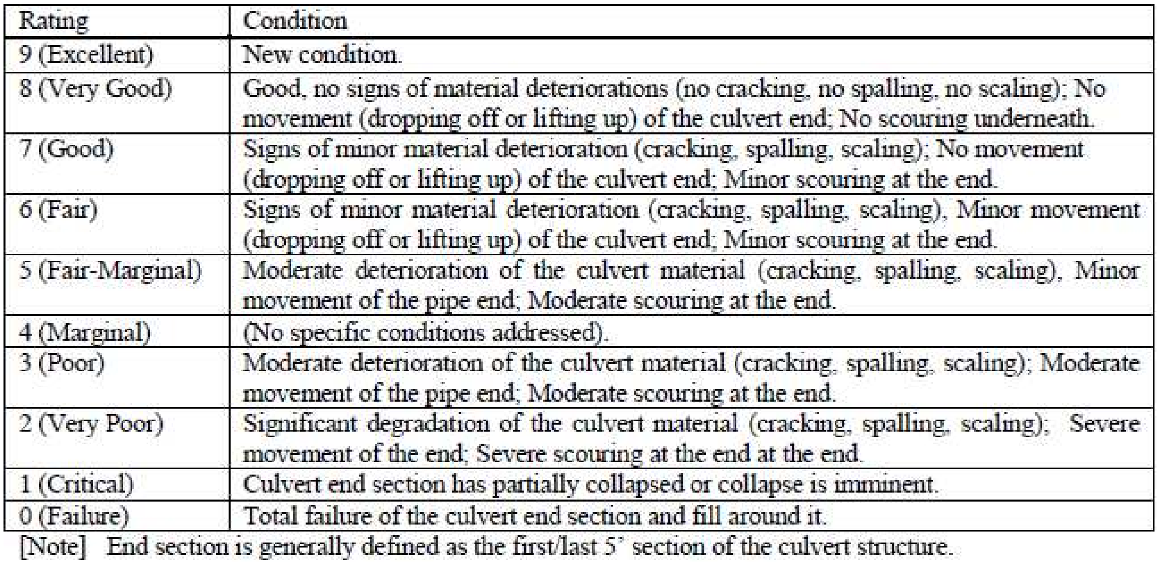
[Note] Items in bold face letters are rated in 1-9 scale.

Figure D.3 Thermoplastic Pipe Culvert Data Items



Rating	Descriptions
9 (Excellent)	Good, intact; No signs of delamination.
8 (Very Good)	Generally good; intact; Minor delamination (hairline cracks) at one location.
7 (Good)	Minor delamination (hairline cracks) of coating at isolated locations.
6 (Fair)	Minor delamination (hairline cracks) of coating at numerous locations.
5 (Fair-Marginal)	Moderate delamination (extensive cracking & peeling) of coating at a few isolated locations as well as minor delamination (hairline cracks) at numerous locations.
4 (Marginal)	Moderate delamination (extensive cracking & peeling) at numerous locations.
3 (Poor)	Coating or paving removed over a large area at isolated locations.
2 (Very Poor)	Coating or paving removed over a large area at numerous locations.
1 (Failure)	Coating or paving is only present in small areas inside the culvert.
0 (Failure)	Coating or paving is totally non-existent in the culvert.

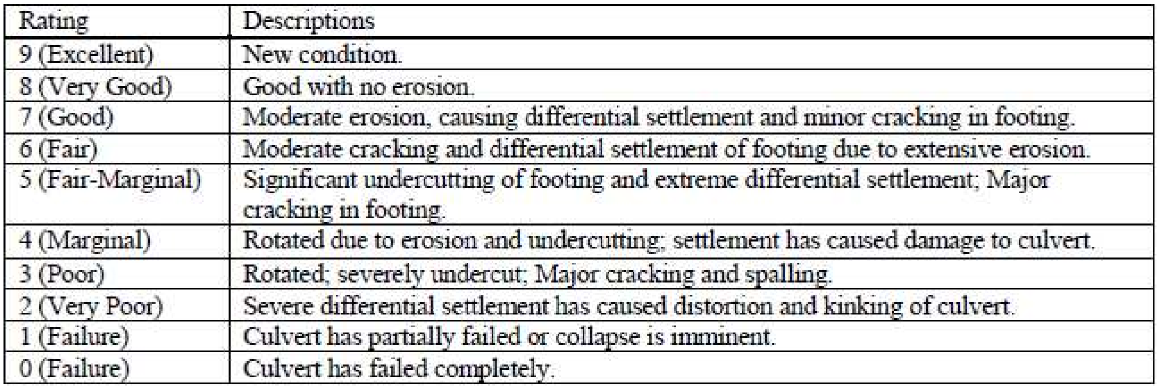
Figure D.4 Protective Coating and Invert Paving Condition Rating Scale



Rating	Condition
9 (Excellent)	New condition.
8 (Very Good)	Good, no signs of material deteriorations (no cracking, no spalling, no scaling); No movement (dropping off or lifting up) of the culvert end; No scouring underneath.
7 (Good)	Signs of minor material deterioration (cracking, spalling, scaling); No movement (dropping off or lifting up) of the culvert end; Minor scouring at the end.
6 (Fair)	Signs of minor material deterioration (cracking, spalling, scaling), Minor movement (dropping off or lifting up) of the culvert end; Minor scouring at the end.
5 (Fair-Marginal)	Moderate deterioration of the culvert material (cracking, spalling, scaling), Minor movement of the pipe end; Moderate scouring at the end.
4 (Marginal)	(No specific conditions addressed).
3 (Poor)	Moderate deterioration of the culvert material (cracking, spalling, scaling); Moderate movement of the pipe end; Moderate scouring at the end.
2 (Very Poor)	Significant degradation of the culvert material (cracking, spalling, scaling); Severe movement of the end; Severe scouring at the end at the end.
1 (Critical)	Culvert end section has partially collapsed or collapse is imminent.
0 (Failure)	Total failure of the culvert end section and fill around it.

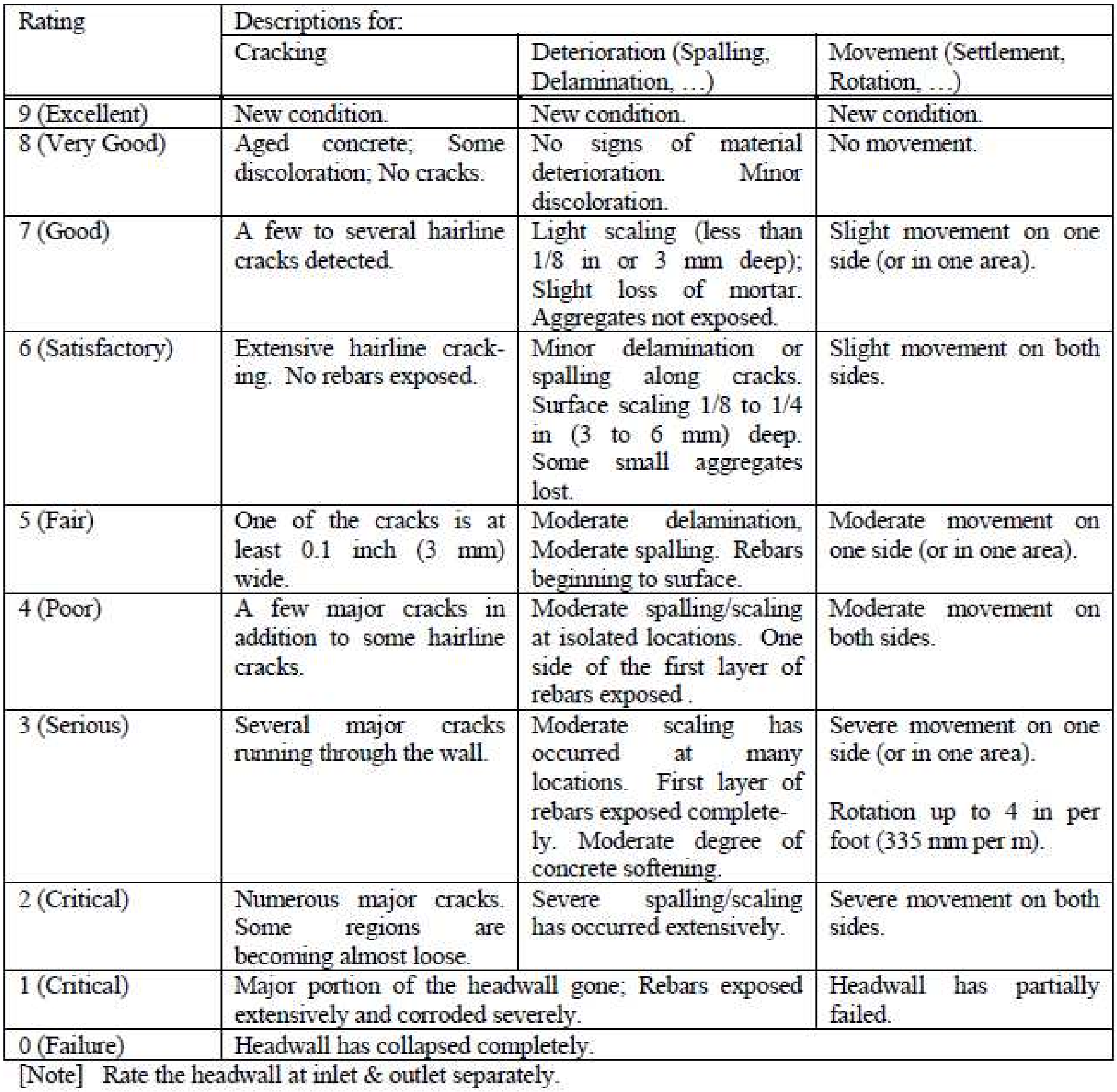
[Note] End section is generally defined as the first/last 5' section of the culvert structure.

Figure D.5 Culvert Inlet and Outlet Sections Condition Rating Scale



Rating	Descriptions
9 (Excellent)	New condition.
8 (Very Good)	Good with no erosion.
7 (Good)	Moderate erosion, causing differential settlement and minor cracking in footing.
6 (Fair)	Moderate cracking and differential settlement of footing due to extensive erosion.
5 (Fair-Marginal)	Significant undercutting of footing and extreme differential settlement; Major cracking in footing.
4 (Marginal)	Rotated due to erosion and undercutting; settlement has caused damage to culvert.
3 (Poor)	Rotated; severely undercut; Major cracking and spalling.
2 (Very Poor)	Severe differential settlement has caused distortion and kinking of culvert.
1 (Failure)	Culvert has partially failed or collapse is imminent.
0 (Failure)	Culvert has failed completely.

Figure D.6 Footings Condition Rating Scale



Rating	Descriptions for:		
	Cracking	Deterioration (Spalling, Delamination, …)	Movement (Settlement, Rotation, …)
9 (Excellent)	New condition.	New condition.	New condition.
8 (Very Good)	Aged concrete; Some discoloration; No cracks.	No signs of material deterioration. Minor discoloration.	No movement.
7 (Good)	A few to several hairline cracks detected.	Light scaling (less than 1/8 in or 3 mm deep); Slight loss of mortar. Aggregates not exposed.	Slight movement on one side (or in one area).
6 (Satisfactory)	Extensive hairline cracking. No rebars exposed.	Minor delamination or spalling along cracks. Surface scaling 1/8 to 1/4 in (3 to 6 mm) deep. Some small aggregates lost.	Slight movement on both sides.
5 (Fair)	One of the cracks is at least 0.1 inch (3 mm) wide.	Moderate delamination, Moderate spalling. Rebars beginning to surface.	Moderate movement on one side (or in one area).
4 (Poor)	A few major cracks in addition to some hairline cracks.	Moderate spalling/scaling at isolated locations. One side of the first layer of rebars exposed .	Moderate movement on both sides.
3 (Serious)	Several major cracks running through the wall.	Moderate scaling has occurred at many locations. First layer of rebars exposed completely. Moderate degree of concrete softening.	Severe movement on one side (or in one area). Rotation up to 4 in per foot (335 mm per m).
2 (Critical)	Numerous major cracks. Some regions are becoming almost loose.	Severe spalling/scaling has occurred extensively.	Severe movement on both sides.
1 (Critical)	Major portion of the headwall gone; Rebars exposed extensively and corroded severely.		Headwall has partially failed.
0 (Failure)	Headwall has collapsed completely.		

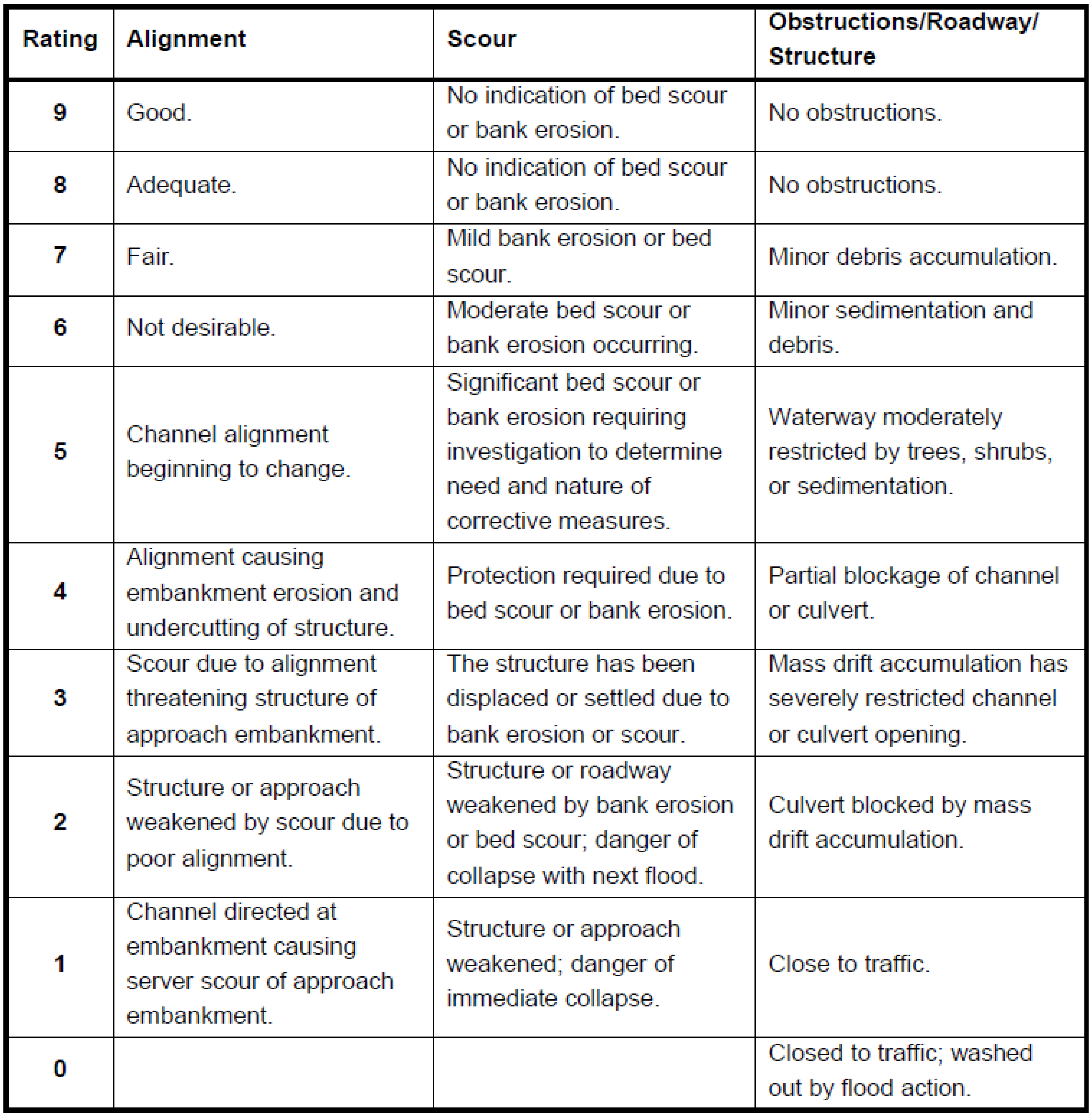
[Note] Rate the headwall at inlet & outlet separately.

Figure D.7 Headwall and Wingwall Condition Rating Scale

Rating	Descriptions for:		
	Alignment	Scouring	Obstruction
9 (Excellent)	New conditions. Channel is straight for more than 100’ at both upstream & downstream. No adverse conditions detected.	New conditions. No scouring at either inlet or outlet ends.	New conditions. No debris or sediment accumulation anywhere.
8 (Very Good)	Channel straight for 50’ to 100’ at one end, for more than 100’ at other end.	Very minor (< 6” deep) scouring at both inlet and outlet ends.	Minor debris accumulation.
7 (Good)	Channel is straight for 50’ to 100’ at both ends; Minor sediment accumulation; Bush growing.	Minor (6” to 12” deep) scouring at one end.	Minor sedimentation and debris accumulation; Up to 5% blockage of channel opening.
6 (Satisfactory)	Channel is straight for 20’ to 50’ at one end; Channel is curved by 20° to 40° angle near inlet; Deposit causing channel to split.	Minor (6” to 12” deep) scouring at both ends; Top of footings is exposed.	Minor sedimentation and debris. Up to 10% blockage of channel opening; Bush or tree growing in channel.
5 (Fair)	Channel is straight for 20’ to 50’ at both ends; Channel curved by 40° to 50° angle near inlet; Flow hitting outside headwall; Stream meandered; Signs of Bank erosion.	Minor (6” to 12” deep) scouring at one end; Moderate (12” to 24” deep) scouring at the other end; Footings along the side are exposed.	Waterway moderately (up to 25%) restricted by tree, shrubs, or sedimentation; Bush or tree growing in channel.
4 (Poor)	Channel curved by 50° to 70° angle near inlet; Flow enters culvert by other means than design opening; Signs of Bank erosion.	Severe (2’ to 3’ deep) scouring at one end; Less scouring at the other end; Bottom of footings is exposed; Not undermining cutoff walls/headwalls.	Partial (up to 50%) blockage of channel opening; Large debris in the waterway; Occasional overtopping of roadway.
3 (Serious)	Channel curved by 70° to 90° turn near inlet; Erosion behind wingwalls; Erosion of embankment encroaching on roadway.	Major (> 3’ deep) scouring at one end; Cutoff walls and/or headwalls being undermined; Footings are undermined; Structure has been displaced or settled.	Mass drift accumulation has restricted 75% of channel opening; Occasional overtopping of roadway.
2 (Critical)	Channel flow piping around culvert; Erosion of embankment encroaching on roadway.	Structure or roadway weakened by bank erosion or scour problem; danger of collapse sometime in the future.	Culvert waterway blocked up to 85% by mass drift accumulation; Frequent overtopping of roadway w/ significant traffic delays.
1 (Failure Imminent)	No channel flow enters culvert; Severe piping problem around culvert; Road may be closed due to channel failure.	Structure or approach weakened; danger of immediate collapse.	Culvert waterway 100% blocked by deposits; Water pooling outside and not flowing through pipe; Road may be closed due to channel failure.
0 (Failed)	Pipe has collapsed.	Pipe has collapsed.	Pipe has collapsed.
- 1 (Under Construction)	Cannot be rated; still under construction.		

Figure D.8 Channel General Condition Rating Scale

APPENDIX E: UTAH DOT CULVERT PERFORMANCE RATING SCALES[10]



Rating	Alignment	Scour	Obstructions/Roadway/ Structure
9	Good.	No indication of bed scour or bank erosion.	No obstructions.
8	Adequate.	No indication of bed scour or bank erosion.	No obstructions.
7	Fair.	Mild bank erosion or bed scour.	Minor debris accumulation.
6	Not desirable.	Moderate bed scour or bank erosion occurring.	Minor sedimentation and debris.
5	Channel alignment beginning to change.	Significant bed scour or bank erosion requiring investigation to determine need and nature of corrective measures.	Waterway moderately restricted by trees, shrubs, or sedimentation.
4	Alignment causing embankment erosion and undercutting of structure.	Protection required due to bed scour or bank erosion.	Partial blockage of channel or culvert.
3	Scour due to alignment threatening structure of approach embankment.	The structure has been displaced or settled due to bank erosion or scour.	Mass drift accumulation has severely restricted channel or culvert opening.
2	Structure or approach weakened by scour due to poor alignment.	Structure or roadway weakened by bank erosion or bed scour; danger of collapse with next flood.	Culvert blocked by mass drift accumulation.
1	Channel directed at embankment causing server scour of approach embankment.	Structure or approach weakened; danger of immediate collapse.	Close to traffic.
0			Closed to traffic; washed out by flood action.

Figure E.1 Waterway & Channel Protection Condition Rating Scale

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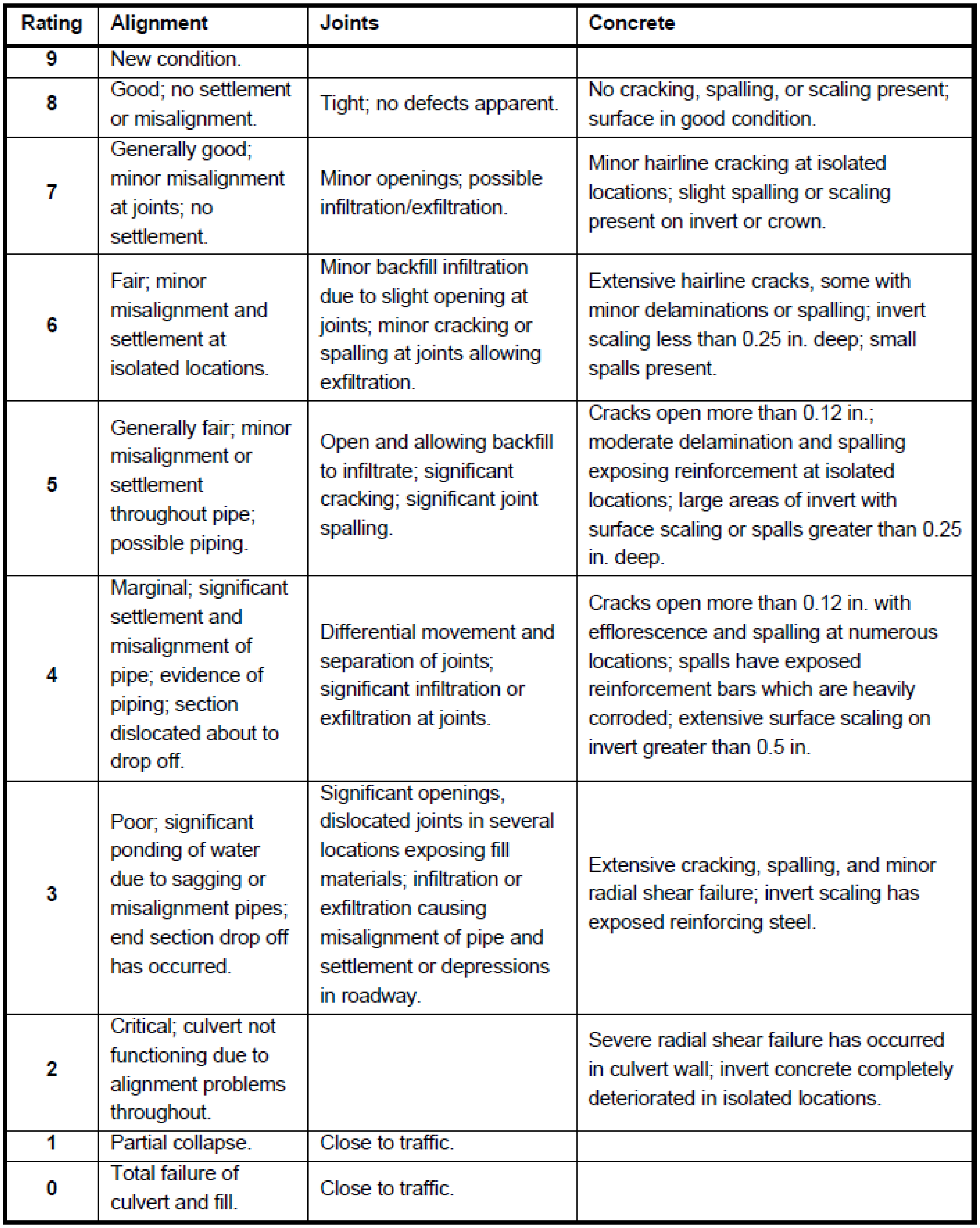
[10] The figures in Appendix E are from: McGrath and Beaver (2004)

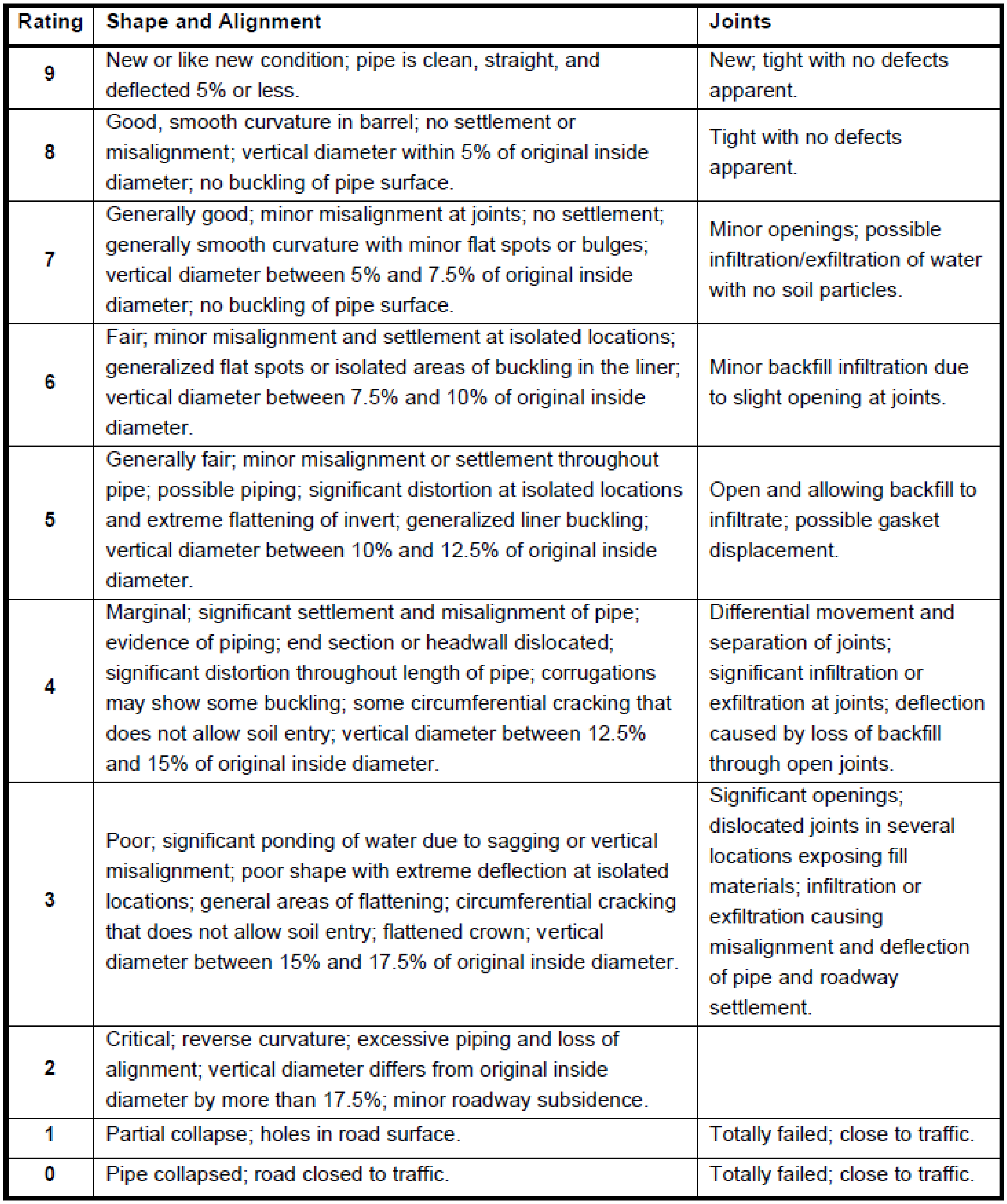
Rating	Shape	Seams and Joints	Metal
9	New.	Tight; no openings.	Near original condition.
8	Good; smooth curvature in barrel; horizontal diameter within 10% of design.	Tight; no openings.	Superficial rust; no pitting.
7	Generally good; top half of pipe smooth but minor flattening of bottom; horizontal diameter within 10% of design.	Minor cracking at a few bolt holes; minor joint or seam openings; potential for backfill infiltration.	Moderate rust; slight pitting.
6	Fair; top half has smooth curvature but bottom half has flattened significantly; horizontal diameter within 10% of design.	Minor cracking at bolts is prevalent in one seam in lower half of pipe; evidence of backfill infiltration through seams or joints.	Fairly heavy rust; moderate pitting; slight thinning.
5	Generally fair; significant distortion at isolated locations in top half and extreme flattening of invert; horizontal diameter 10% to 15% greater than design.	Moderate cracking at bolt holes along one seam near bottom of pipe; deflection of pipe caused by backfill.	Extensive heavy rust; deep pitting; moderate thinning.
4	Marginal significant distortion throughout length of pipe; lower third may be kinked; horizontal diameter 10% to 15% greater than design.	Moderate cracking at bolt holes on one seam near top of pipe; deflection caused by loss of backfill through open joints.	Pronounced thinning with some deflection; penetration when struck with pick hammer.
3	Poor shape; extreme deflection at isolated locations; flattening of crown, crown radius 20 to 30 ft; horizontal diameter in excess of 15% greater than design.	3-in long crack at bolt holes on one seam.	Extensive heavy rust; deep pitting; scattered perforations.
2	Critical; extreme distortion and deflection throughout pipe; flattening of crown, crown radius over 30 ft; horizontal diameter more than 20% greater than design.	Plate cracked from bolt to bolt on one seam.	Extensive perforation due to rust.
1	Partially collapsed; crown in reverse curve.	Failed; close to traffic.	Invert completely deteriorated.
0	Closed to traffic.	Totally failed.	Partial or complete collapse.

Figure E.2 Round/Vertical Elongated Corrugated Metal Pipe Barrels Condition Rating Scale



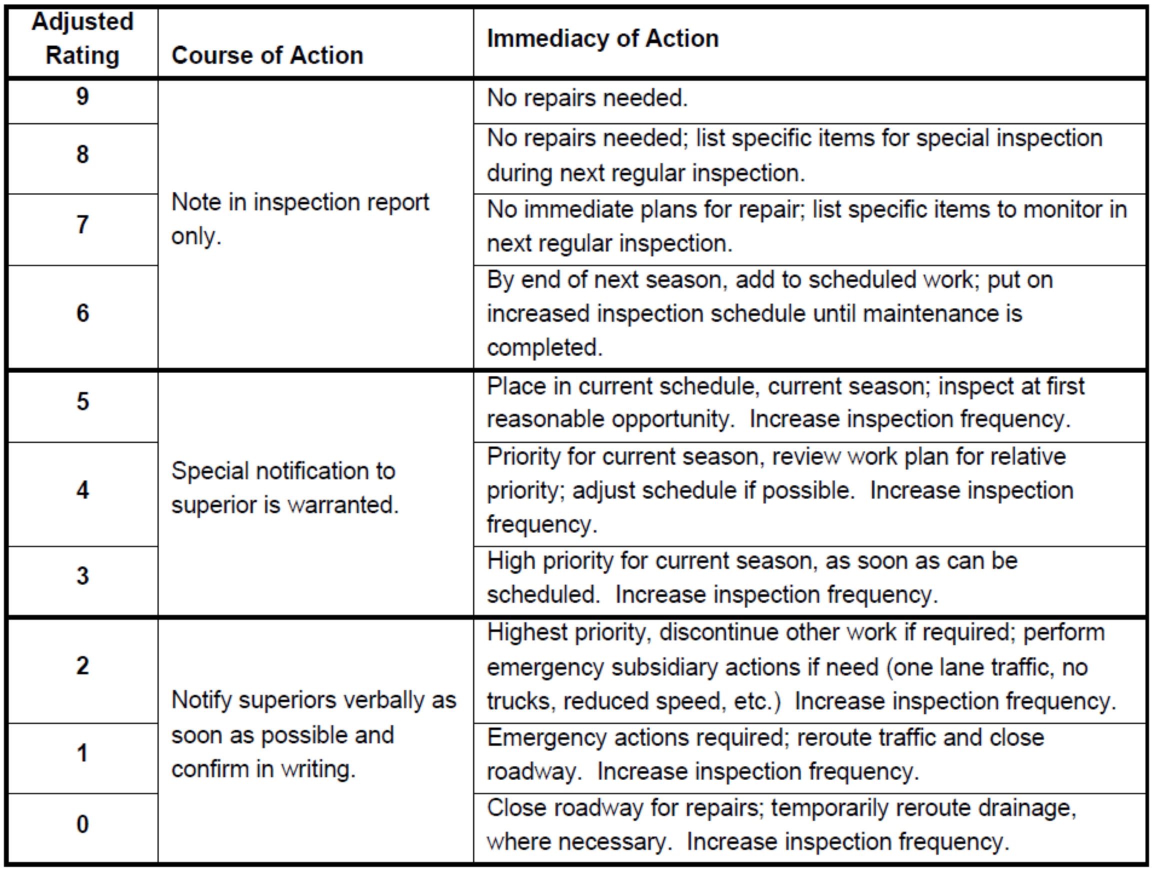
Rating	Alignment	Joints	Concrete
9	New condition.		
8	Good; no settlement or misalignment.	Tight; no defects apparent.	No cracking, spalling, or scaling present; surface in good condition.
7	Generally good; minor misalignment at joints; no settlement.	Minor openings; possible infiltration/exfiltration.	Minor hairline cracking at isolated locations; slight spalling or scaling present on invert or crown.
6	Fair; minor misalignment and settlement at isolated locations.	Minor backfill infiltration due to slight opening at joints; minor cracking or spalling at joints allowing exfiltration.	Extensive hairline cracks, some with minor delaminations or spalling; invert scaling less than 0.25 in. deep; small spalls present.
5	Generally fair; minor misalignment or settlement throughout pipe; possible piping.	Open and allowing backfill to infiltrate; significant cracking; significant joint spalling.	Cracks open more than 0.12 in.; moderate delamination and spalling exposing reinforcement at isolated locations; large areas of invert with surface scaling or spalls greater than 0.25 in. deep.
4	Marginal; significant settlement and misalignment of pipe; evidence of piping; section dislocated about to drop off.	Differential movement and separation of joints; significant infiltration or exfiltration at joints.	Cracks open more than 0.12 in. with efflorescence and spalling at numerous locations; spalls have exposed reinforcement bars which are heavily corroded; extensive surface scaling on invert greater than 0.5 in.
3	Poor; significant ponding of water due to sagging or misalignment pipes; end section drop off has occurred.	Significant openings, dislocated joints in several locations exposing fill materials; infiltration or exfiltration causing misalignment of pipe and settlement or depressions in roadway.	Extensive cracking, spalling, and minor radial shear failure; invert scaling has exposed reinforcing steel.
2	Critical; culvert not functioning due to alignment problems throughout.		Severe radial shear failure has occurred in culvert wall; invert concrete completely deteriorated in isolated locations.
1	Partial collapse.	Close to traffic.	
0	Total failure of culvert and fill.	Close to traffic.	

Figure E.3 Concrete Pipe Barrel Condition Rating Scale



Rating	Shape and Alignment	Joints
9	New or like new condition; pipe is clean, straight, and deflected 5% or less.	New; tight with no defects apparent.
8	Good, smooth curvature in barrel; no settlement or misalignment; vertical diameter within 5% of original inside diameter; no buckling of pipe surface.	Tight with no defects apparent.
7	Generally good; minor misalignment at joints; no settlement; generally smooth curvature with minor flat spots or bulges; vertical diameter between 5% and 7.5% of original inside diameter; no buckling of pipe surface.	Minor openings; possible infiltration/exfiltration of water with no soil particles.
6	Fair; minor misalignment and settlement at isolated locations; generalized flat spots or isolated areas of buckling in the liner; vertical diameter between 7.5% and 10% of original inside diameter.	Minor backfill infiltration due to slight opening at joints.
5	Generally fair; minor misalignment or settlement throughout pipe; possible piping; significant distortion at isolated locations and extreme flattening of invert; generalized liner buckling; vertical diameter between 10% and 12.5% of original inside diameter.	Open and allowing backfill to infiltrate; possible gasket displacement.
4	Marginal; significant settlement and misalignment of pipe; evidence of piping; end section or headwall dislocated; significant distortion throughout length of pipe; corrugations may show some buckling; some circumferential cracking that does not allow soil entry; vertical diameter between 12.5% and 15% of original inside diameter.	Differential movement and separation of joints; significant infiltration or exfiltration at joints; deflection caused by loss of backfill through open joints.
3	Poor; significant ponding of water due to sagging or vertical misalignment; poor shape with extreme deflection at isolated locations; general areas of flattening; circumferential cracking that does not allow soil entry; flattened crown; vertical diameter between 15% and 17.5% of original inside diameter.	Significant openings; dislocated joints in several locations exposing fill materials; infiltration or exfiltration causing misalignment and deflection of pipe and roadway settlement.
2	Critical; reverse curvature; excessive piping and loss of alignment; vertical diameter differs from original inside diameter by more than 17.5%; minor roadway subsidence.	
1	Partial collapse; holes in road surface.	Totally failed; close to traffic.
0	Pipe collapsed; road closed to traffic.	Totally failed; close to traffic.

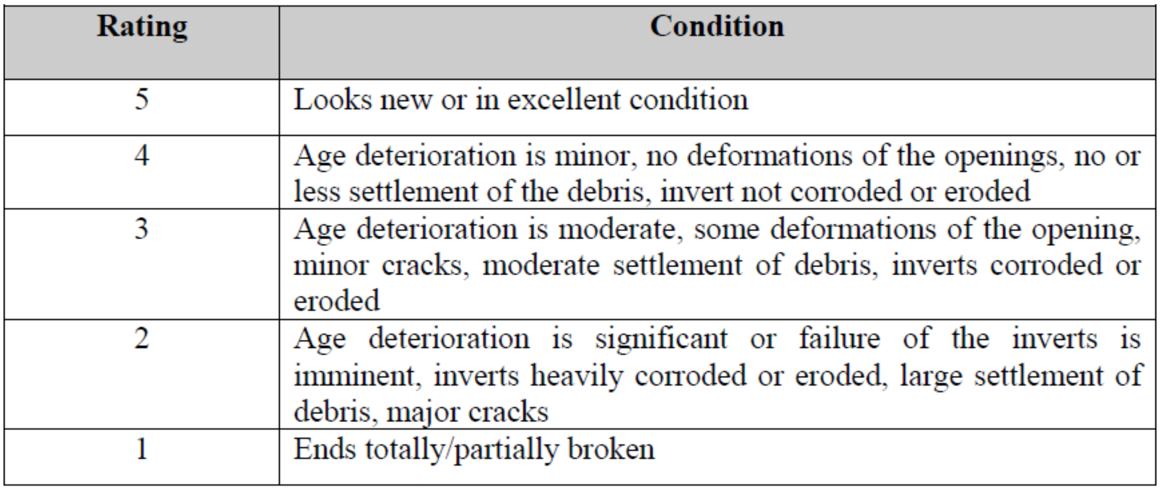
Figure E.4 Plastic Pipe Barrel Condition Rating Scale



Adjusted Rating	Course of Action	Immediacy of Action
9	Note in inspection report only.	No repairs needed.
8		No repairs needed; list specific items for special inspection during next regular inspection.
7		No immediate plans for repair; list specific items to monitor in next regular inspection.
6		By end of next season, add to scheduled work; put on increased inspection schedule until maintenance is completed.
5	Special notification to superior is warranted.	Place in current schedule, current season; inspect at first reasonable opportunity. Increase inspection frequency.
4		Priority for current season, review work plan for relative priority; adjust schedule if possible. Increase inspection frequency.
3		High priority for current season, as soon as can be scheduled. Increase inspection frequency.
2	Notify superiors verbally as soon as possible and confirm in writing.	Highest priority, discontinue other work if required; perform emergency subsidiary actions if need (one lane traffic, no trucks, reduced speed, etc.) Increase inspection frequency.
1		Emergency actions required; reroute traffic and close roadway. Increase inspection frequency.
0		Close roadway for repairs; temporarily reroute drainage, where necessary. Increase inspection frequency.

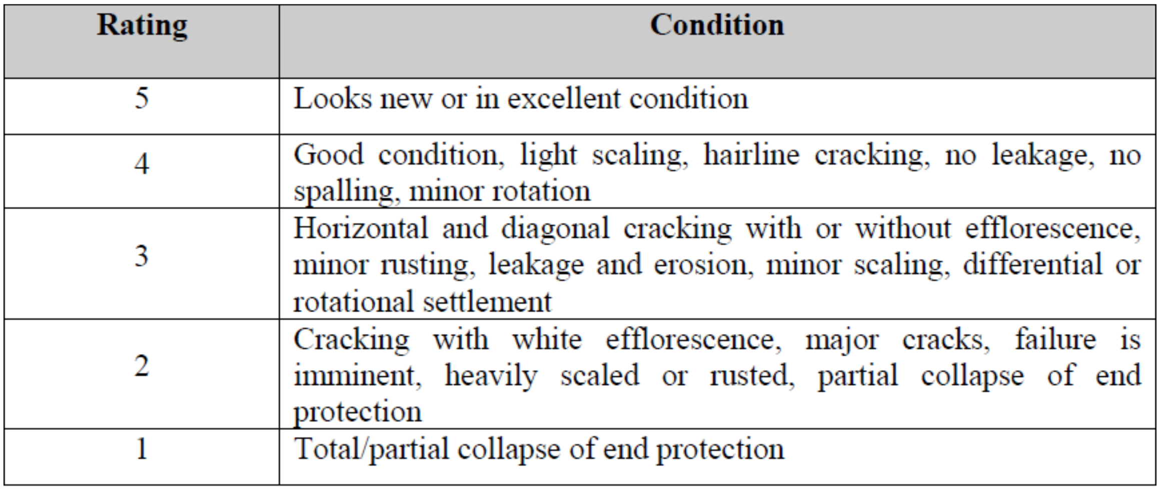
Figure E.5 Culvert Maintenance Ratings

APPENDIX F: MRUTC BASIC CONDITION ASSESSMENT RATING ITEMS AND SCALES[11]



Rating	Condition
5	Looks new or in excellent condition
4	Age deterioration is minor, no deformations of the openings, no or less settlement of the debris, invert not corroded or eroded
3	Age deterioration is moderate, some deformations of the opening, minor cracks, moderate settlement of debris, inverts corroded or eroded
2	Age deterioration is significant or failure of the inverts is imminent, inverts heavily corroded or eroded, large settlement of debris, major cracks
1	Ends totally/partially broken

Figure F.1 Culvert Invert Condition Rating Scale



Rating	Condition
5	Looks new or in excellent condition
4	Good condition, light scaling, hairline cracking, no leakage, no spalling, minor rotation
3	Horizontal and diagonal cracking with or without efflorescence, minor rusting, leakage and erosion, minor scaling, differential or rotational settlement
2	Cracking with white efflorescence, major cracks, failure is imminent, heavily scaled or rusted, partial collapse of end protection
1	Total/partial collapse of end protection

Figure F.2 Culvert End Protection (Headwall/Wingwall) Condition Rating Scale

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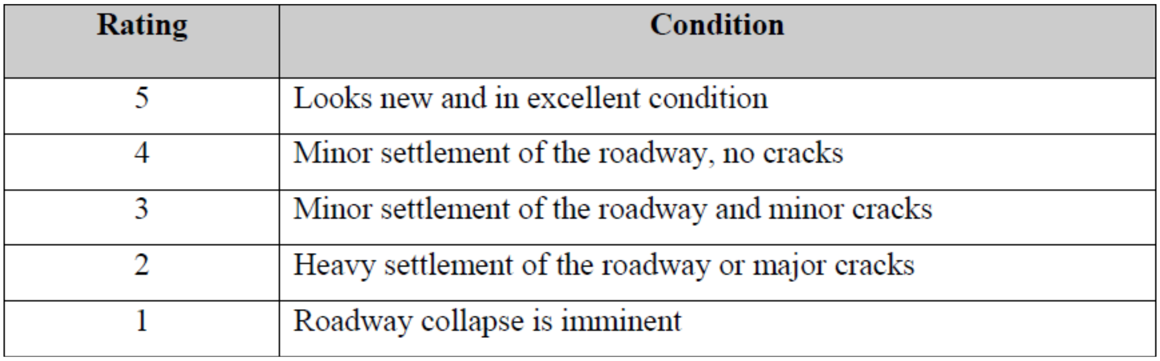
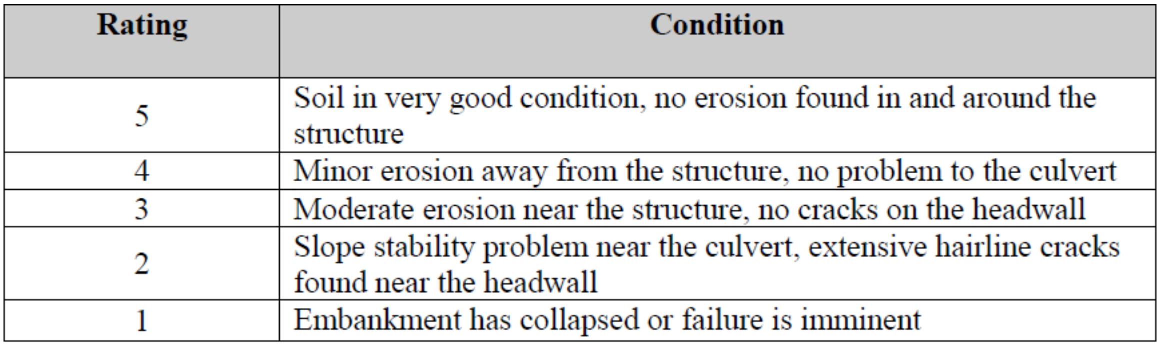
[11] The figures in Appendix F are from: Najafi et al. (2008)



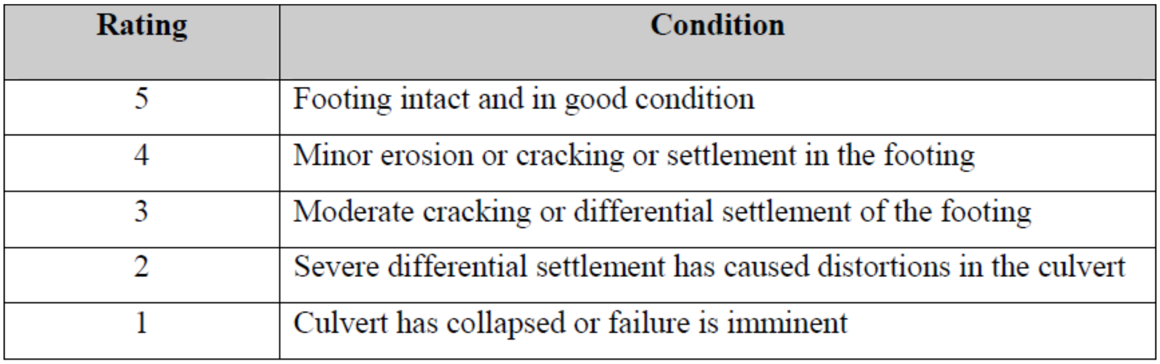
Rating	Condition
5	Looks new and in excellent condition
4	Minor settlement of the roadway, no cracks
3	Minor settlement of the roadway and minor cracks
2	Heavy settlement of the roadway or major cracks
1	Roadway collapse is imminent

Figure F.3 Culvert Roadway Condition Rating Scale



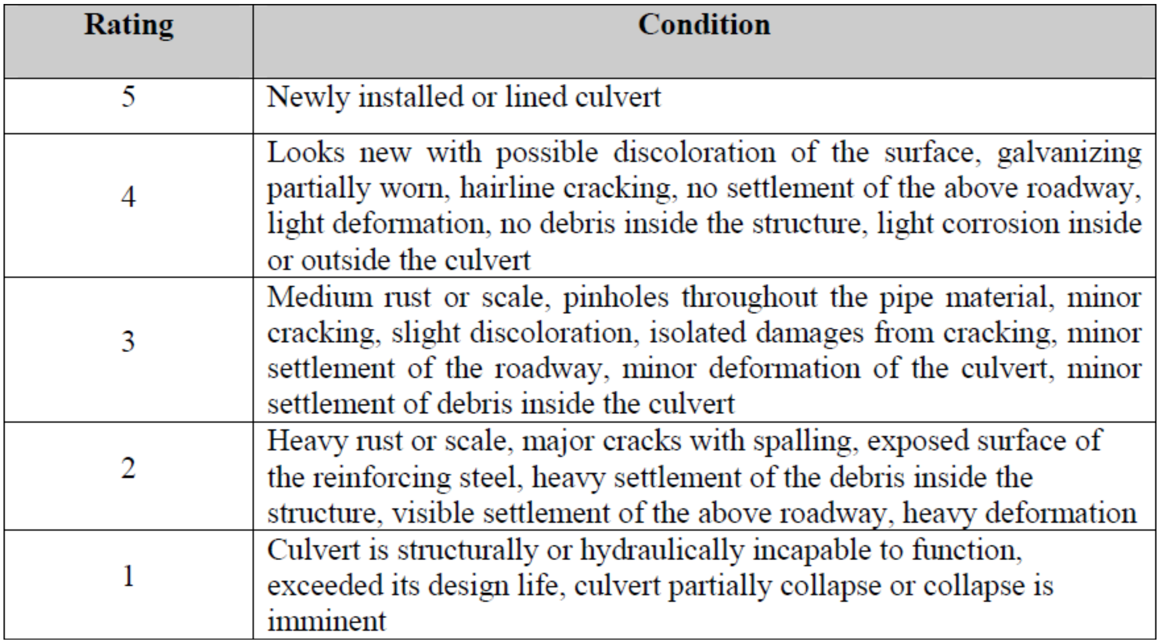
Rating	Condition
5	Soil in very good condition, no erosion found in and around the structure
4	Minor erosion away from the structure, no problem to the culvert
3	Moderate erosion near the structure, no cracks on the headwall
2	Slope stability problem near the culvert, extensive hairline cracks found near the headwall
1	Embankment has collapsed or failure is imminent

Figure F.4 Culvert Embankment Condition Rating Scale



Rating	Condition
5	Footing intact and in good condition
4	Minor erosion or cracking or settlement in the footing
3	Moderate cracking or differential settlement of the footing
2	Severe differential settlement has caused distortions in the culvert
1	Culvert has collapsed or failure is imminent

Figure F.5 Culvert Footing Condition Rating Scale



Rating	Condition
5	Newly installed or lined culvert
4	Looks new with possible discoloration of the surface, galvanizing partially worn, hairline cracking, no settlement of the above roadway, light deformation, no debris inside the structure, light corrosion inside or outside the culvert
3	Medium rust or scale, pinholes throughout the pipe material, minor cracking, slight discoloration, isolated damages from cracking, minor settlement of the roadway, minor deformation of the culvert, minor settlement of debris inside the culvert
2	Heavy rust or scale, major cracks with spalling, exposed surface of the reinforcing steel, heavy settlement of the debris inside the structure, visible settlement of the above roadway, heavy deformation
1	Culvert is structurally or hydraulically incapable to function, exceeded its design life, culvert partially collapse or collapse is imminent

Figure F.6 Culvert Overall Condition Rating Scale

APPENDIX G: PRECIPITATION EXPOSURE ANALYSIS MAP RESULTS

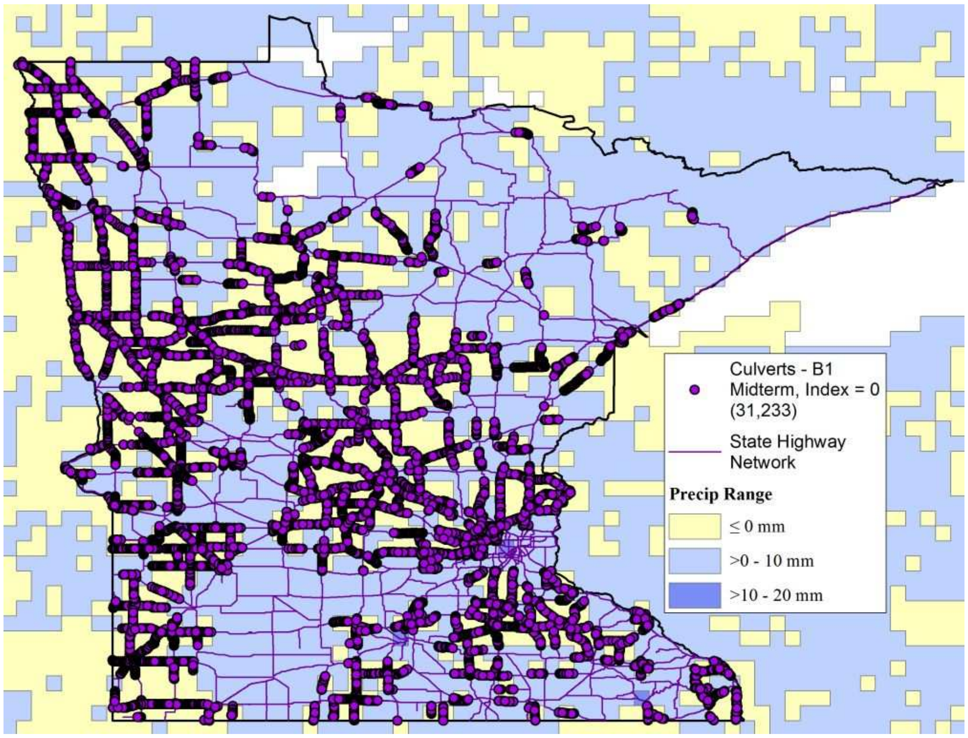


Figure G.1 Minnesota Precipitation Exposure Index = 0 (B1, Mid-Century)

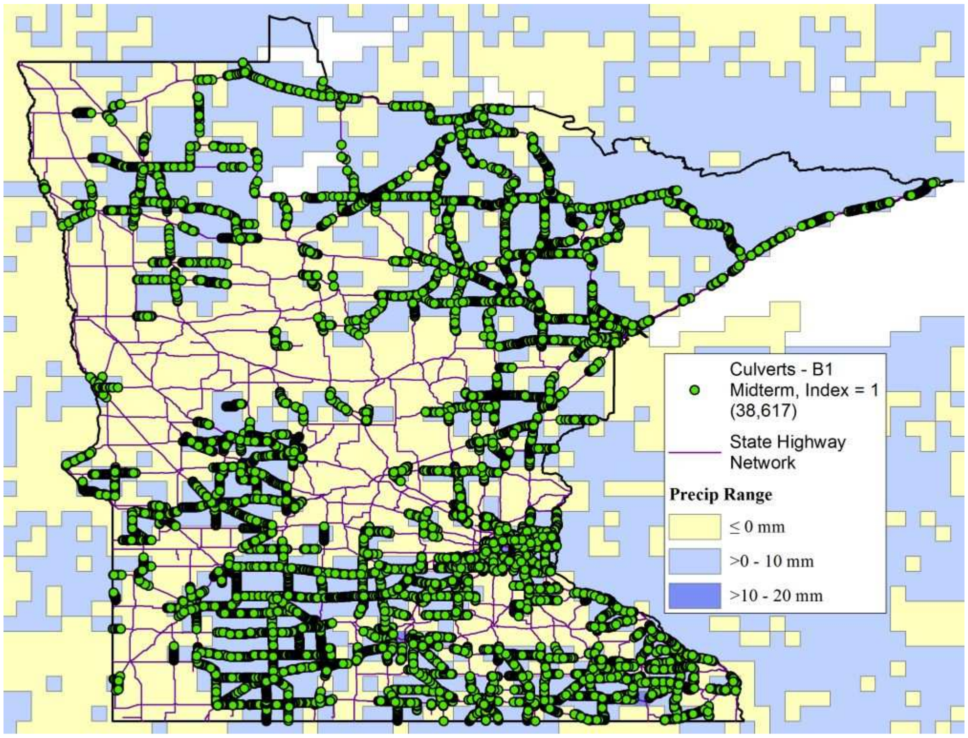


Figure G.2 Minnesota Precipitation Exposure Index = 1 (B1, Mid-Century)

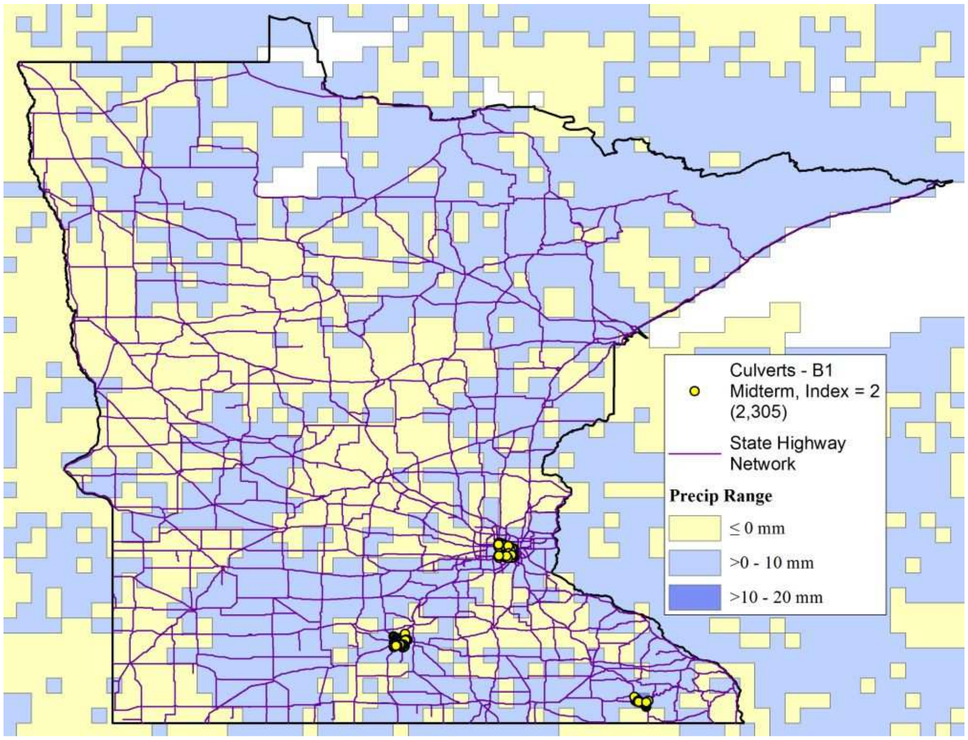


Figure G.3 Minnesota Precipitation Exposure Index = 2 (B1, Mid-Century)

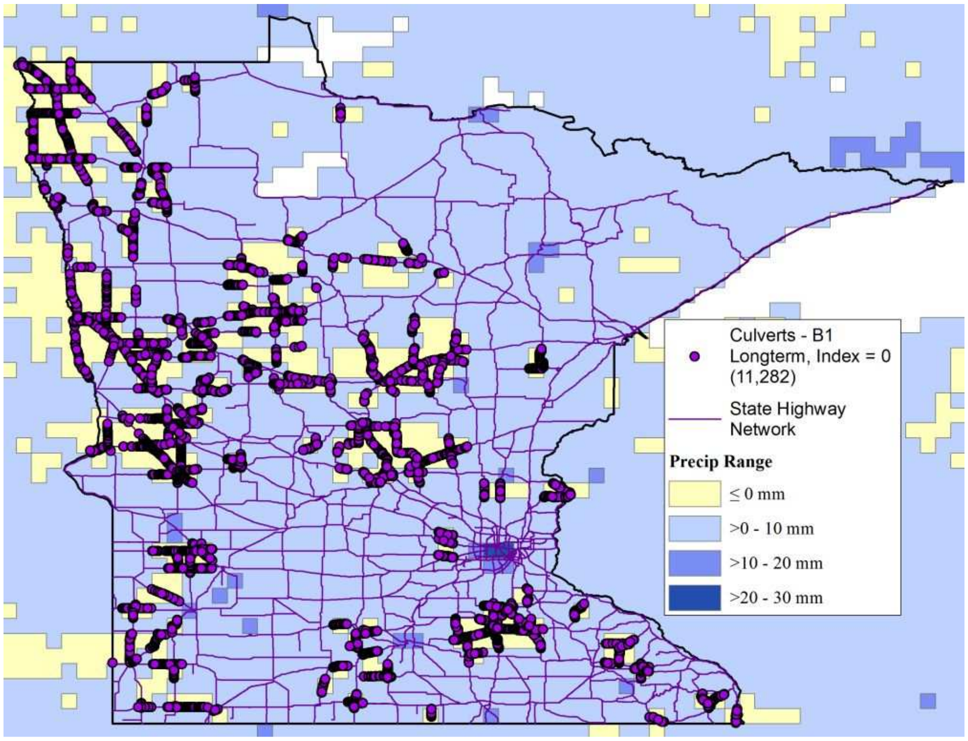


Figure G.4 Minnesota Precipitation Exposure Index = 0 (B1, End-Of-Century)

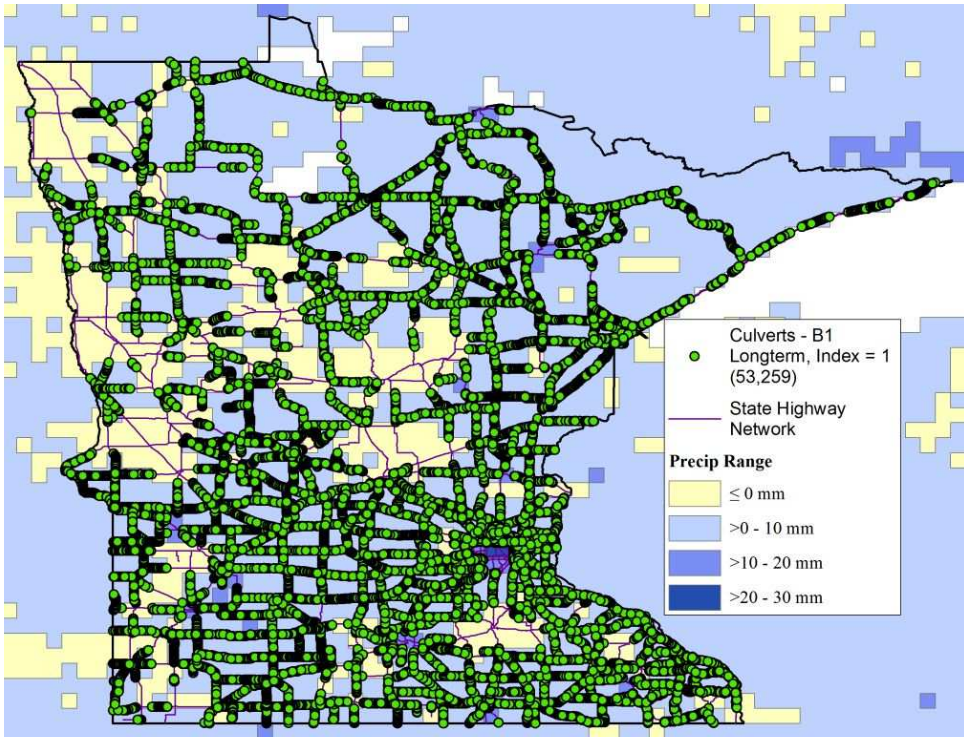


Figure G.5 Minnesota Precipitation Exposure Index = 1 (B1, End-Of-Century)

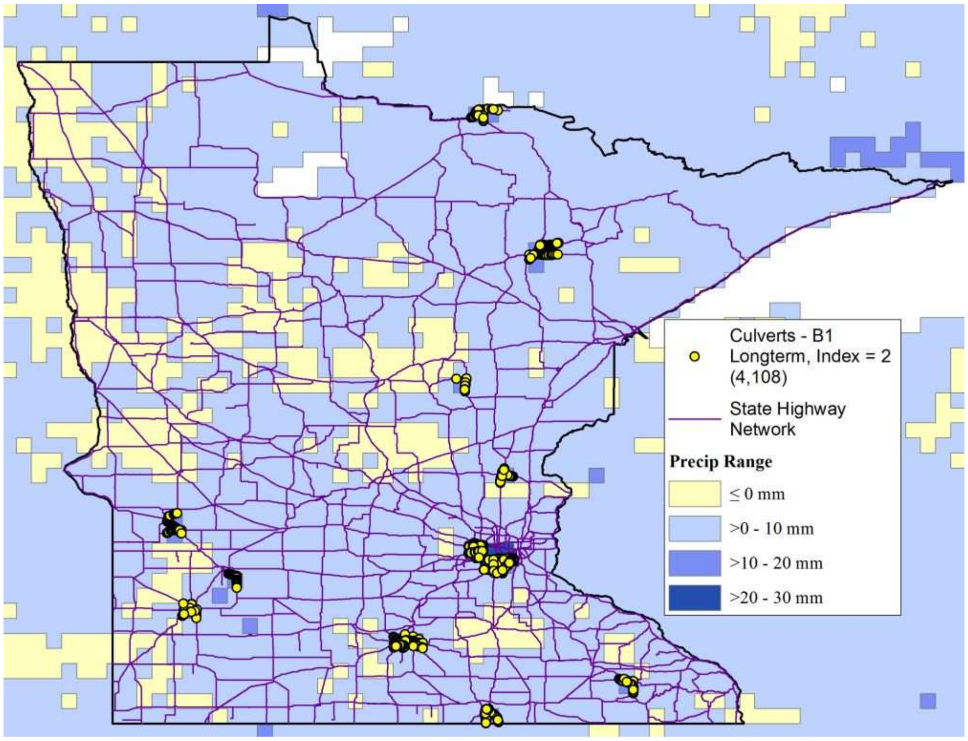


Figure G.6 Minnesota Precipitation Exposure Index = 2 (B1, End-Of-Century)

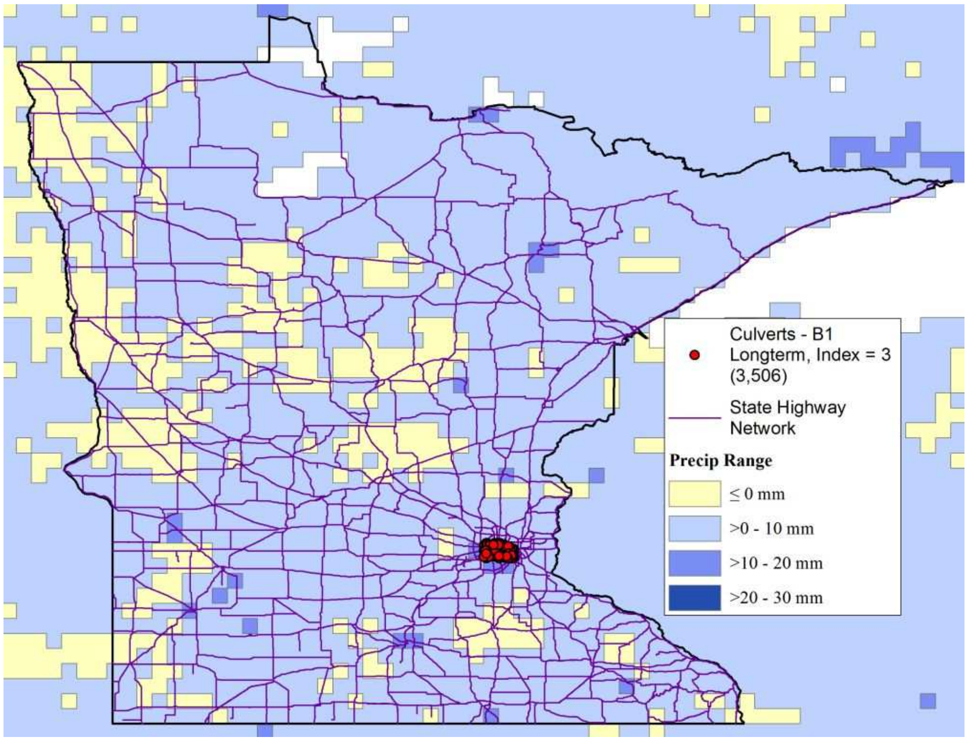


Figure G.7 Minnesota Precipitation Exposure Index = 3 (B1, End-Of-Century)

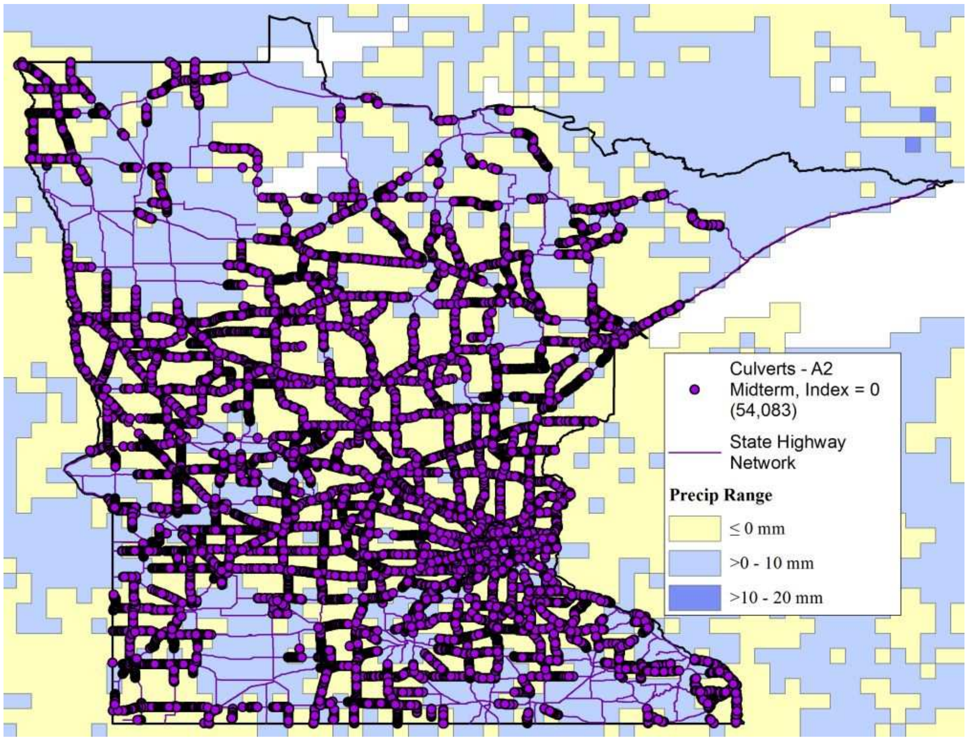


Figure G.8 Minnesota Precipitation Exposure Index = 0 (A2, Mid-Century)

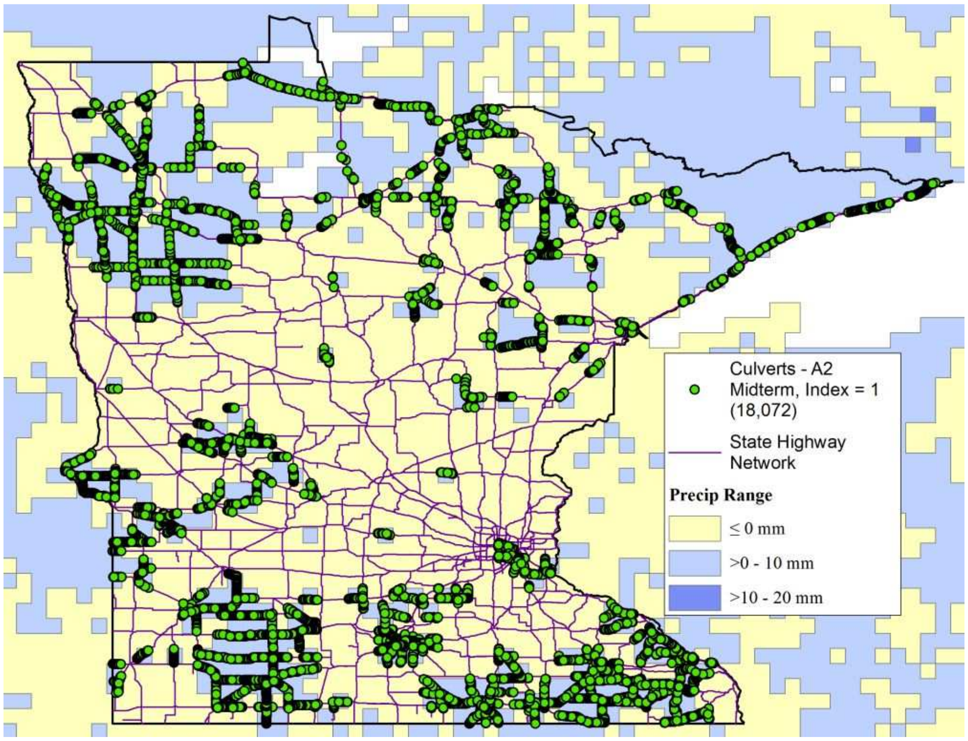


Figure G.9 Minnesota Precipitation Exposure Index = 1 (A2, Mid-Century)

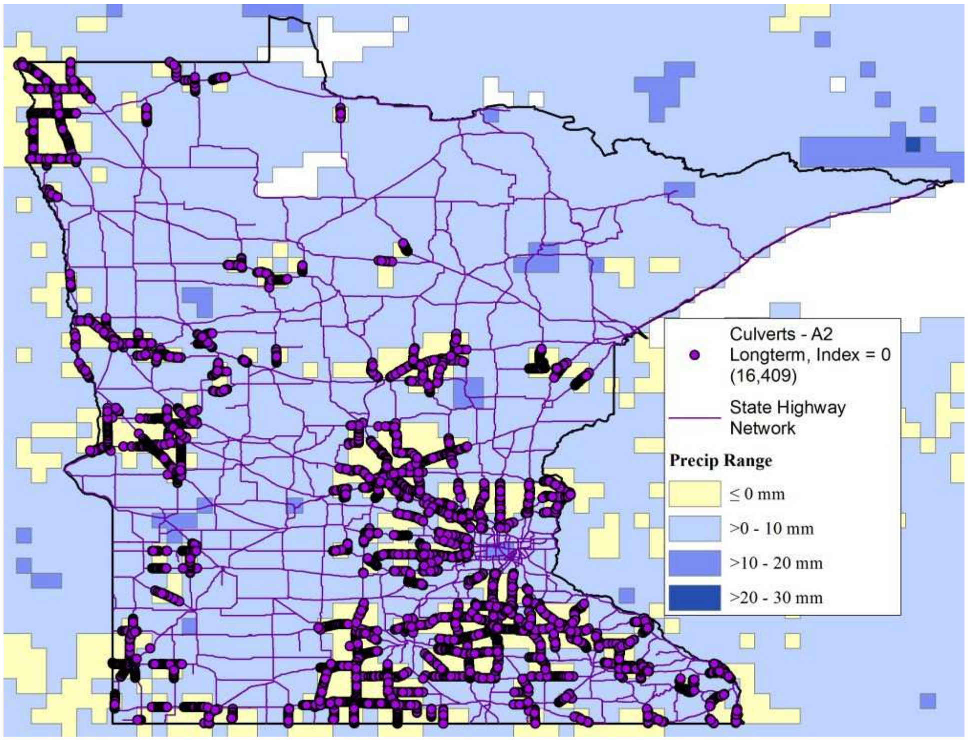


Figure G.10 Minnesota Precipitation Exposure Index = 0 (A2, End-of-Century)

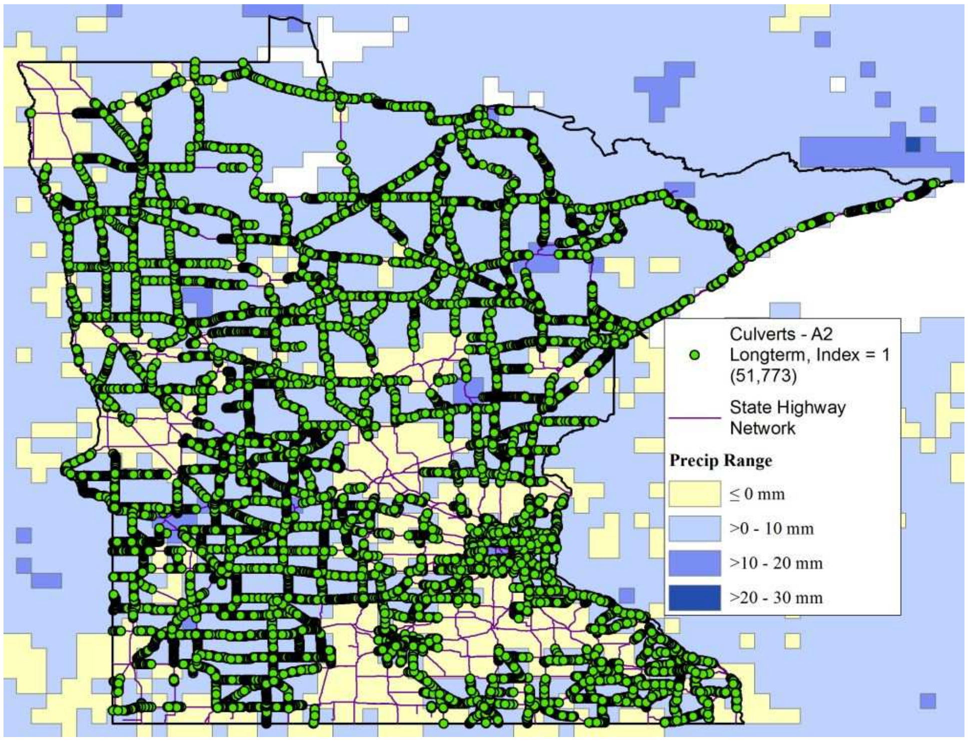


Figure G.11 Minnesota Precipitation Exposure Index = 1 (A2, End-of-Century)

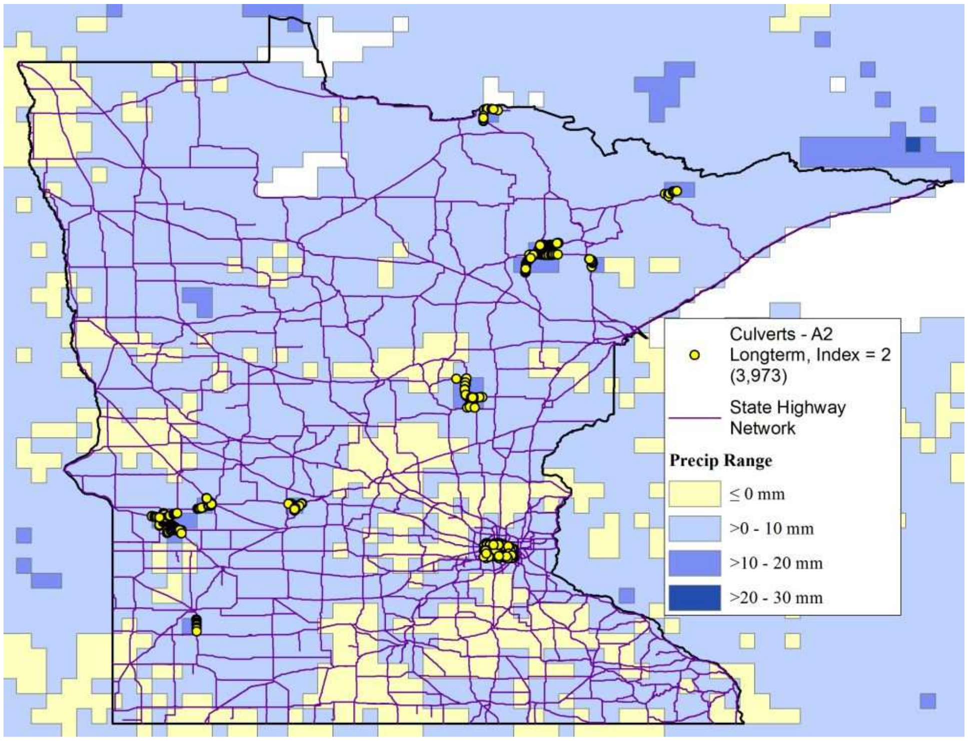


Figure G.12 Minnesota Precipitation Exposure Index = 2 (A2, End-of-Century)

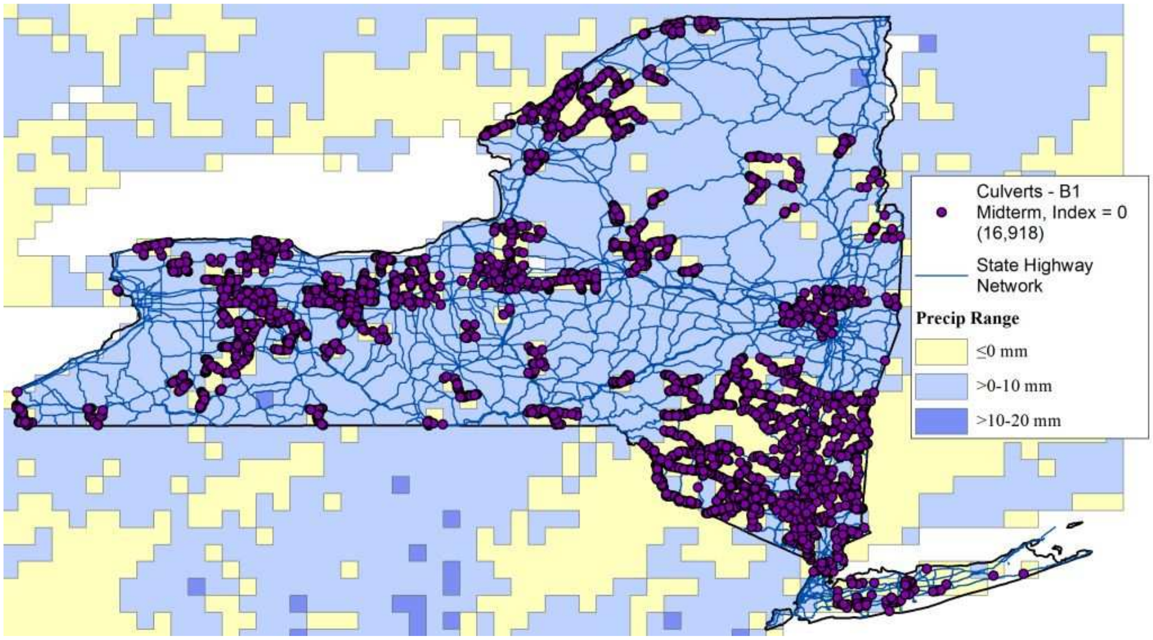


Figure G.13 New York Precipitation Exposure Index = 0 (B1, Mid-Century)

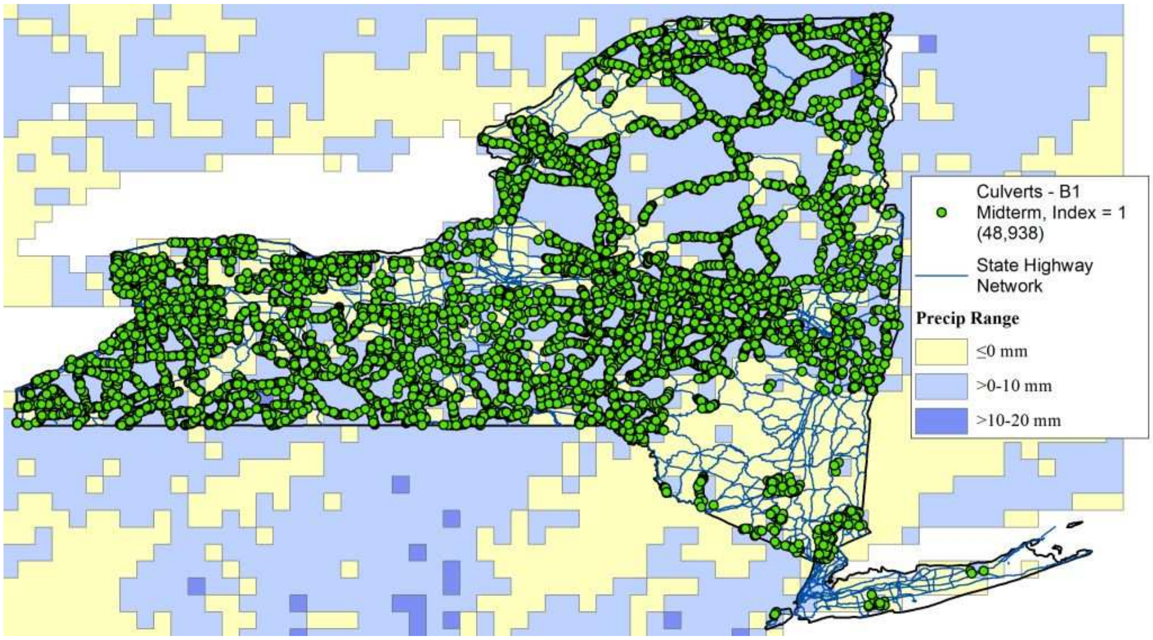


Figure G.14 New York Precipitation Exposure Index = 1 (B1, Mid-Century)

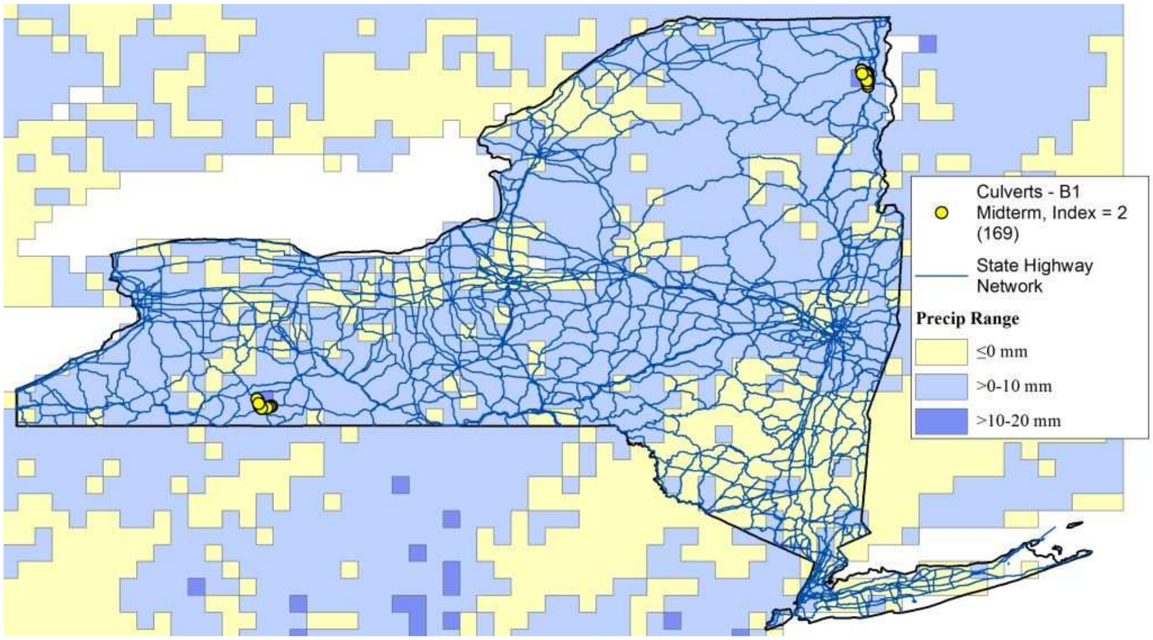


Figure G.15 New York Precipitation Exposure Index = 2 (B1, Mid-Century)

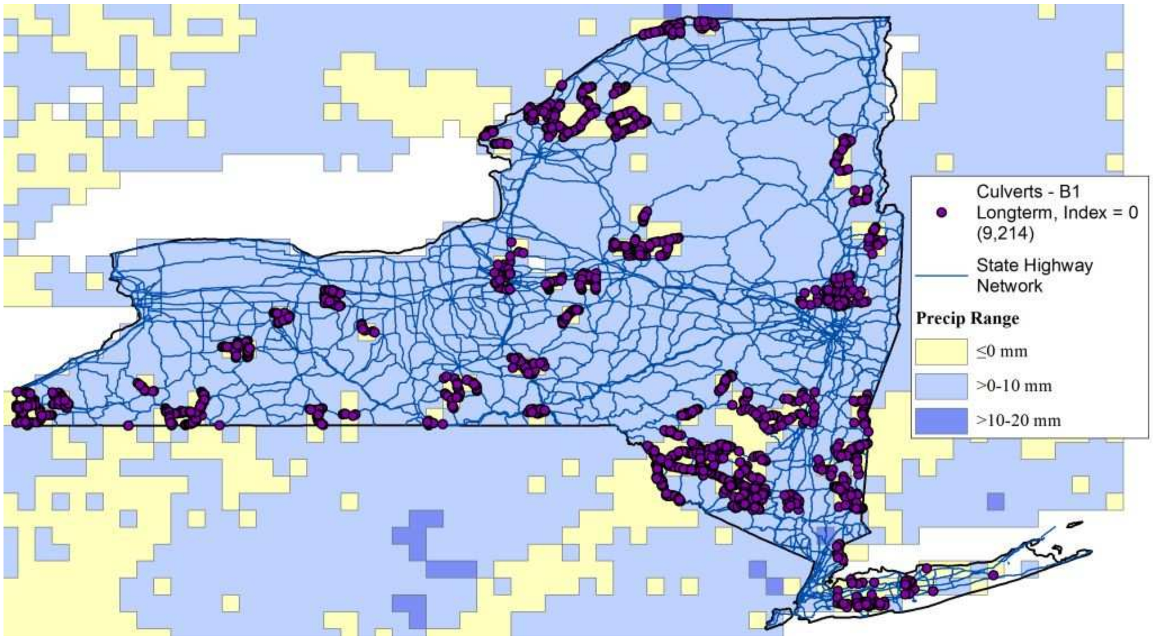


Figure G.16 New York Precipitation Exposure Index = 0 (B1, End-Of-Century)

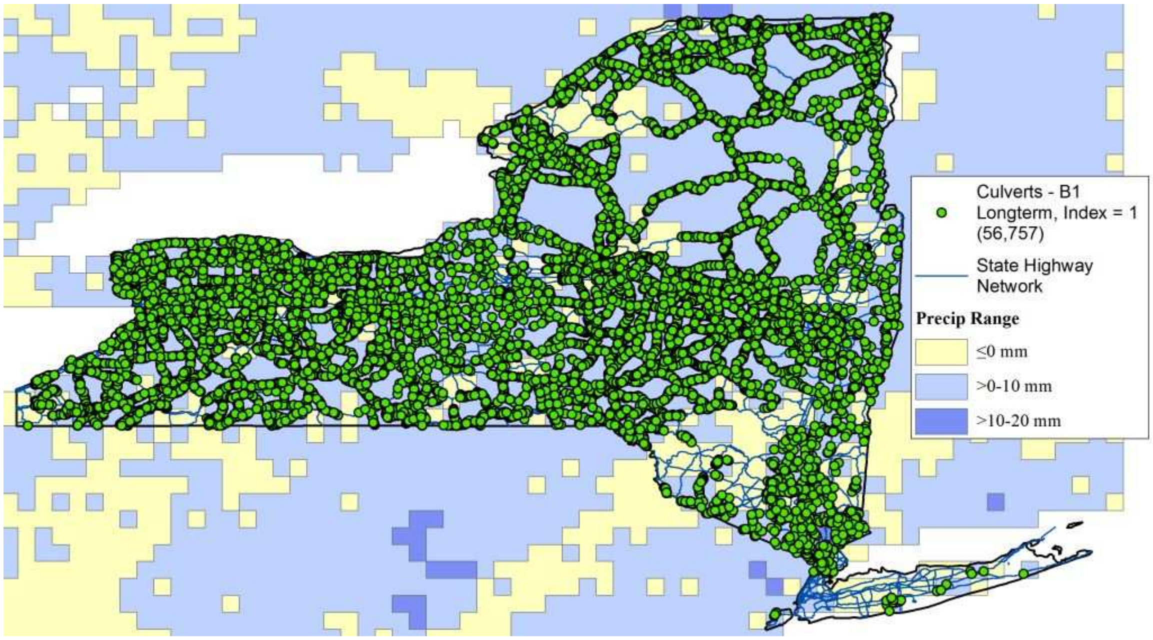


Figure G.17 New York Precipitation Exposure Index = 1 (B1, End-Of-Century)

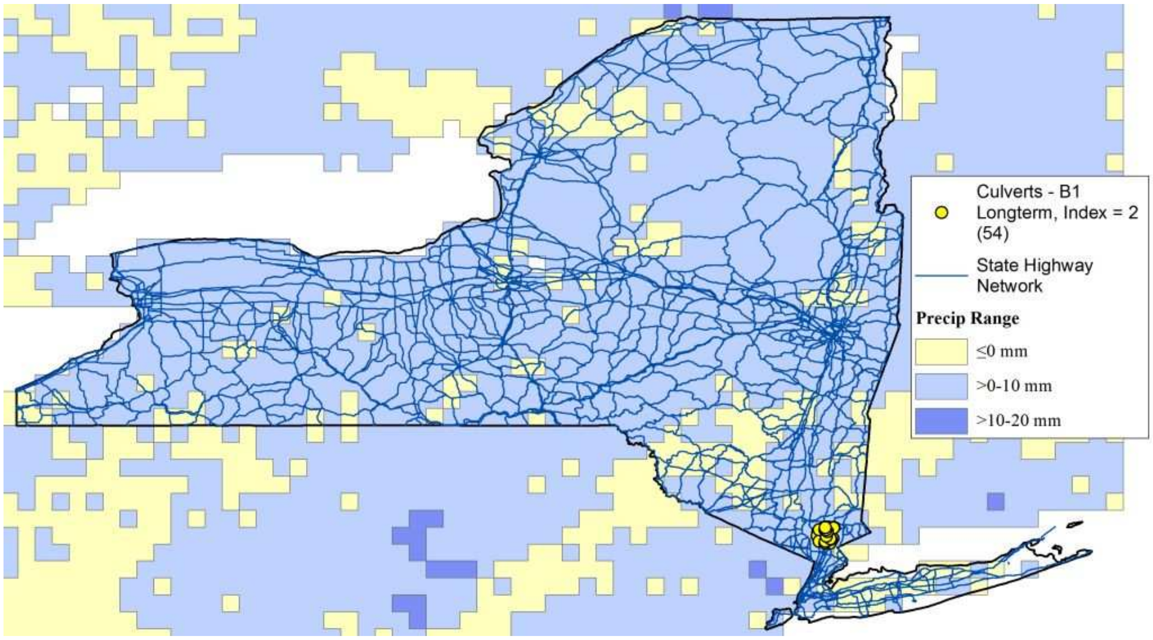


Figure G.18 New York Precipitation Exposure Index = 2 (B1, End-Of-Century)

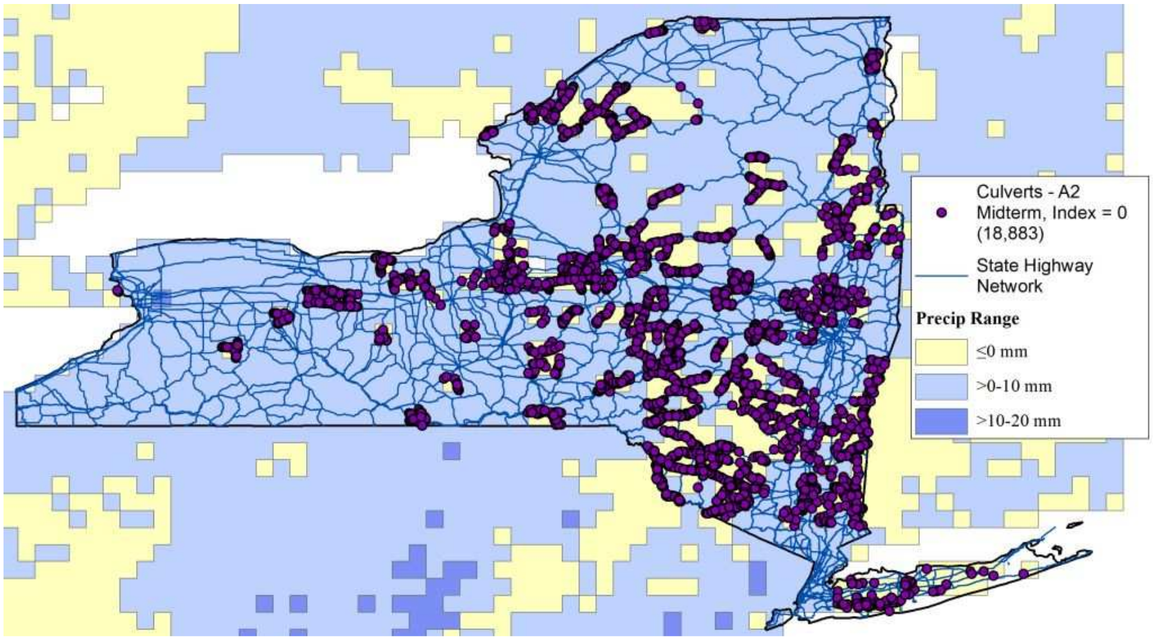


Figure G.19 New York Precipitation Exposure Index = 0 (A2, Mid-Century)

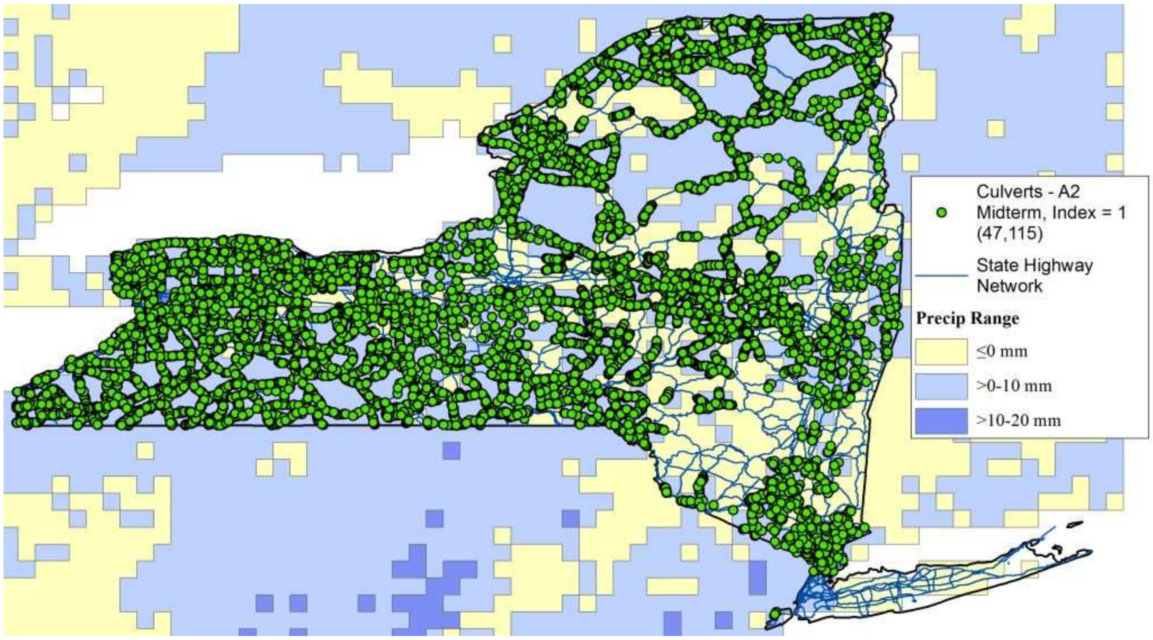


Figure G.20 New York Precipitation Exposure Index = 1 (A2, Mid-Century)

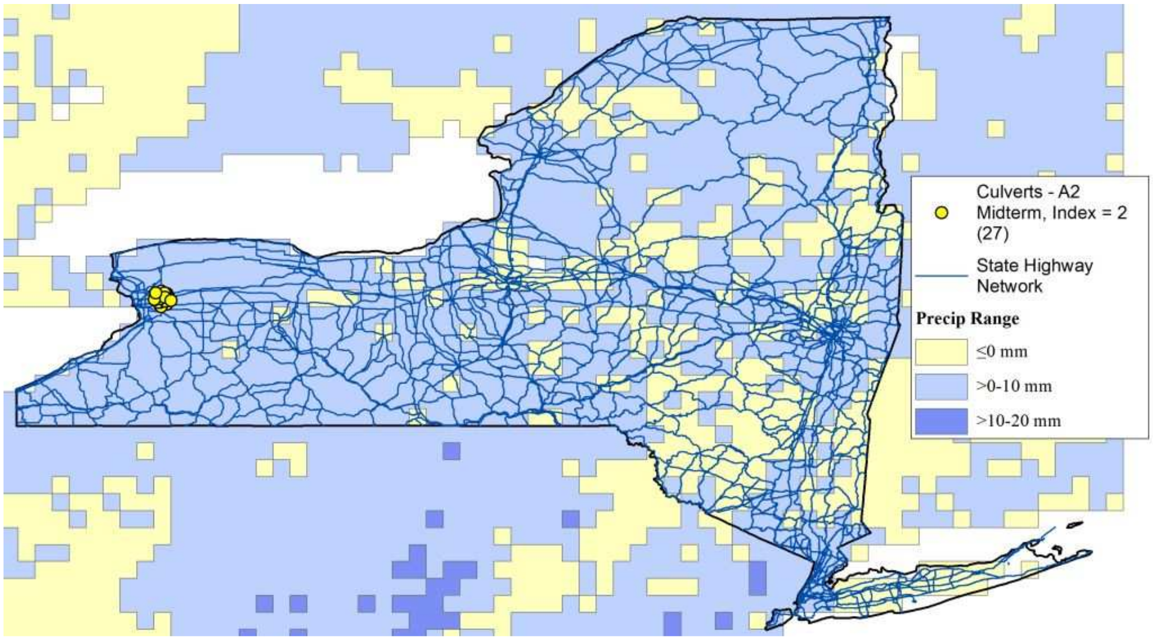


Figure G.21 New York Precipitation Exposure Index = 2 (A2, Mid-Century)

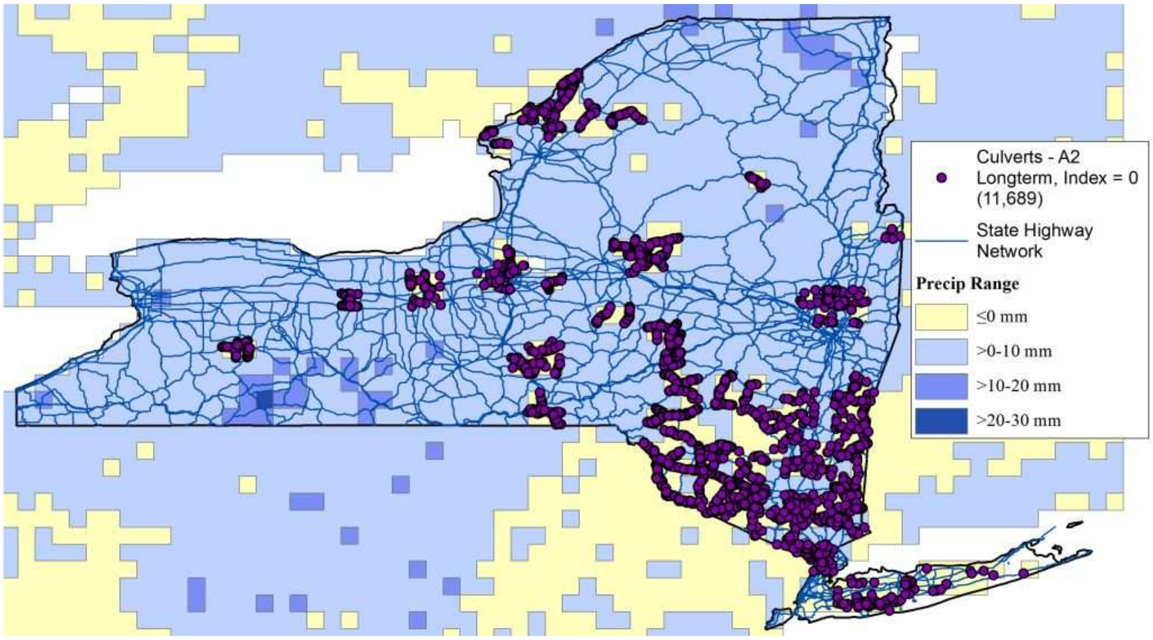


Figure G.22 New York Precipitation Exposure Index = 0 (A2, End-Of-Century)

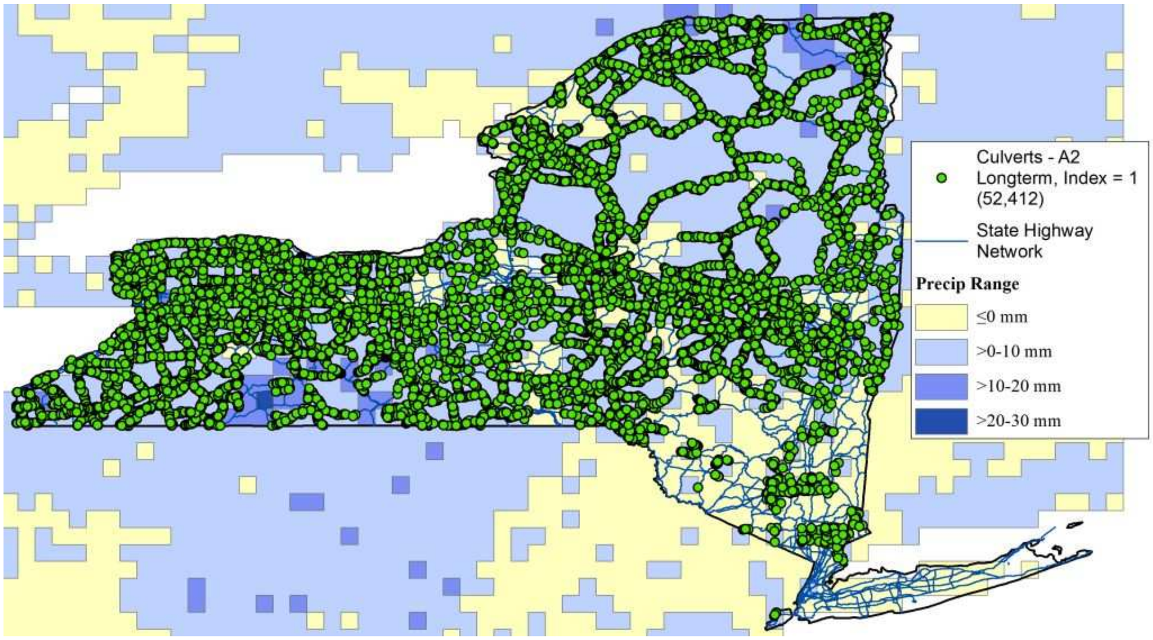


Figure G.23 New York Precipitation Exposure Index = 1 (A2, End-Of-Century)

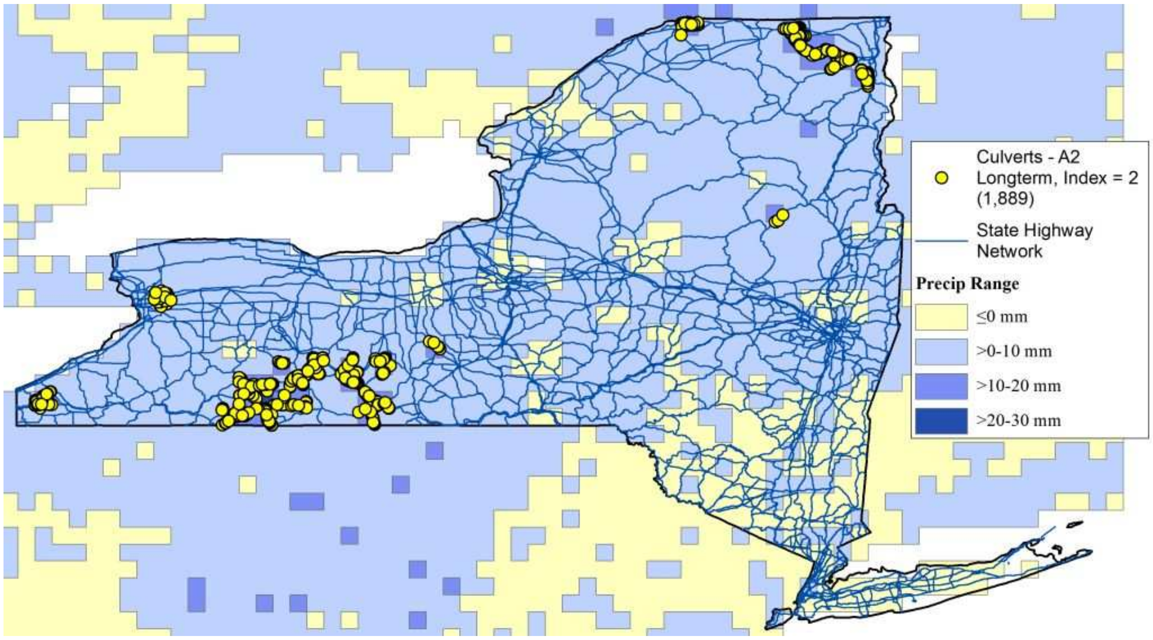


Figure G.24 New York Precipitation Exposure Index = 2 (A2, End-Of-Century)

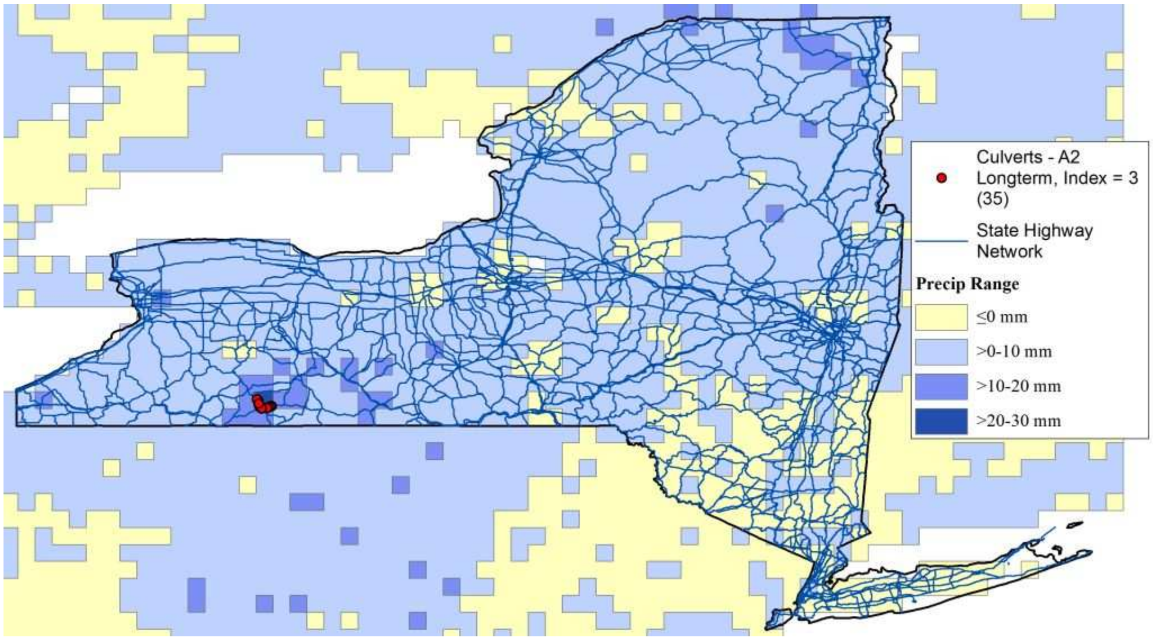


Figure G.25 New York Precipitation Exposure Index = 3 (A2, End-Of-Century)

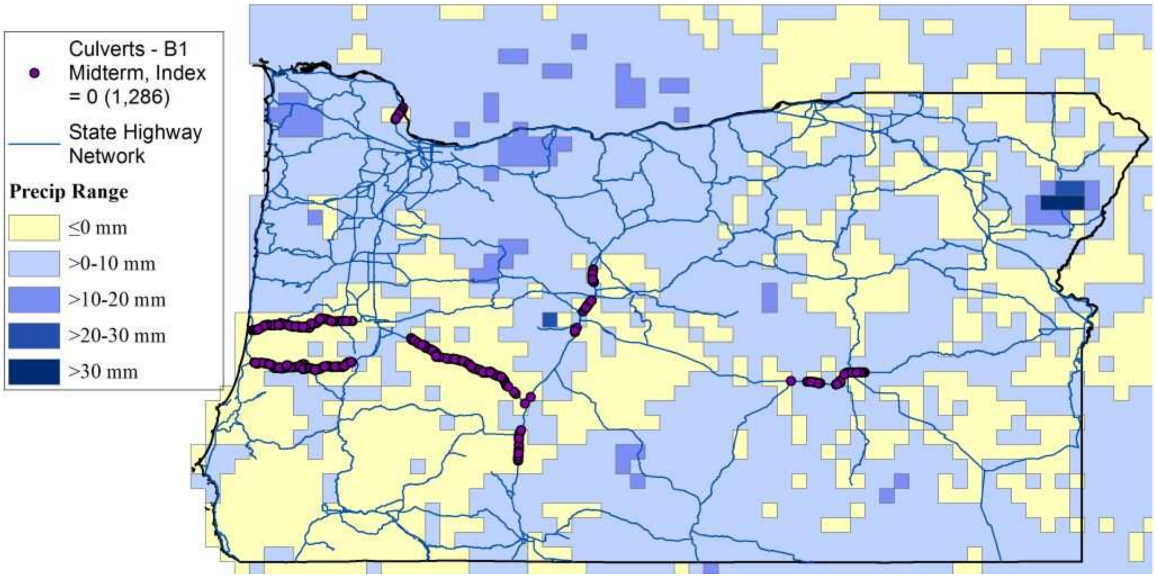


Figure G.26 Oregon Precipitation Exposure Index = 0 (B1, Mid-Century)

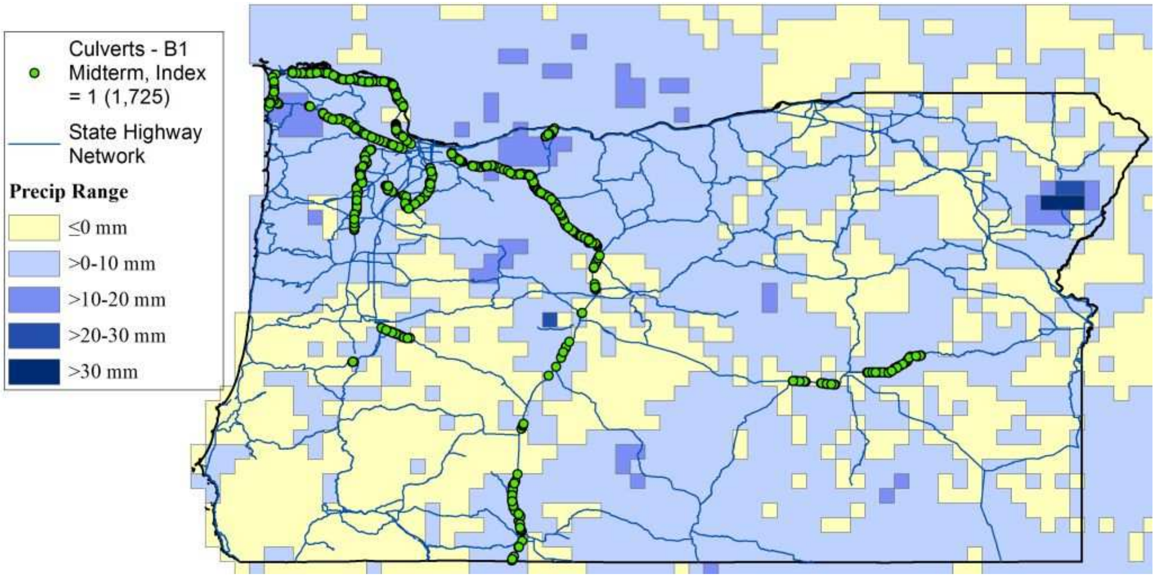


Figure G.27 Oregon Precipitation Exposure Index = 1 (B1, Mid-Century)

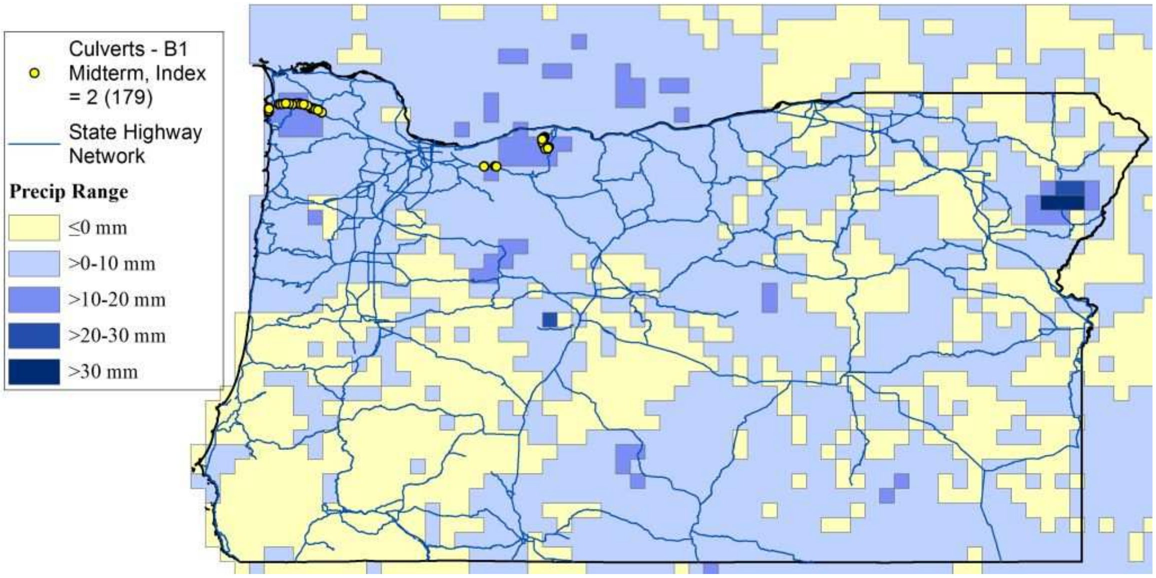


Figure G.28 Oregon Precipitation Exposure Index = 2 (B1, Mid-Century)

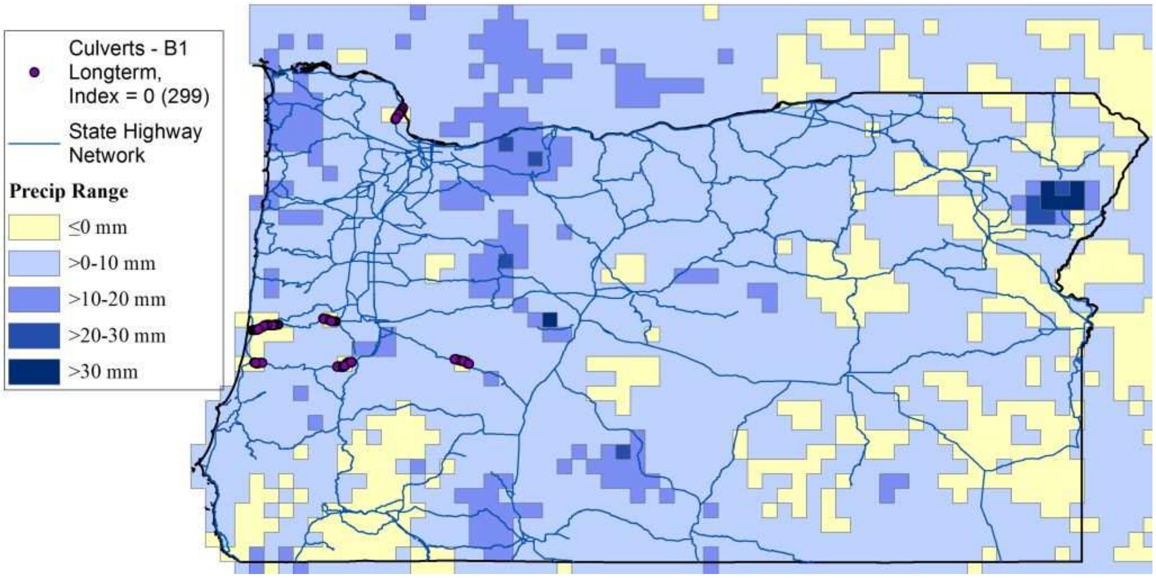


Figure G.29 Oregon Precipitation Exposure Index = 0 (B1, End-Of-Century)

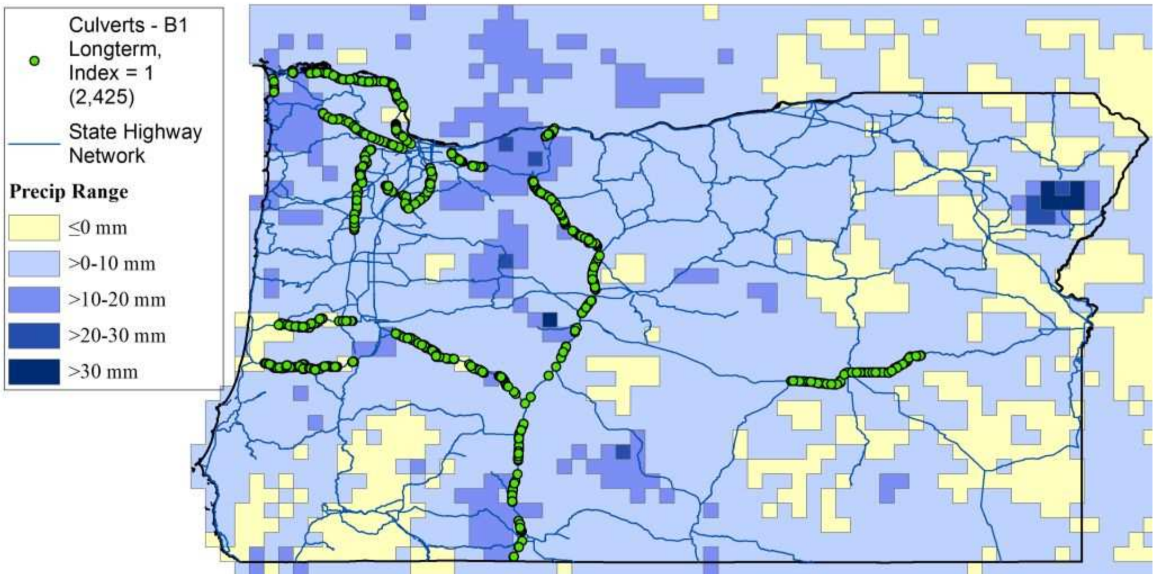


Figure G.30 Oregon Precipitation Exposure Index = 1 (B1, End-Of-Century)

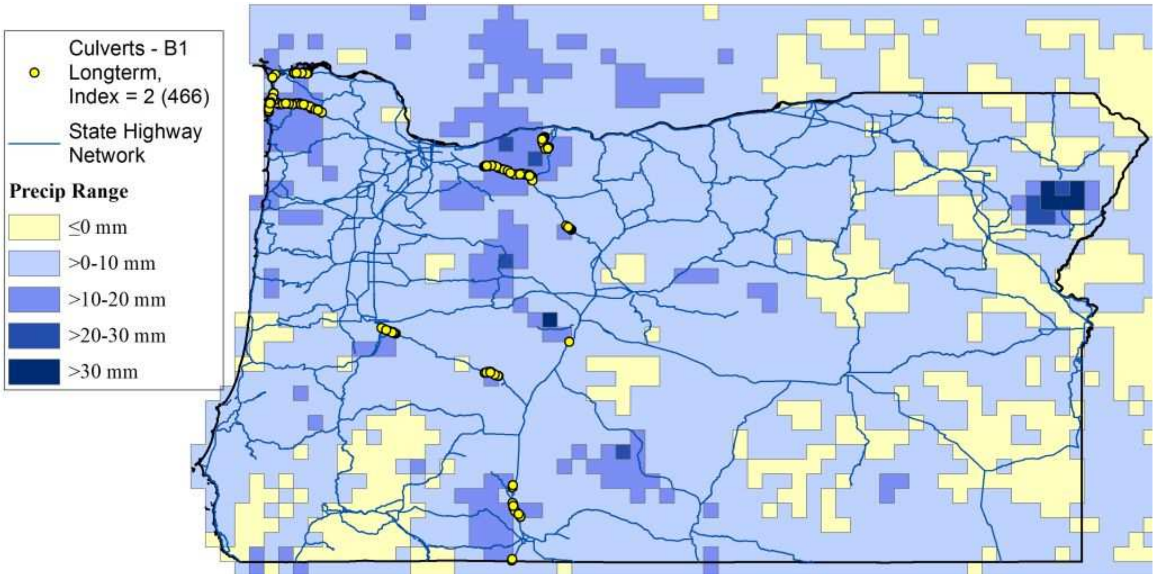


Figure G.31 Oregon Precipitation Exposure Index = 2 (B1, End-Of-Century)

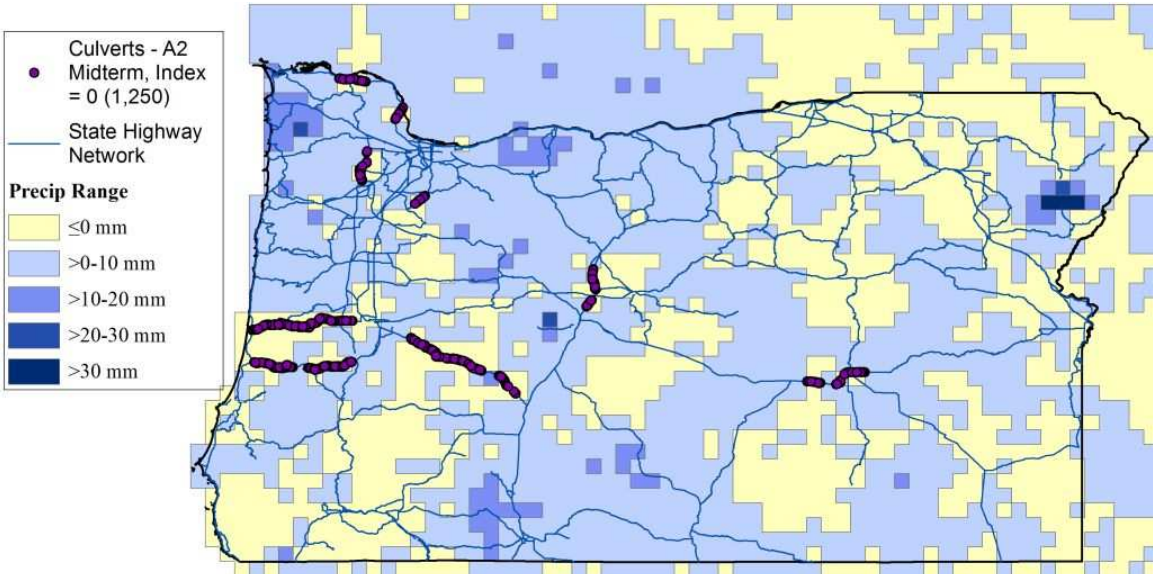


Figure G.32 Oregon Precipitation Exposure Index = 0 (A2, Mid-Century)

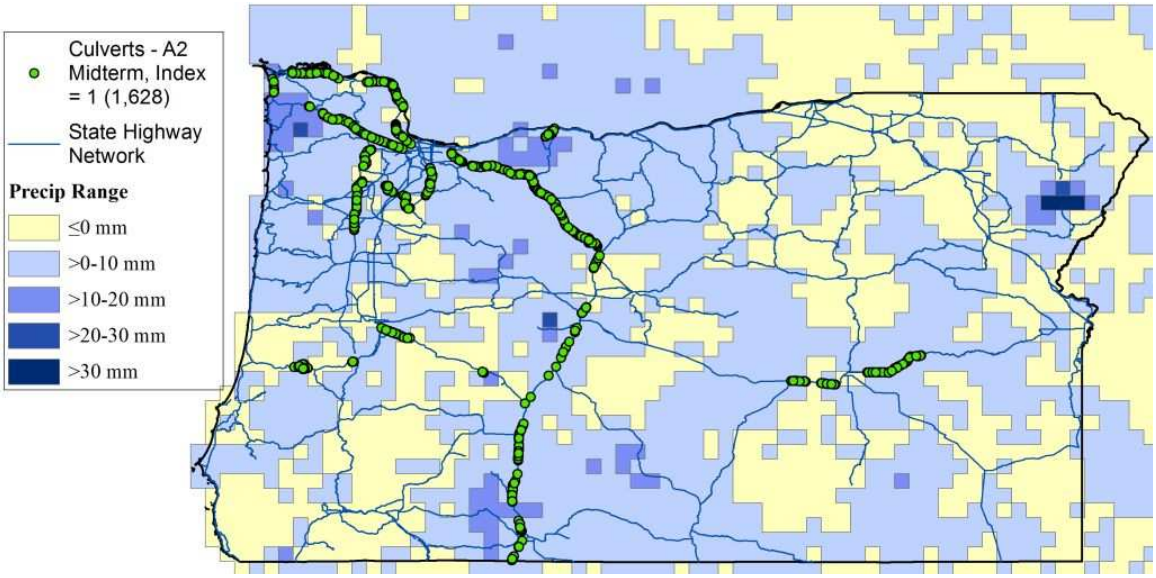


Figure G.33 Oregon Precipitation Exposure Index = 1 (A2, Mid-Century)

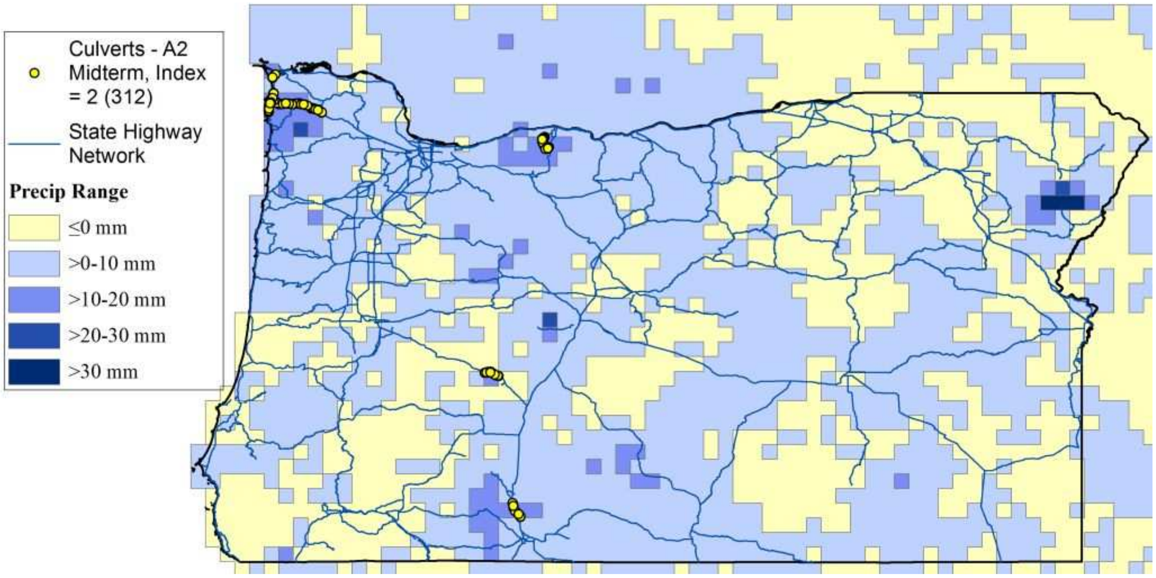


Figure G.34 Oregon Precipitation Exposure Index = 2 (A2, Mid-Century)

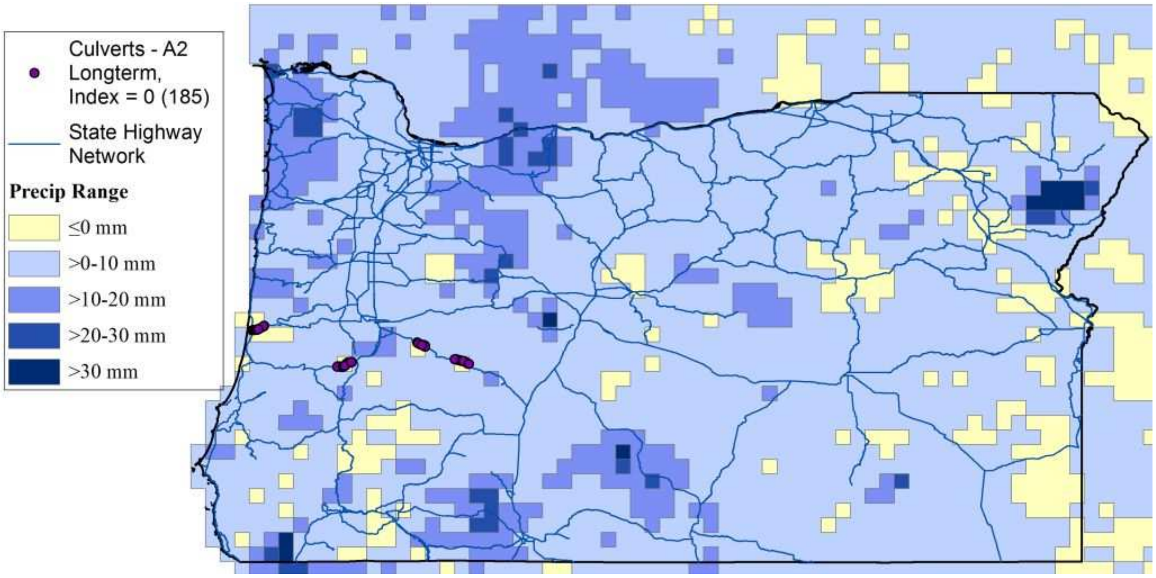


Figure G.35 Oregon Precipitation Exposure Index = 0 (A2, End-Of-Century)

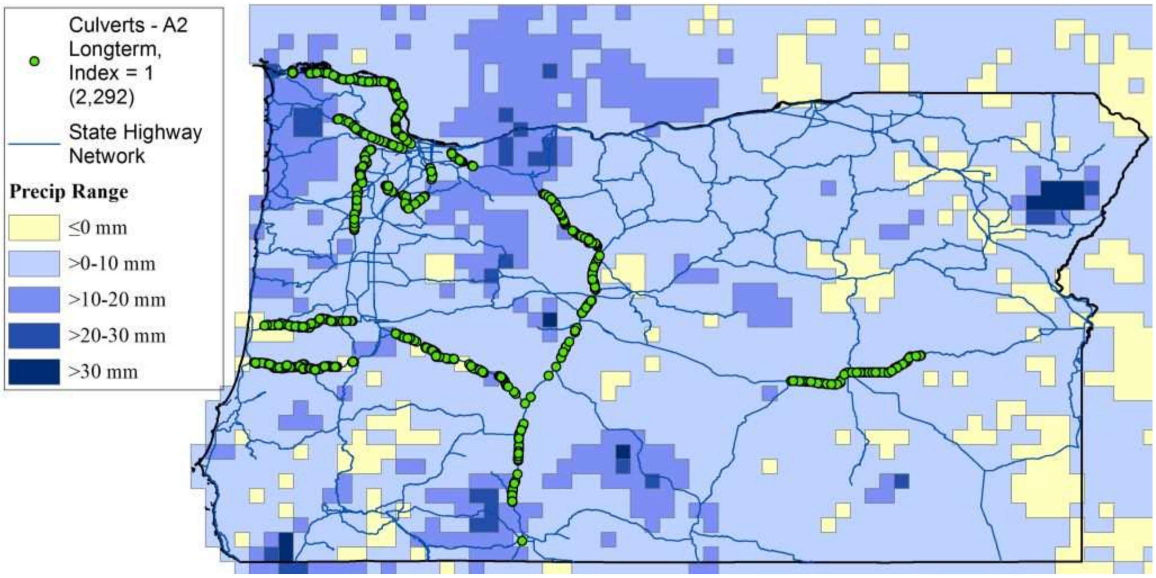


Figure G.36 Oregon Precipitation Exposure Index = 1 (A2, End-Of-Century)

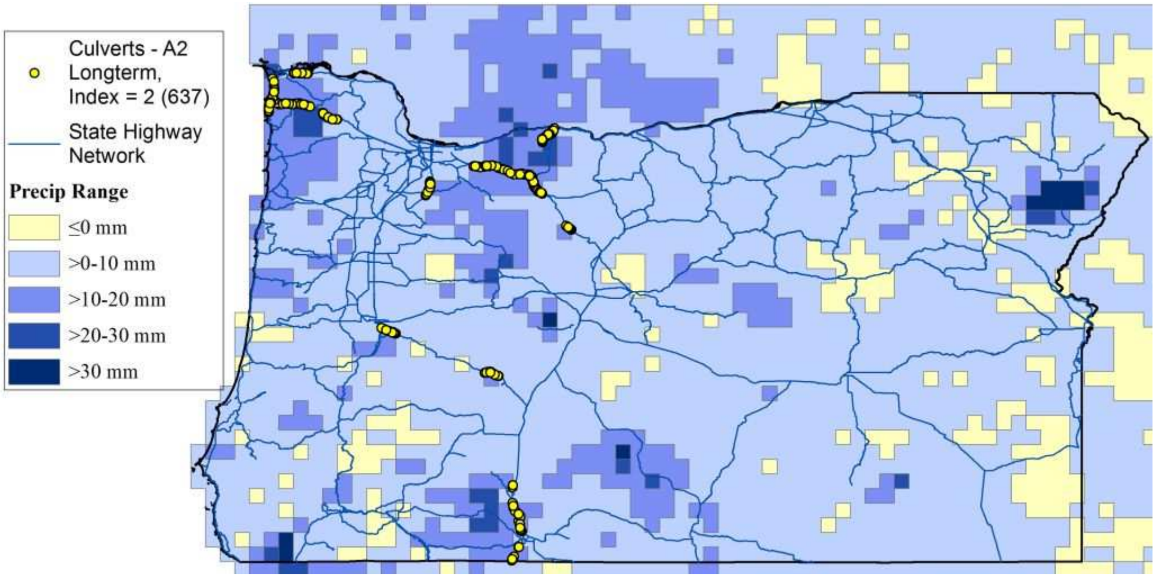


Figure G.37 Oregon Precipitation Exposure Index = 2 (A2, End-Of-Century)

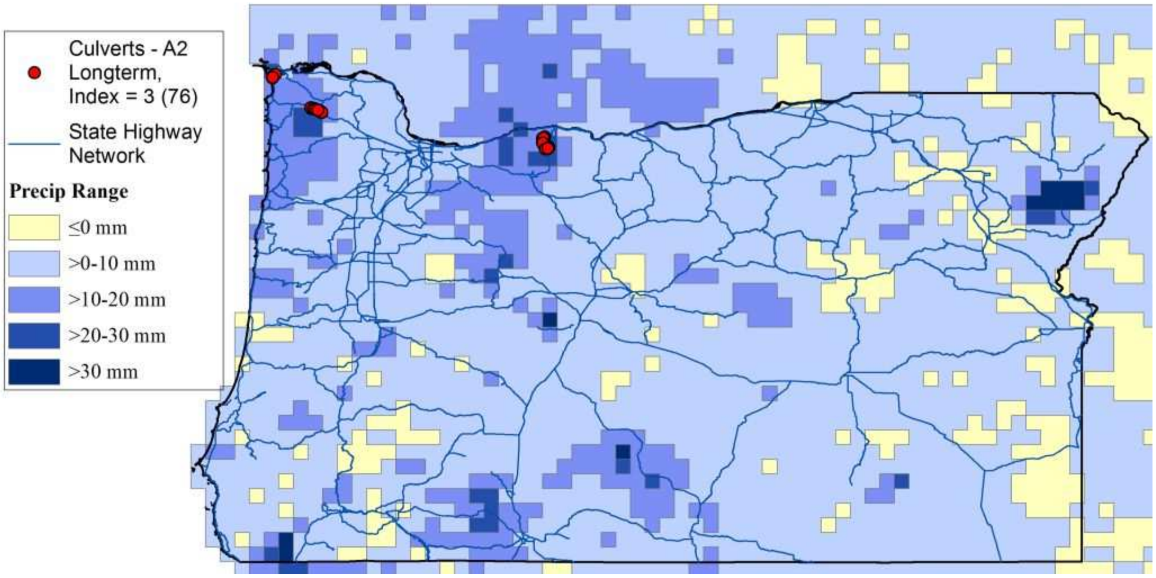


Figure G.38 Oregon Precipitation Exposure Index = 3 (A2, End-Of-Century)

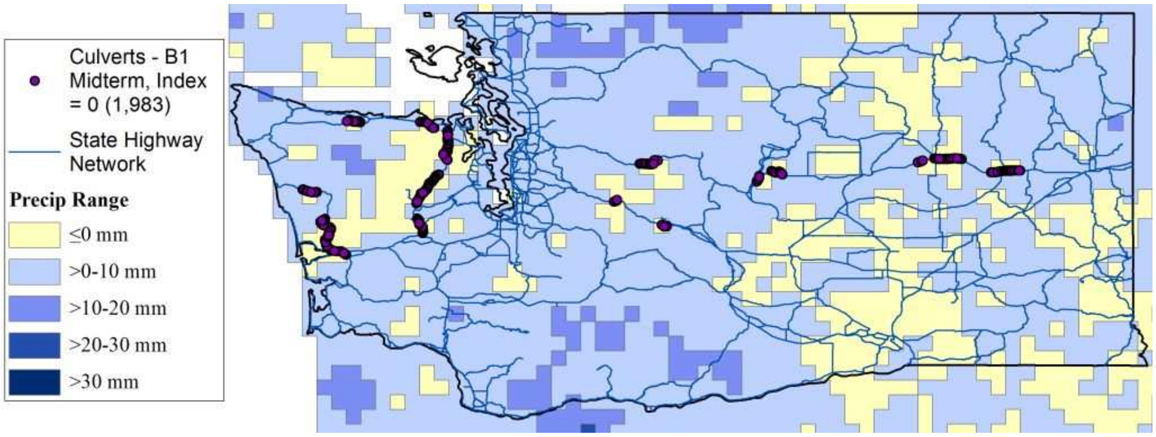


Figure G.39 Washington Precipitation Exposure Index = 0 (B1, Mid-Century)

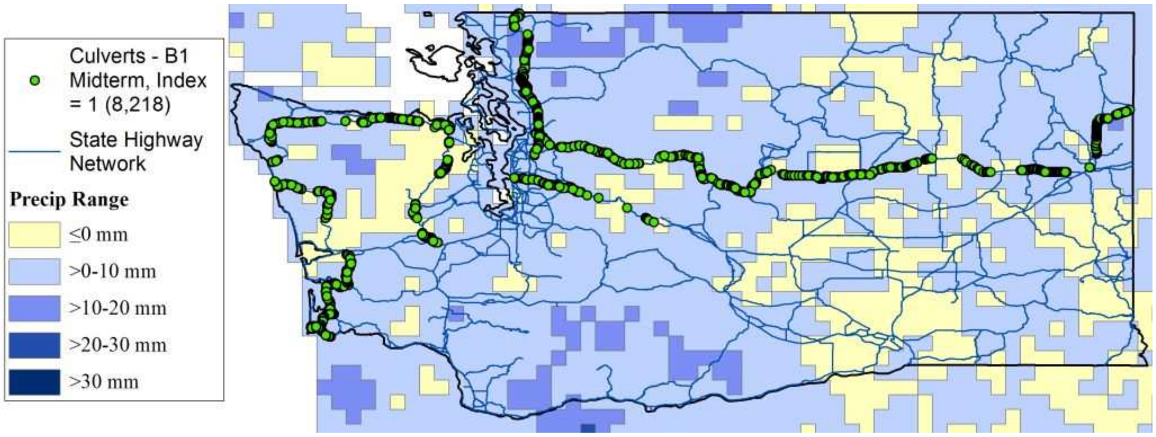


Figure G.40 Washington Precipitation Exposure Index = 1 (B1, Mid-Century)

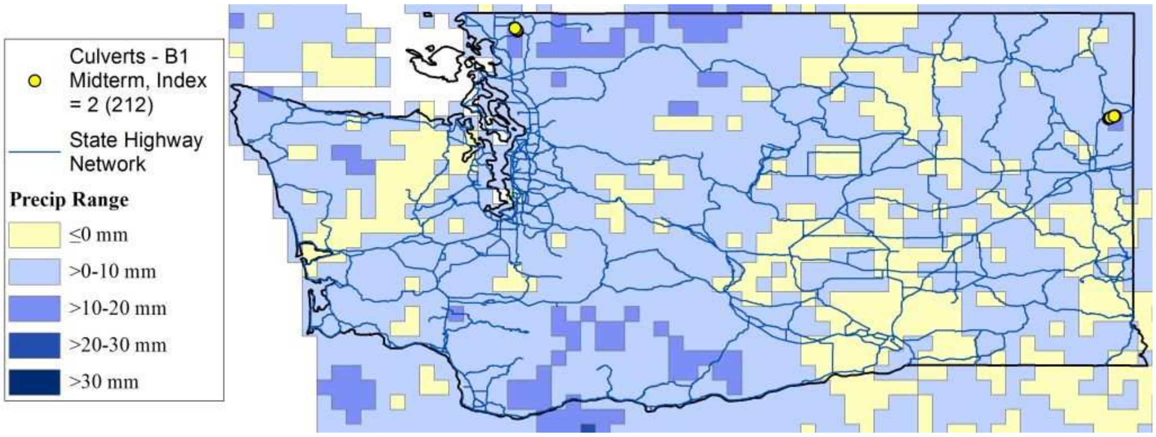


Figure G.41 Washington Precipitation Exposure Index = 2 (B1, Mid-Century)

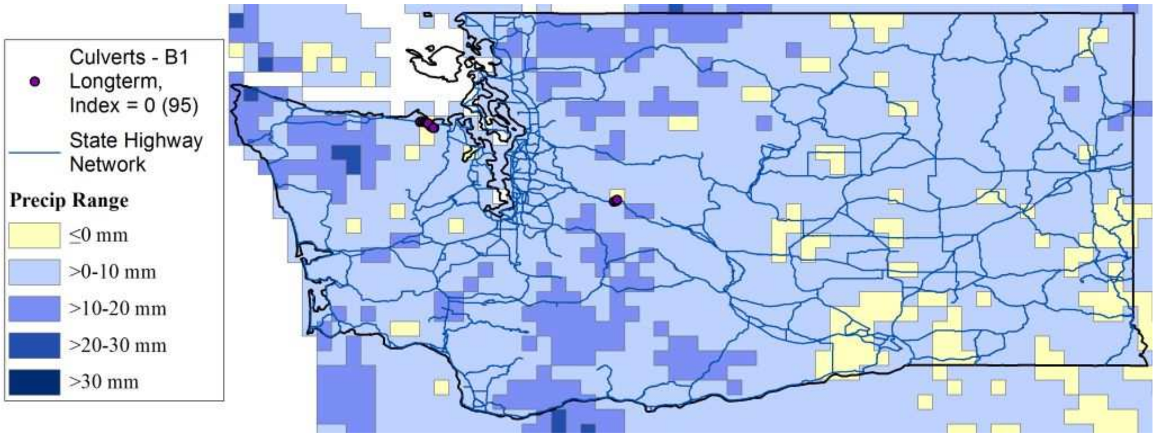


Figure G.42 Washington Precipitation Exposure Index = 0 (B1, End-Of-Century)

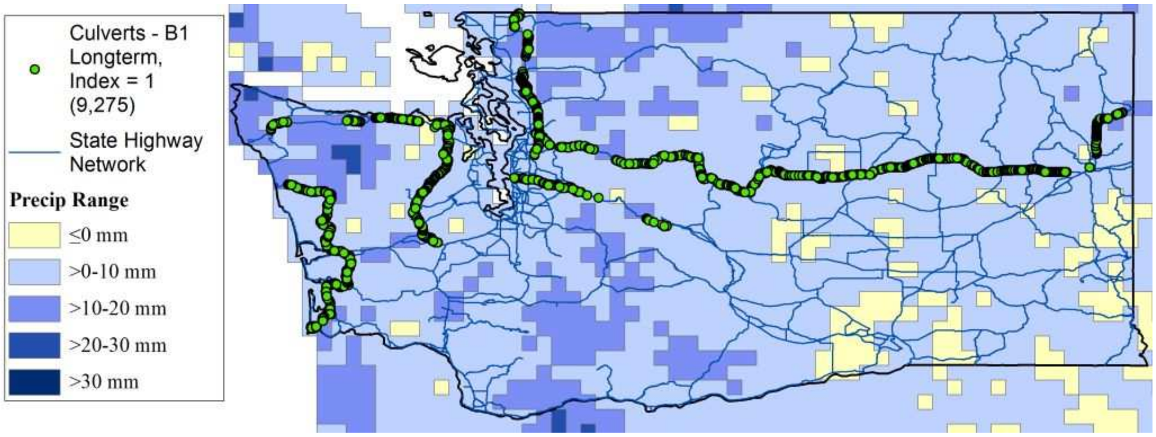


Figure G.43 Washington Precipitation Exposure Index = 1 (B1, End-Of-Century)

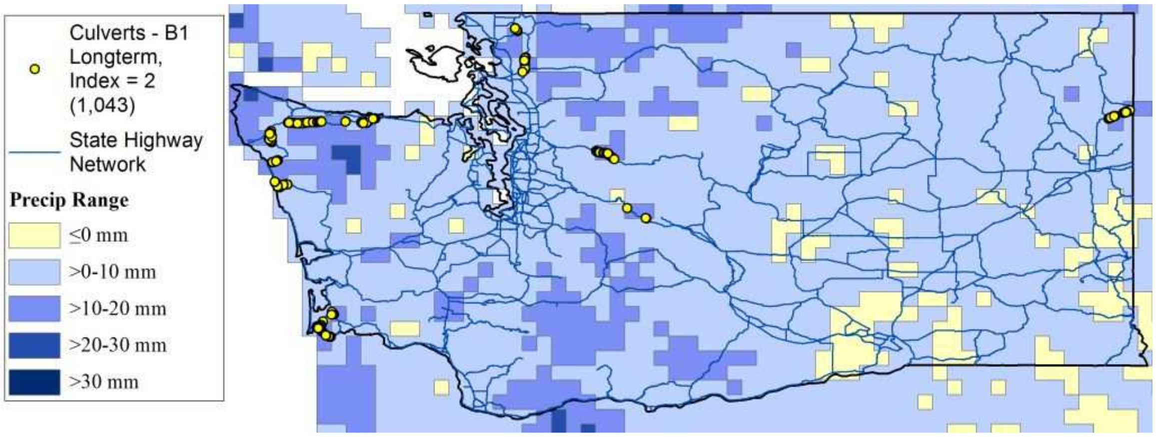


Figure G.44 Washington Precipitation Exposure Index = 2 (B1, End-Of-Century)

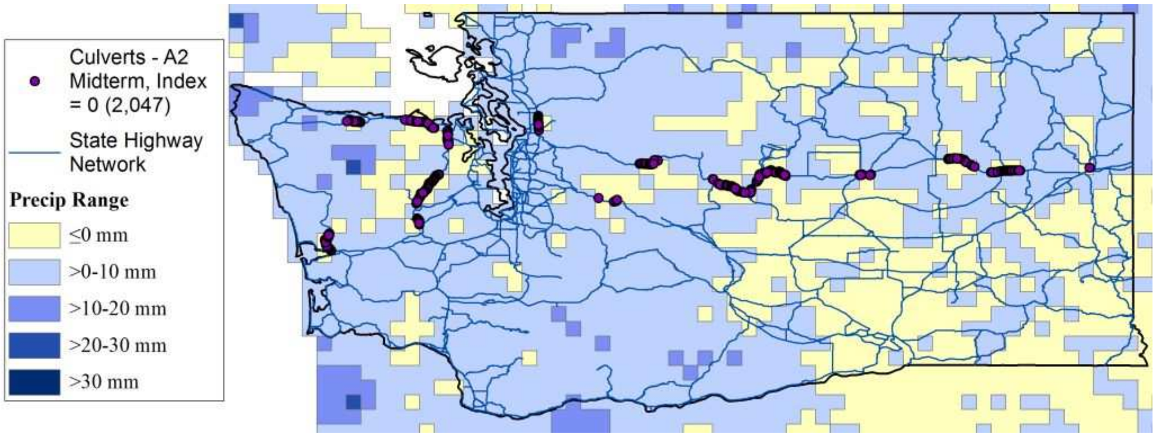


Figure G.45 Washington Precipitation Exposure Index = 0 (A2, Mid-Century)

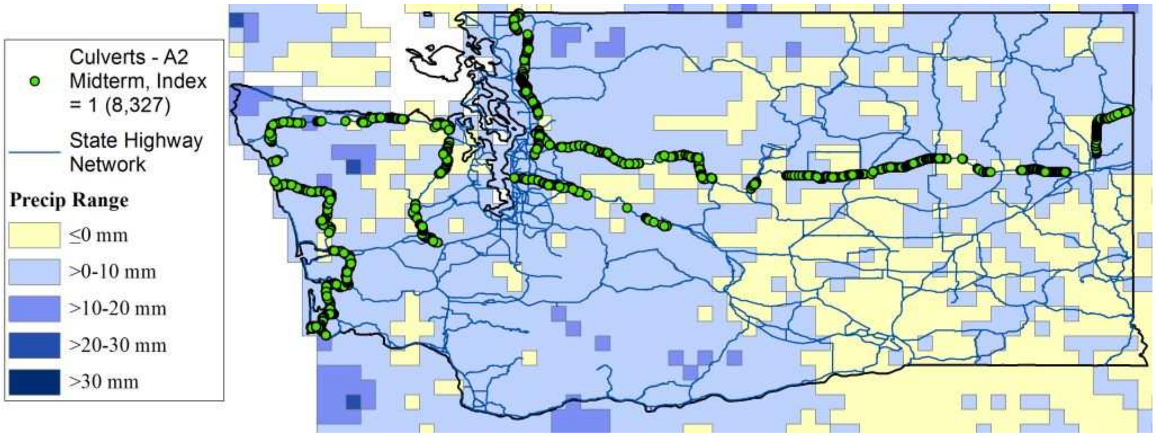


Figure G.46 Washington Precipitation Exposure Index = 1 (A2, Mid-Century)

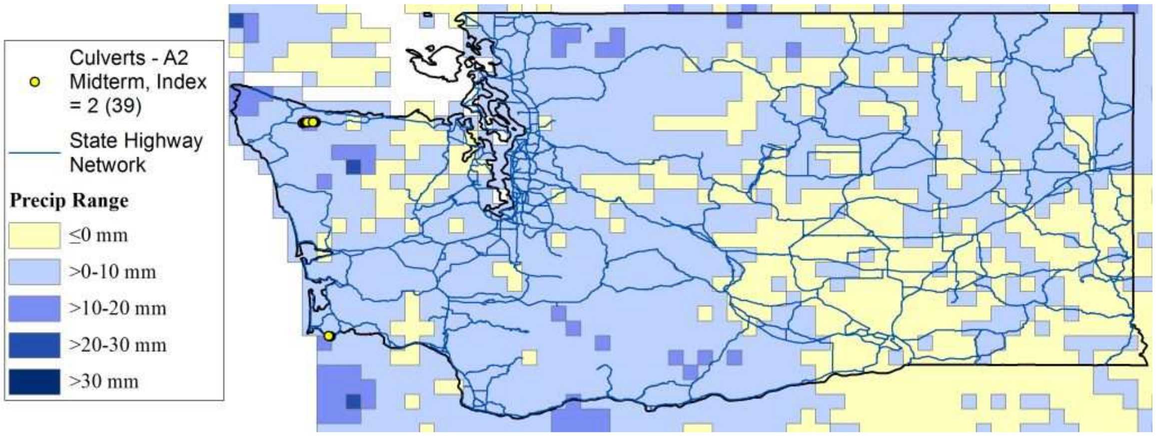


Figure G.47 Washington Precipitation Exposure Index = 2 (A2, Mid-Century)

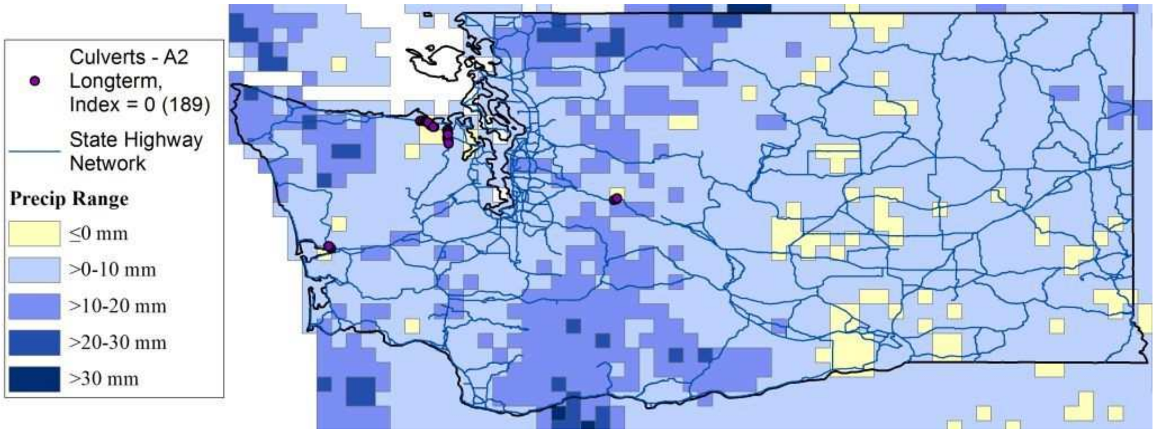


Figure G.48 Washington Precipitation Exposure Index = 0 (A2, End-Of-Century)

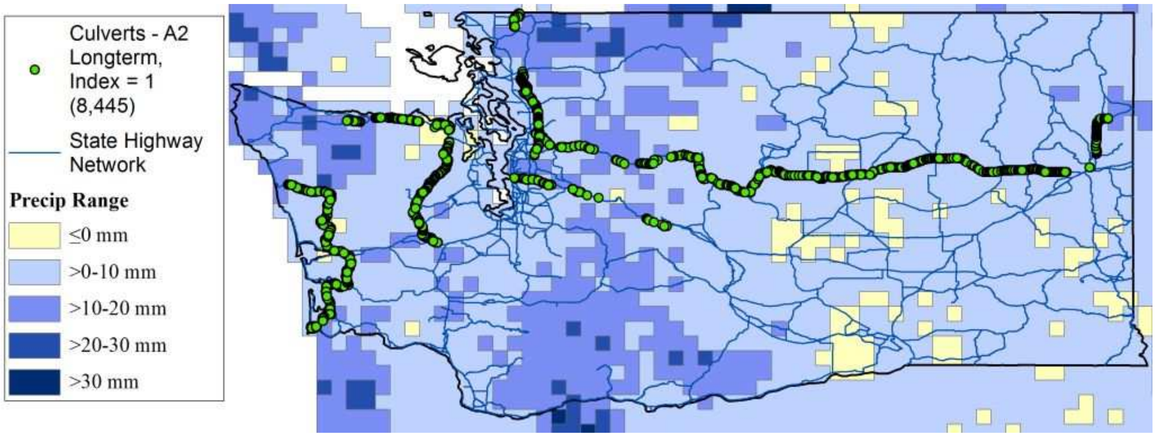


Figure G.49 Washington Precipitation Exposure Index = 1 (A2, End-Of-Century)

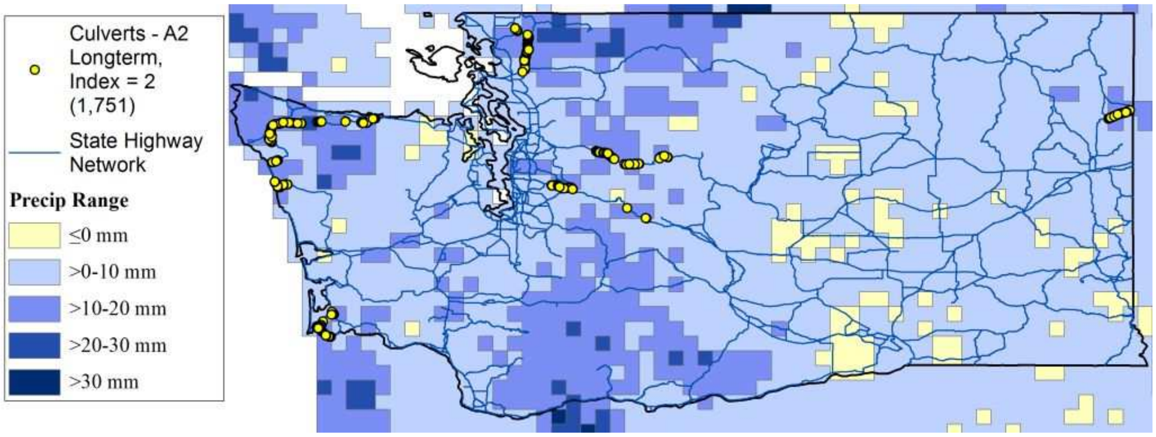


Figure G.50 Washington Precipitation Exposure Index = 2 (A2, End-Of-Century)

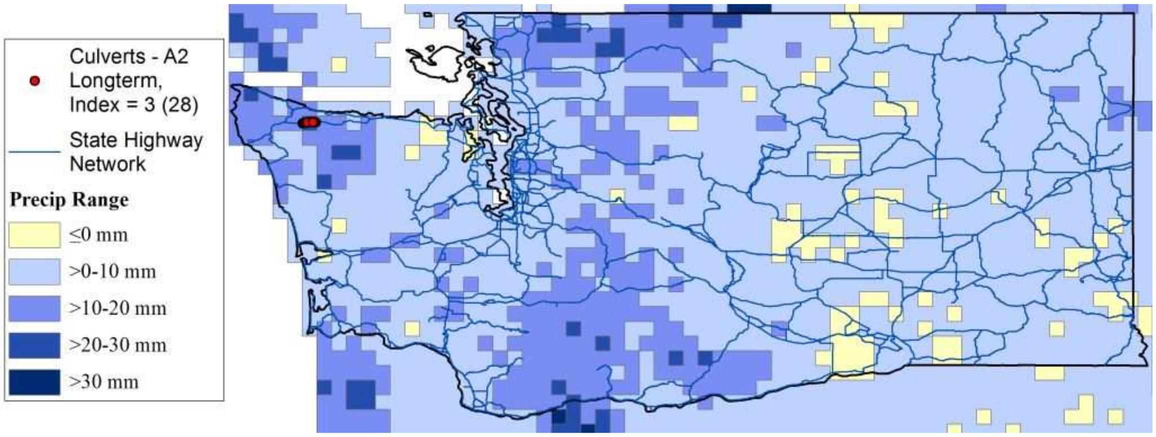


Figure G.51 Washington Precipitation Exposure Index = 3 (A2, End-Of-Century)

APPENDIX H: VULNERABILITY ANALYSIS MAP RESULTS

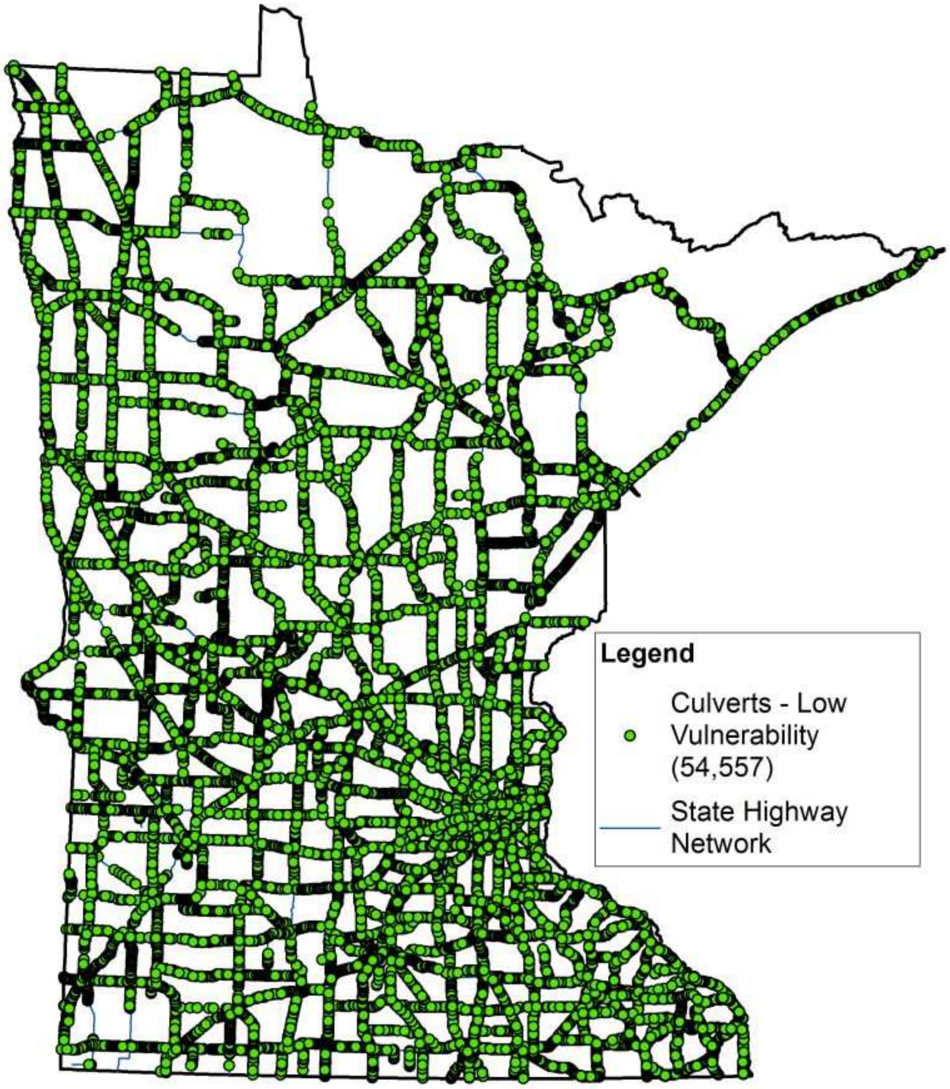


Figure H.1 Minnesota Vulnerability Index = 1 (Low), Method 2

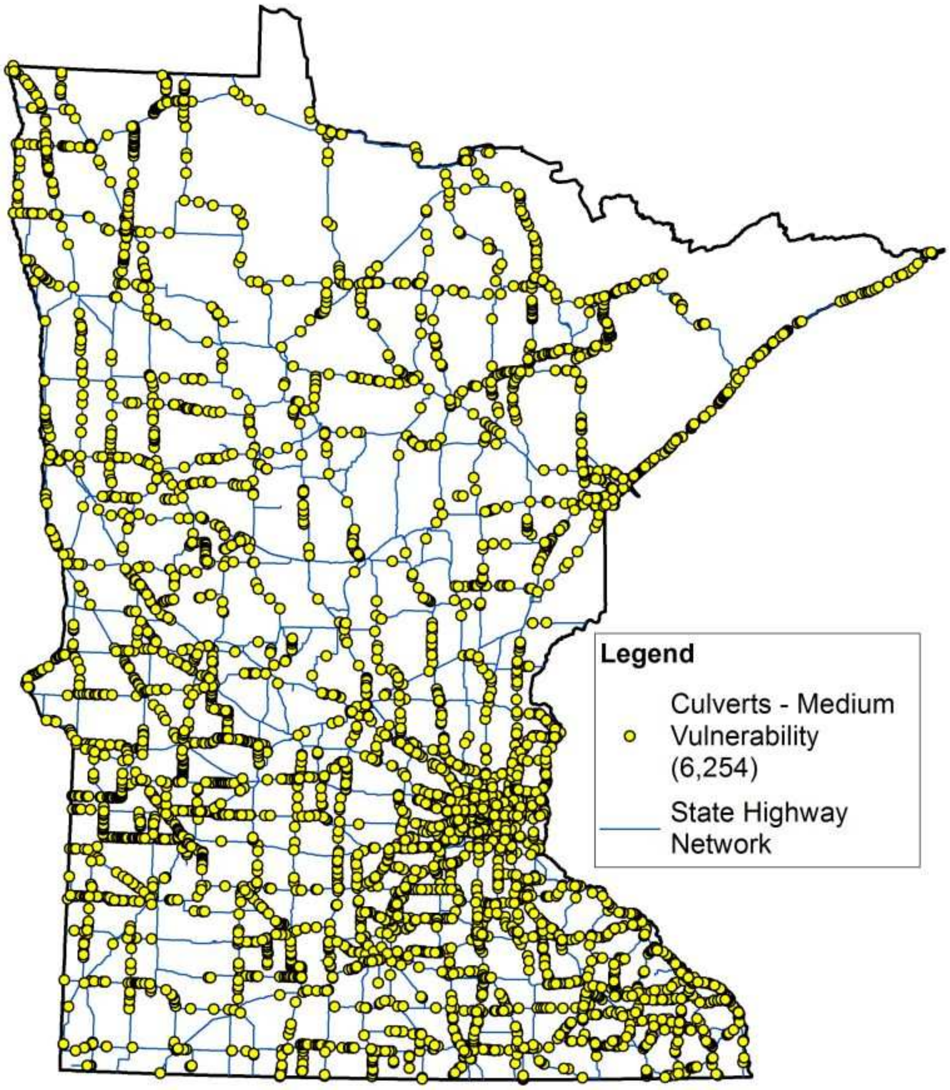


Figure H.2 Minnesota Vulnerability Index = 2 (Medium), Method 2

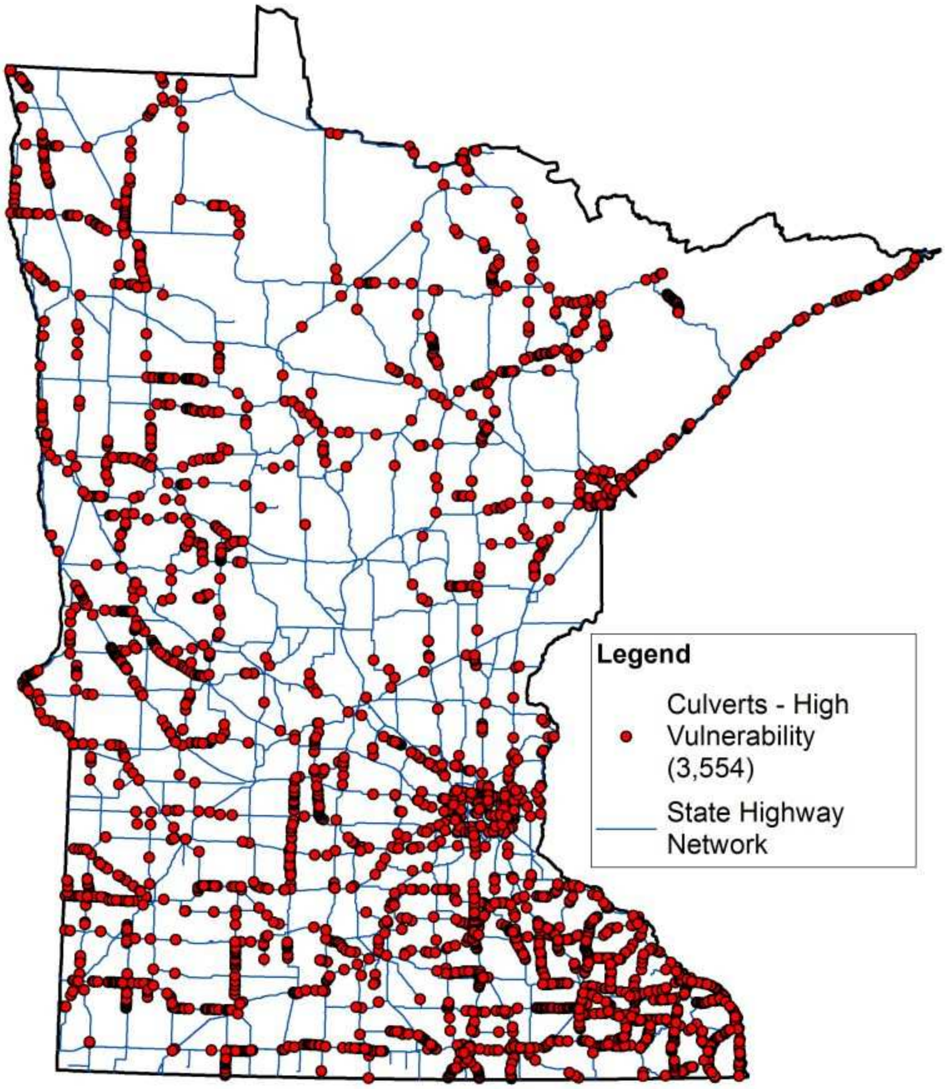


Figure H.3 Minnesota Vulnerability Index = 3 (High), Method 2

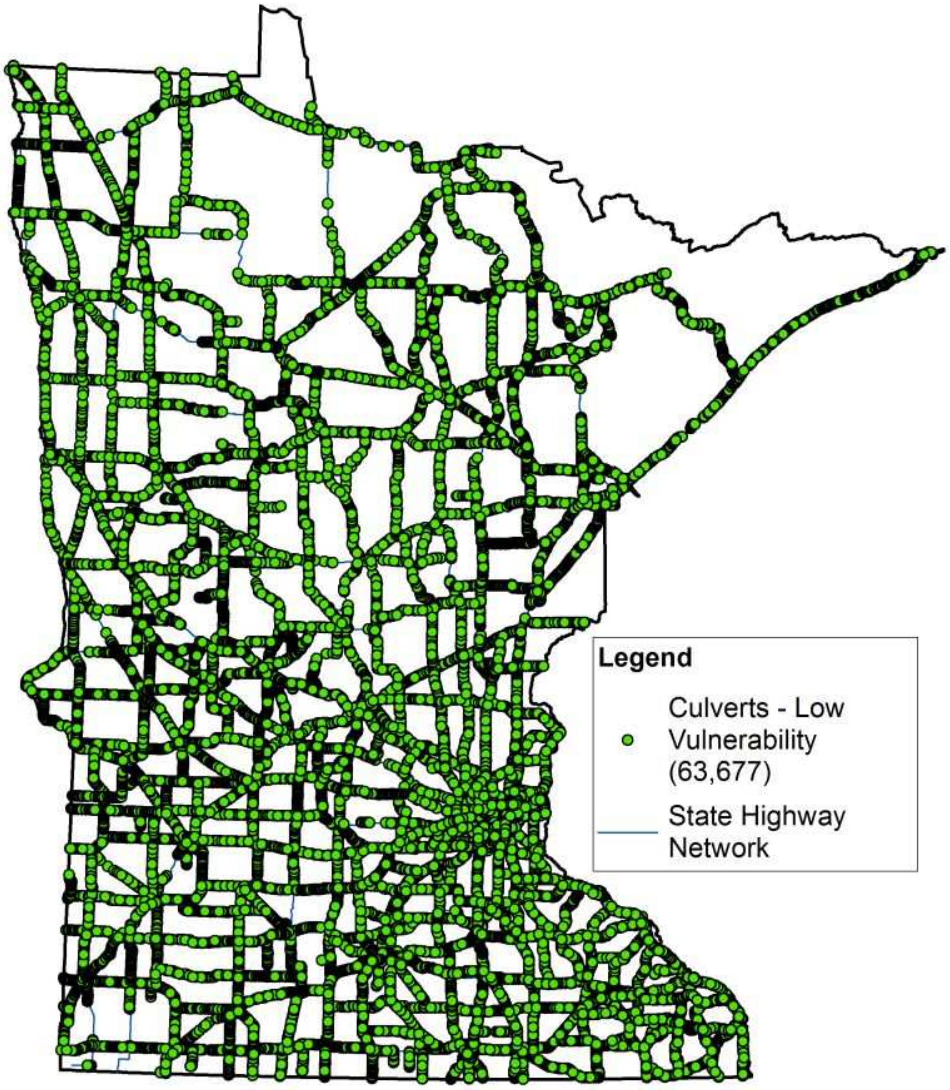


Figure H.4 Minnesota Vulnerability Index = 1 (Low), Method 3

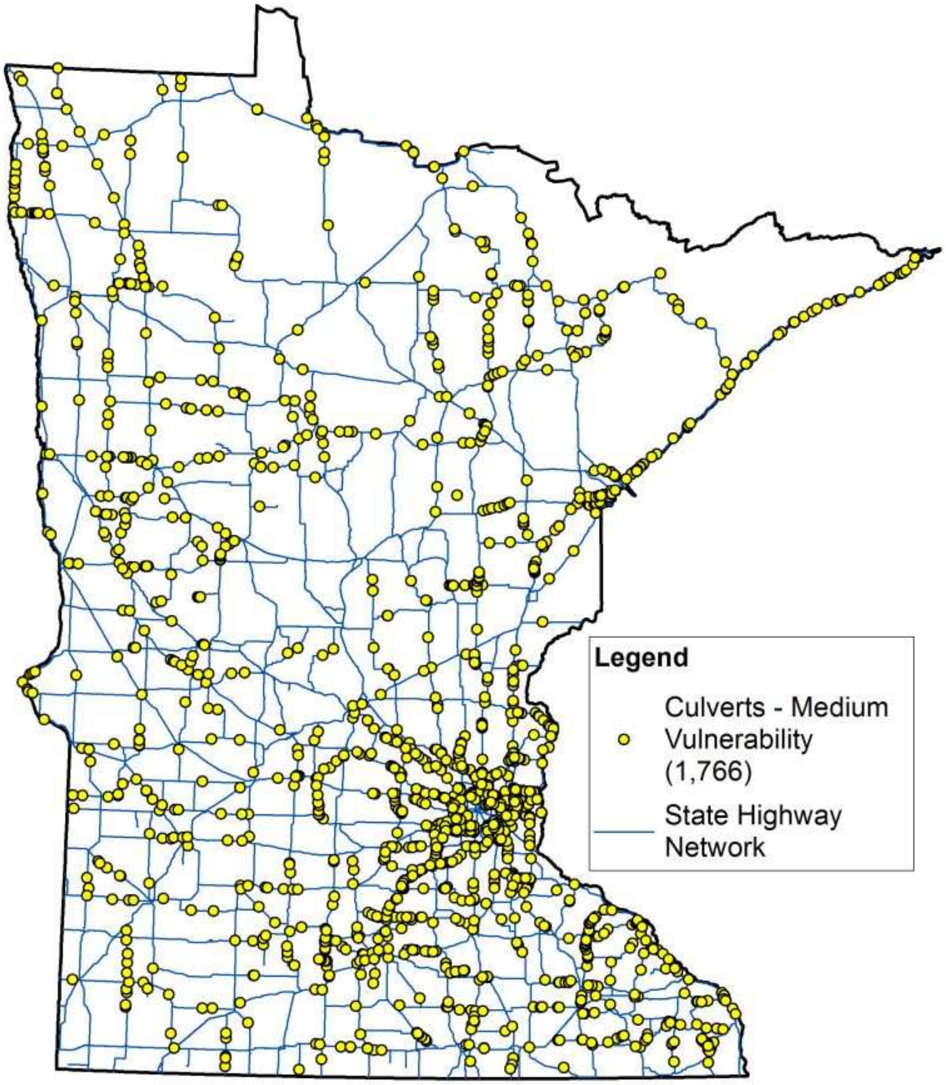


Figure H.5 Minnesota Vulnerability Index = 2 (Medium), Method 3

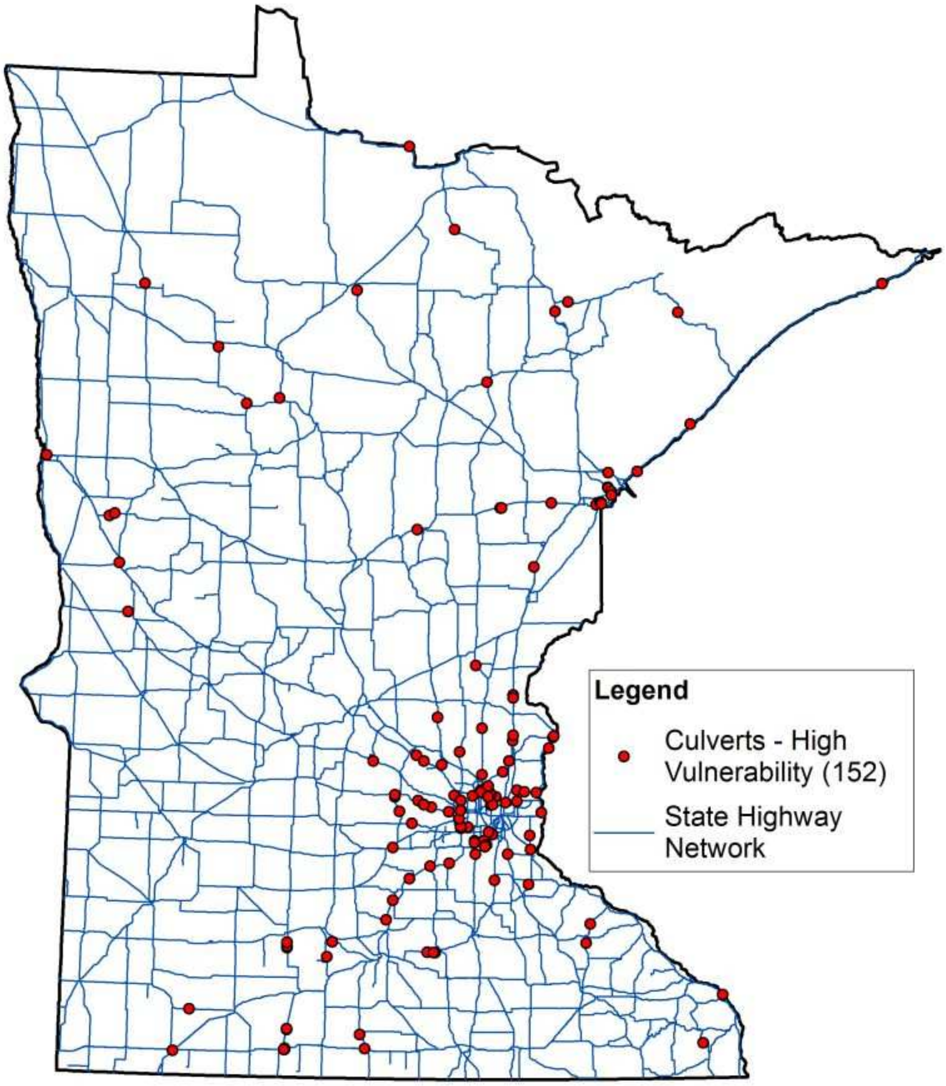


Figure H.6 Minnesota Vulnerability Index = 3 (High), Method 3

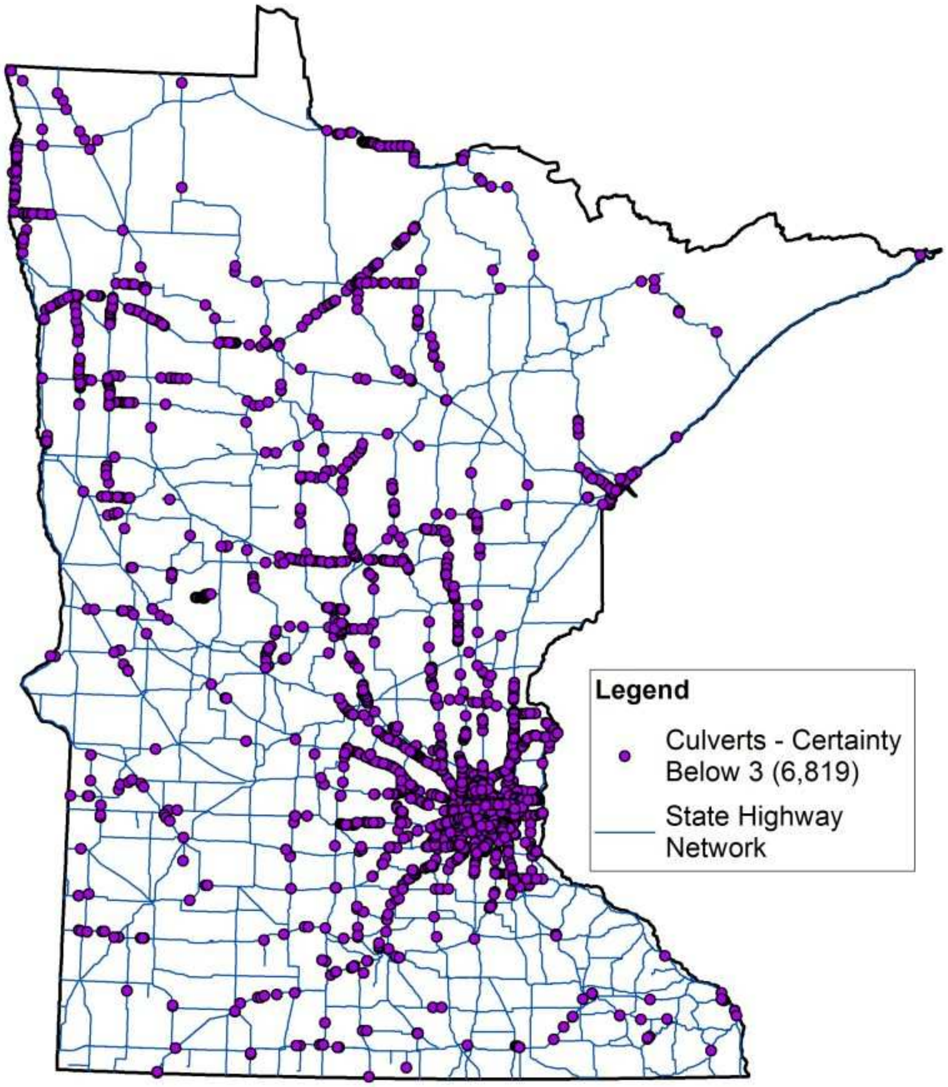


Figure H.7 Minnesota Vulnerability Index Method 3, Certainty Rating Below 3

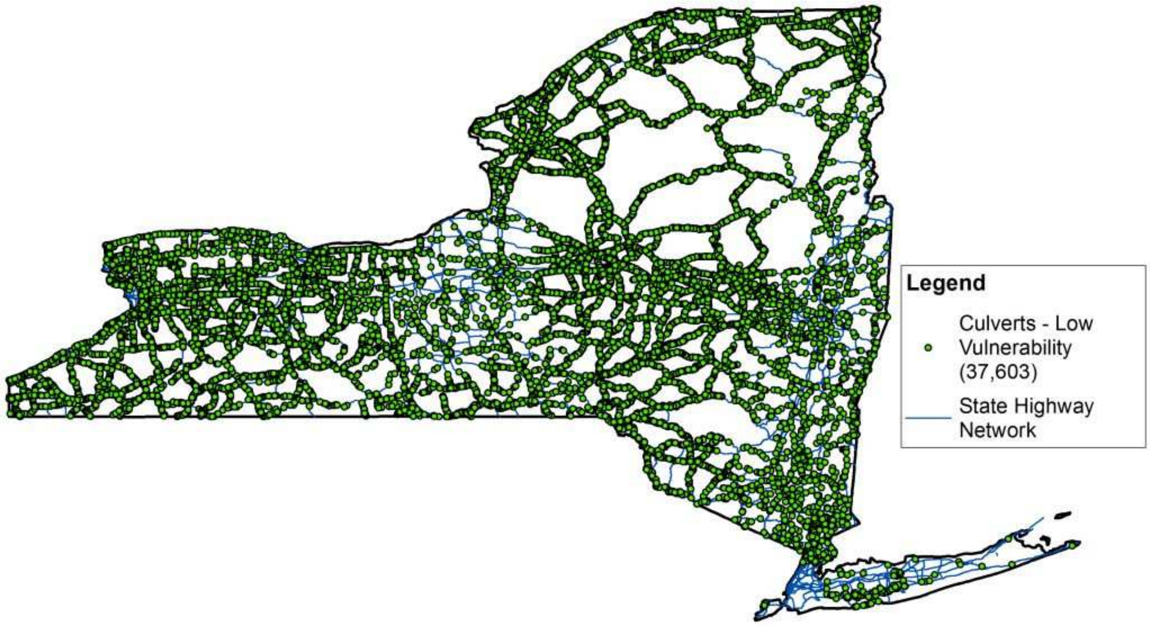


Figure H.8 New York Vulnerability Index = 1 (Low), Method 2

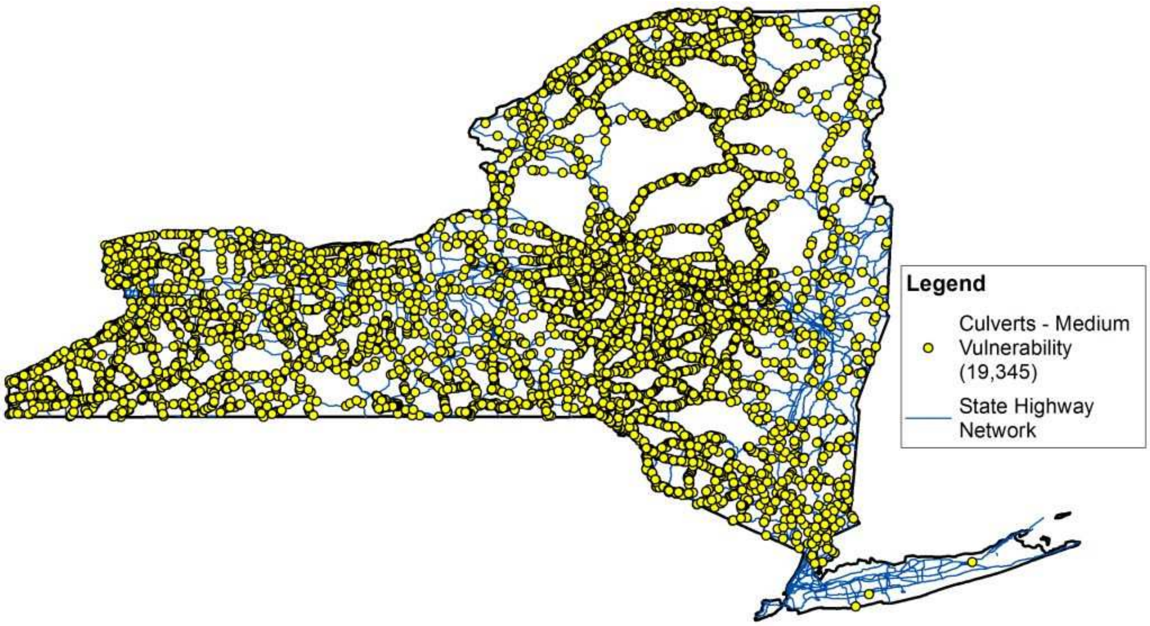


Figure H.9 New York Vulnerability Index = 2 (Medium), Method 2

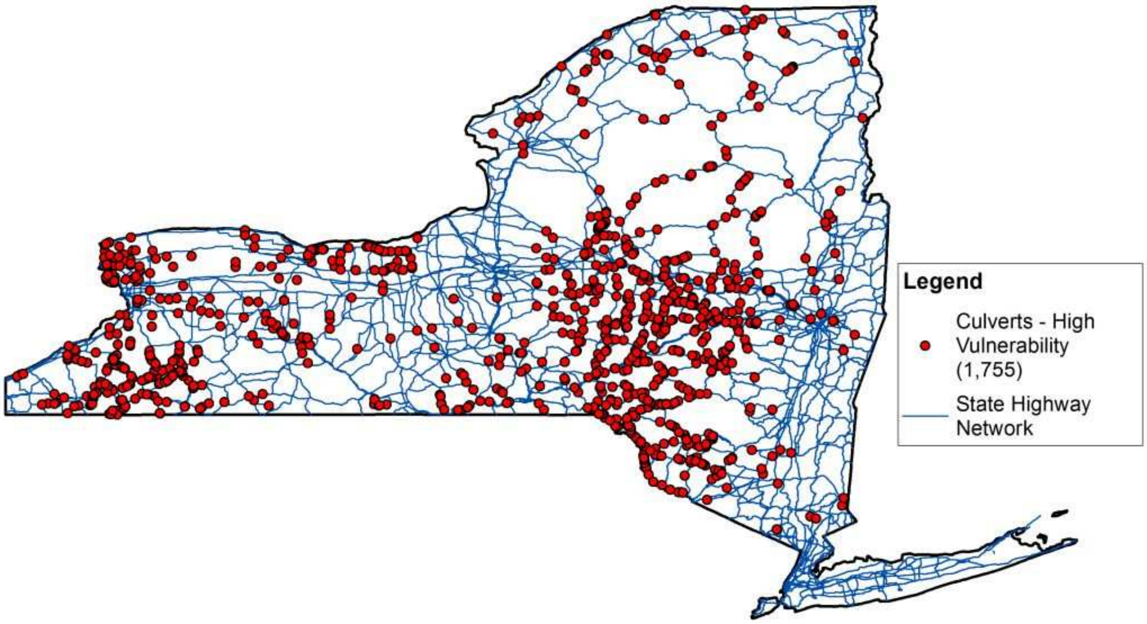


Figure H.10 New York Vulnerability Index = 3 (High), Method 2

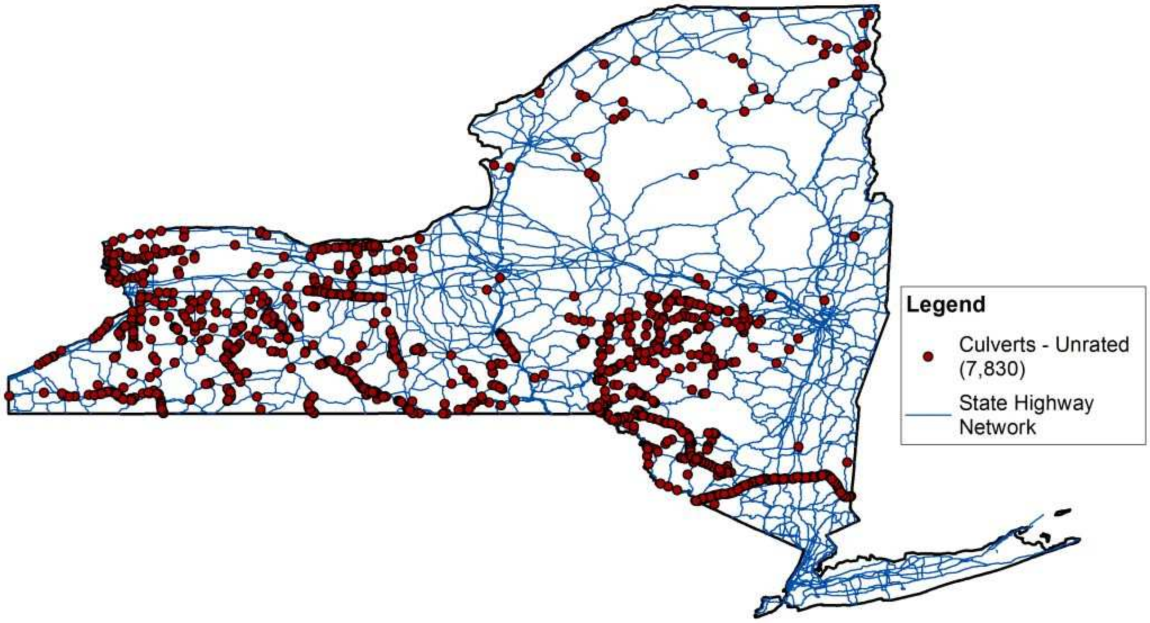


Figure H.11 New York Vulnerability Index Method 2, Overall Condition Unrated

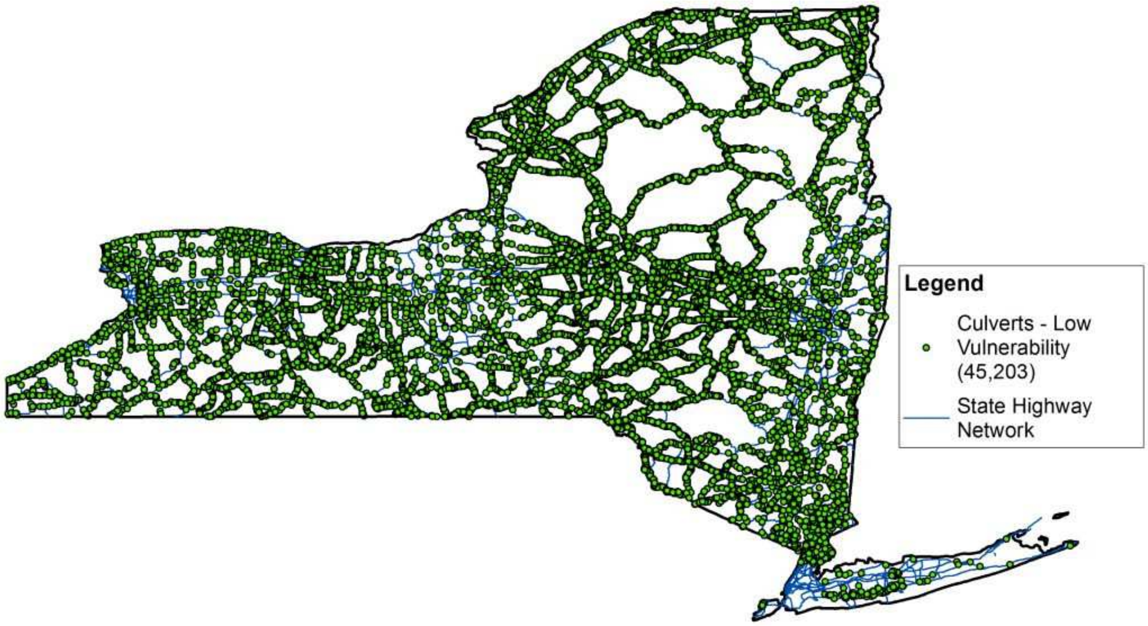


Figure H.12 New York Vulnerability Index = 1 (Low), Method 3

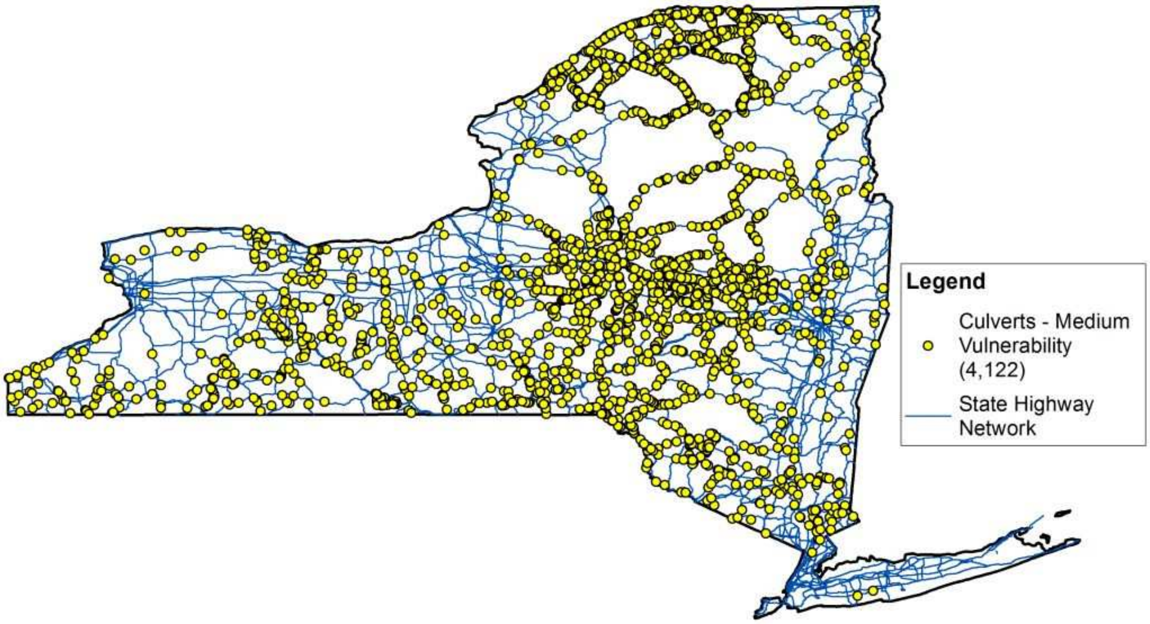


Figure H.13 New York Vulnerability Index = 2 (Medium), Method 3

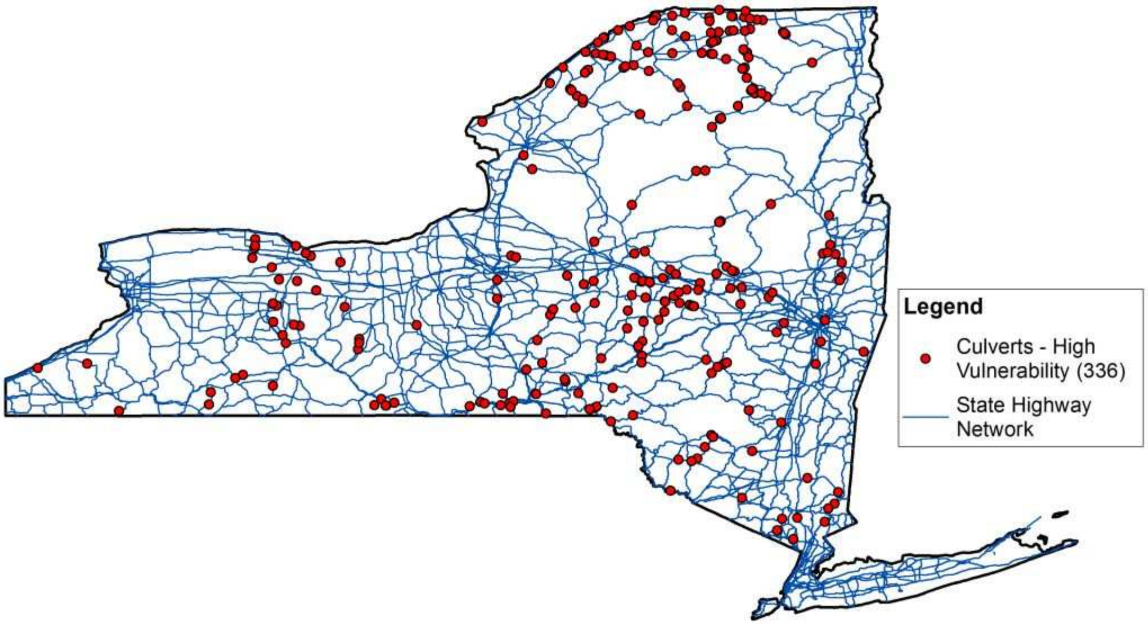


Figure H.14 New York Vulnerability Index = 3 (High), Method 3

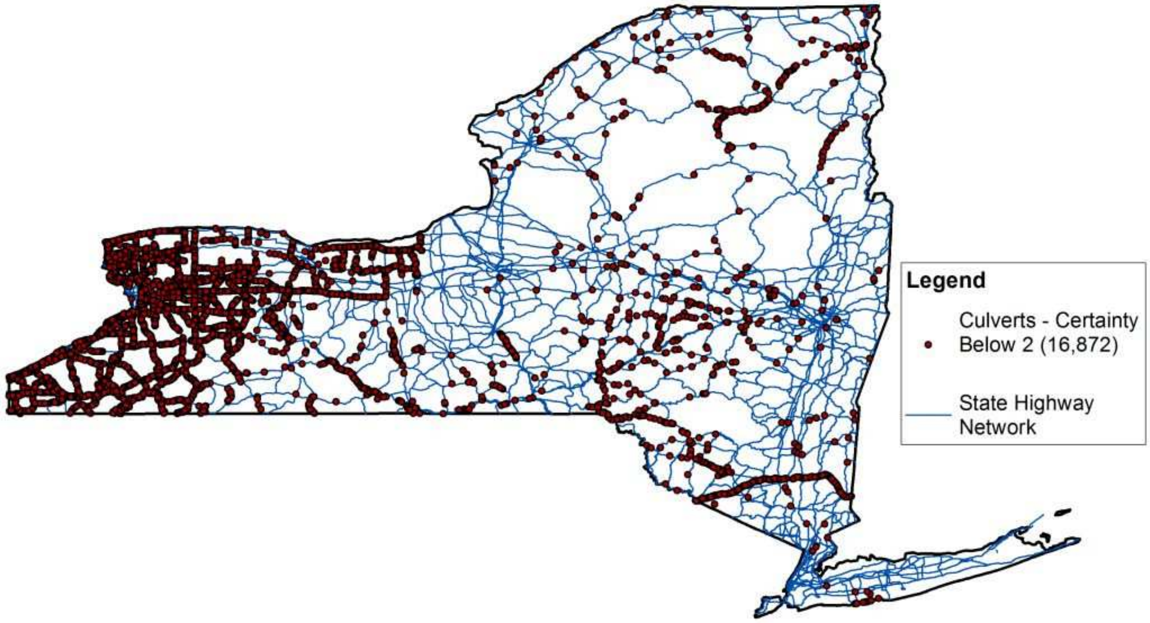


Figure H.15 New York Vulnerability Index Method 3, Certainty Rating Below 2

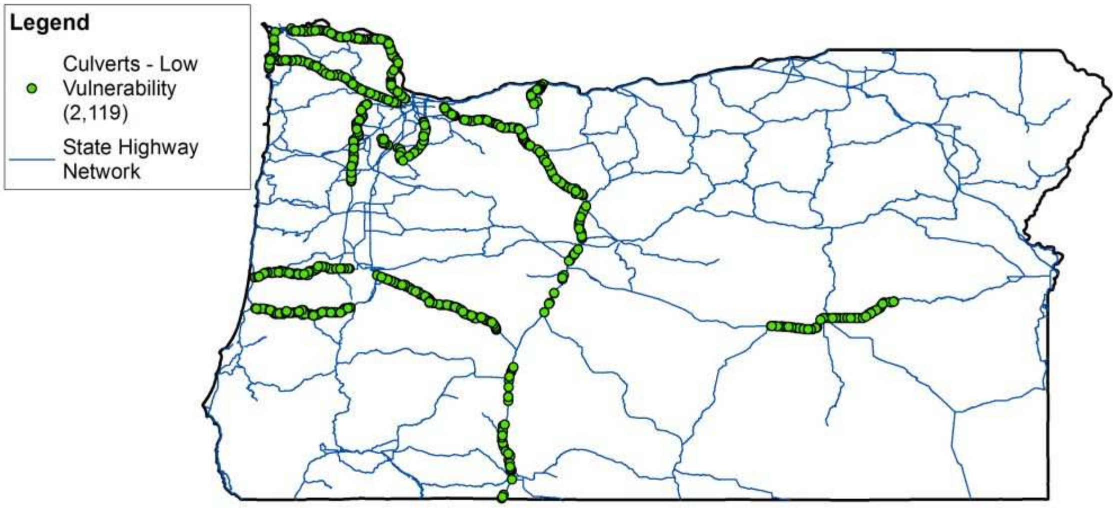


Figure H.16 Oregon Vulnerability Index = 1 (Low), Method 3

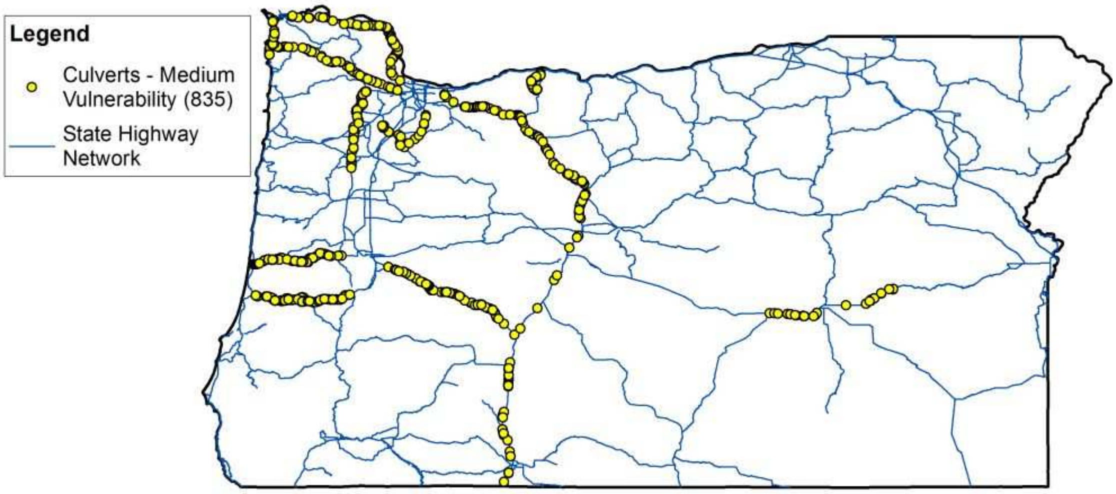


Figure H.17 Oregon Vulnerability Index = 2 (Medium), Method 3

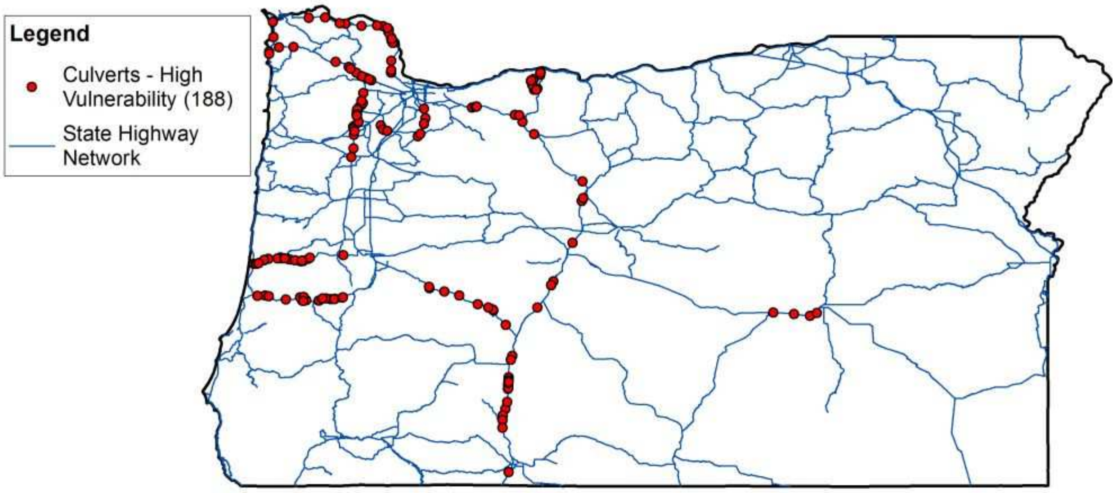


Figure H.18 Oregon Vulnerability Index = 3 (High), Method 3

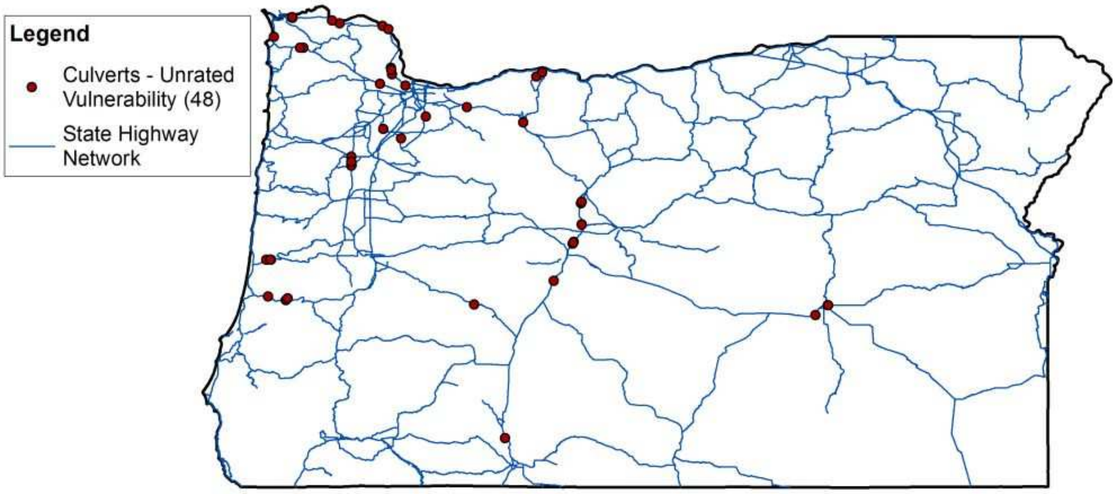


Figure H.19 Oregon Vulnerability Index Method 3, No Rated Blockage Conditions

APPENDIX I: COMBINED CRITICALITY ANALYSIS MAP RESULTS

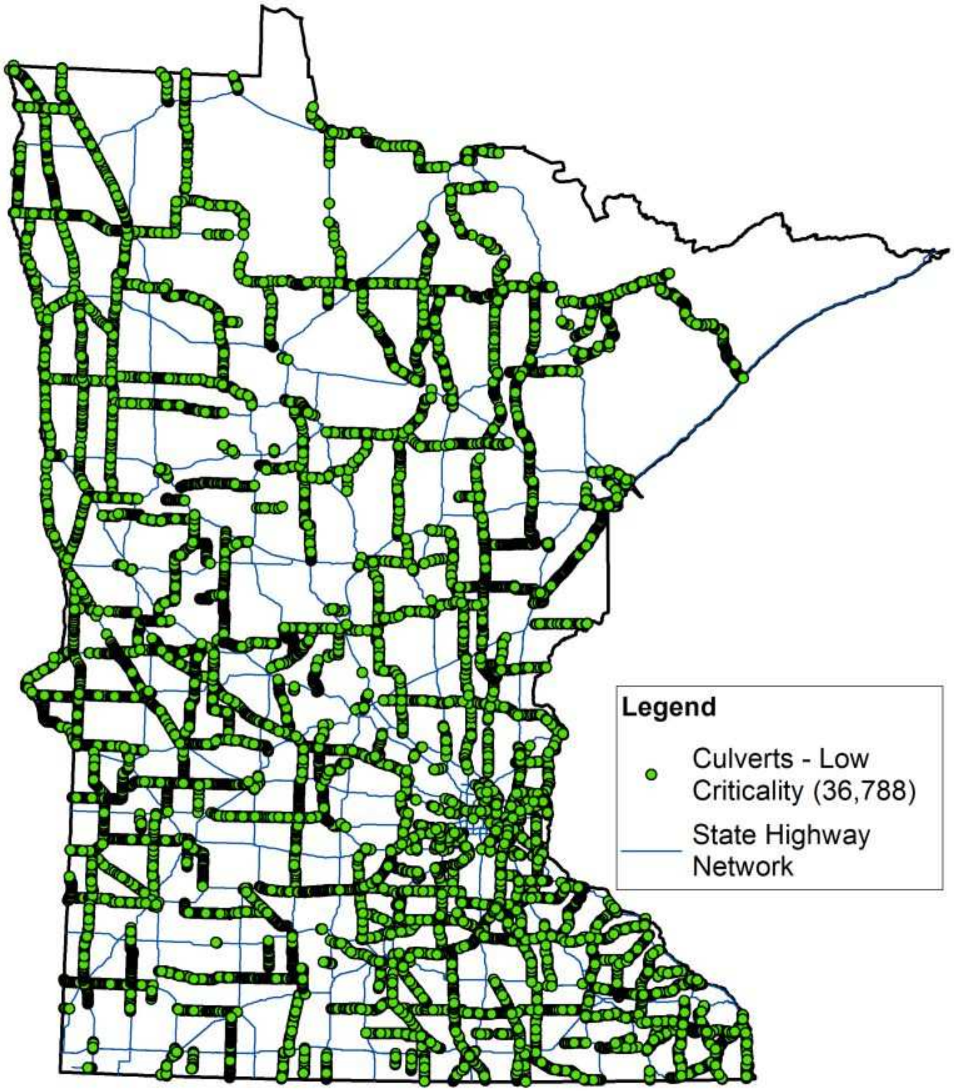


Figure I.1 Minnesota Combined Criticality Index = 1 (Low)

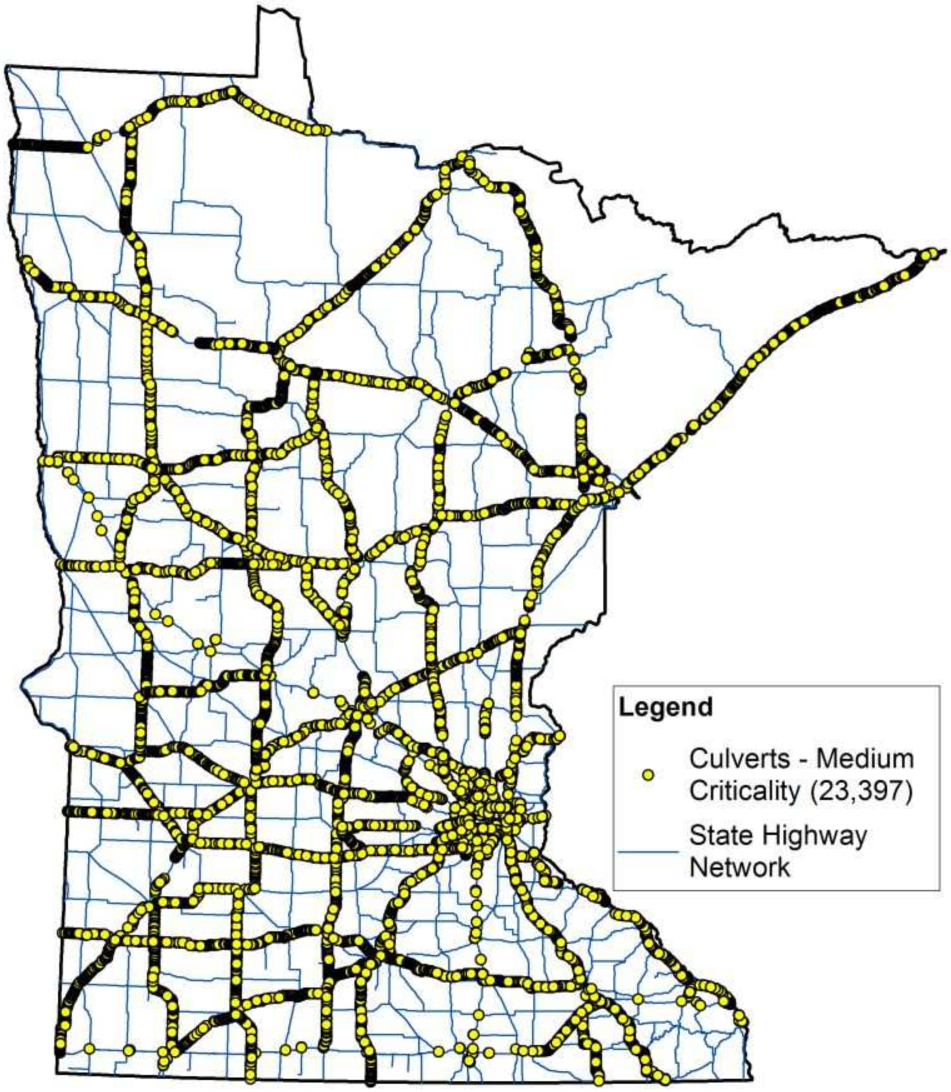


Figure I.2 Minnesota Combined Criticality Index = 2 (Medium)

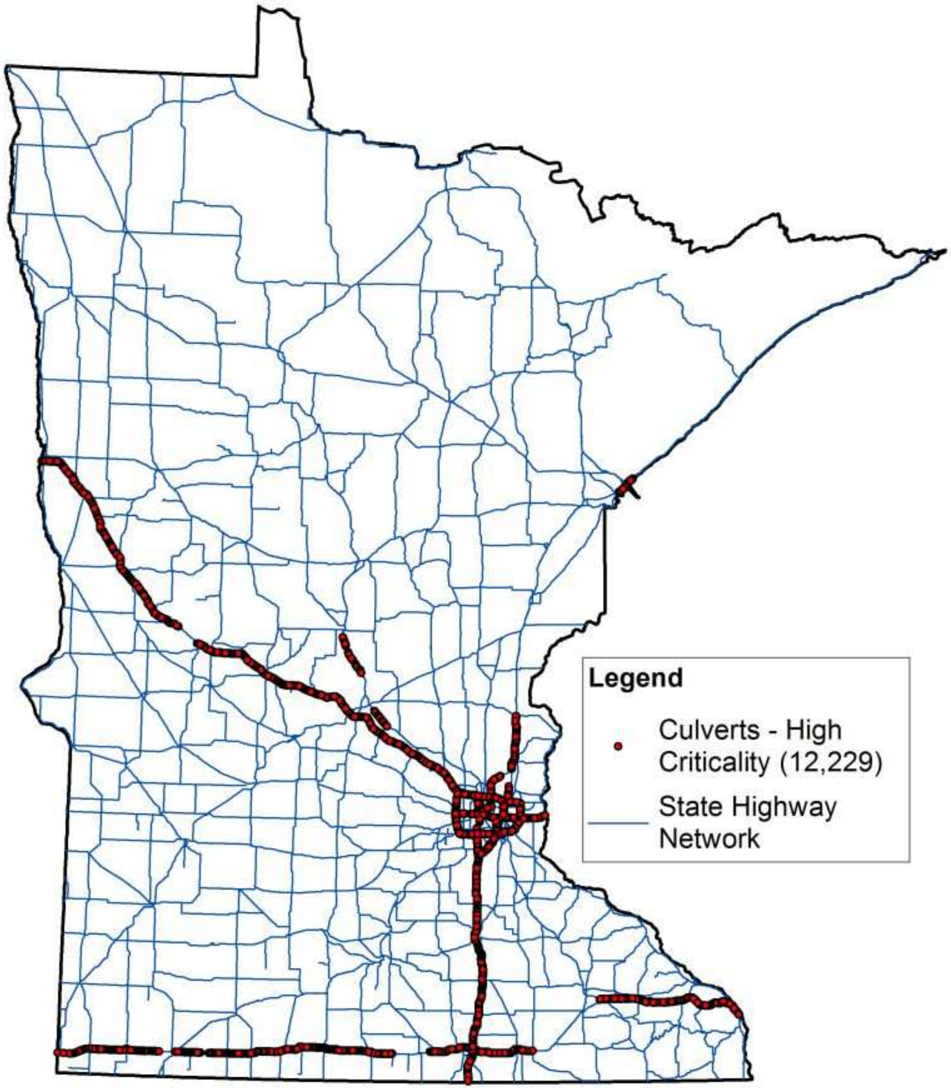


Figure I.3 Minnesota Combined Criticality Index = 3 (High)

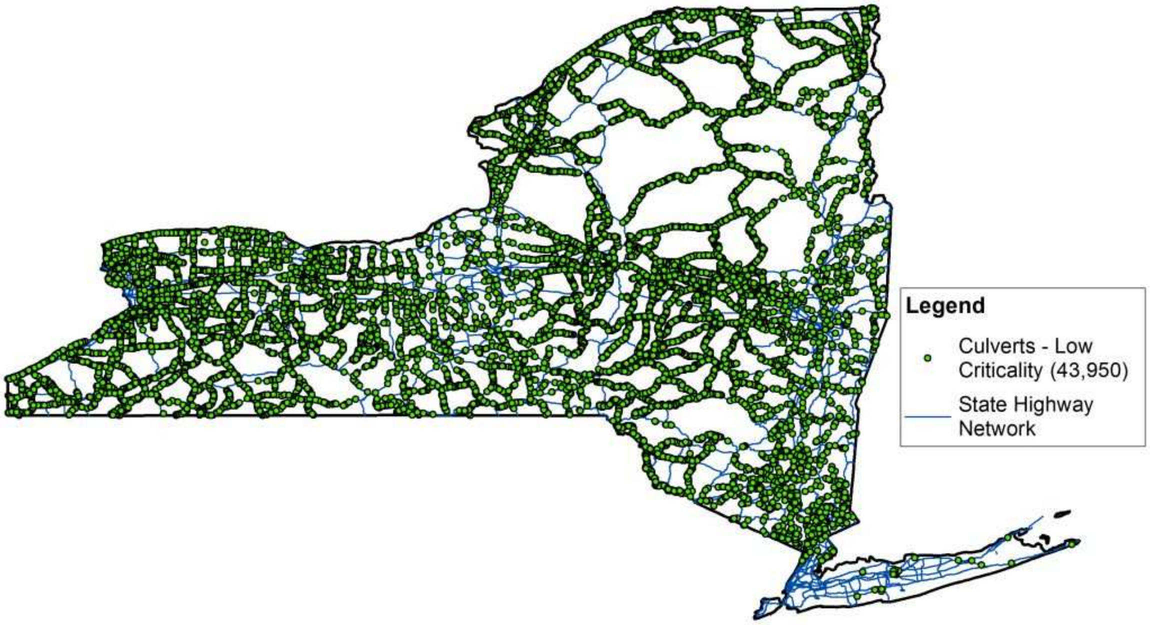


Figure I.4 New York Combined Criticality Index = 1 (Low)

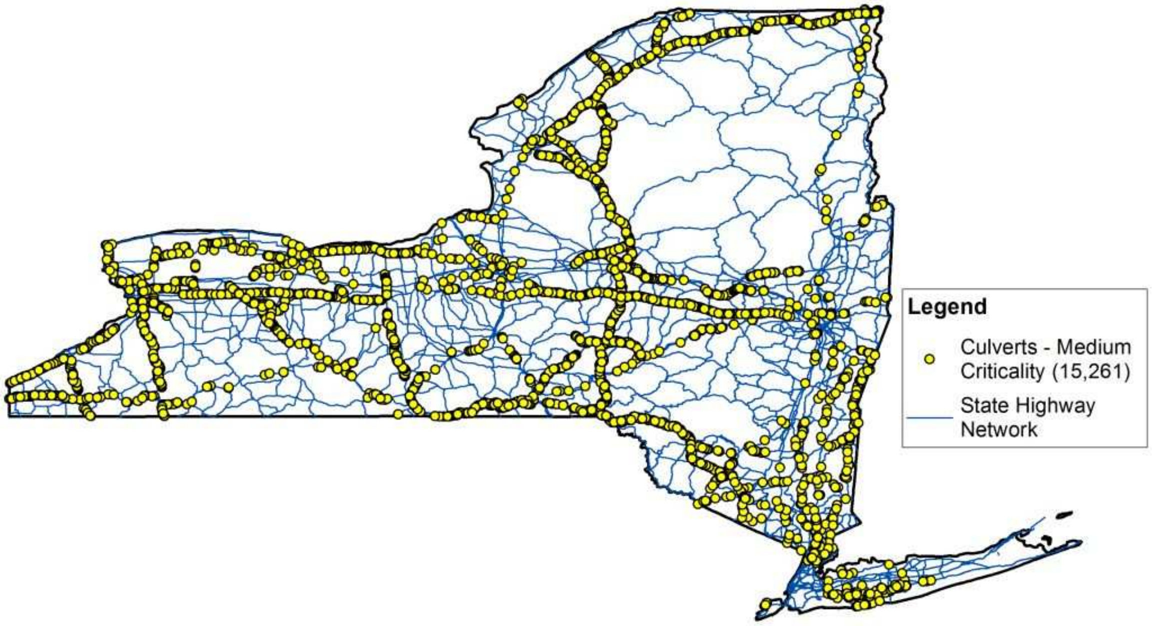


Figure I.5 New York Combined Criticality Index = 2 (Medium)

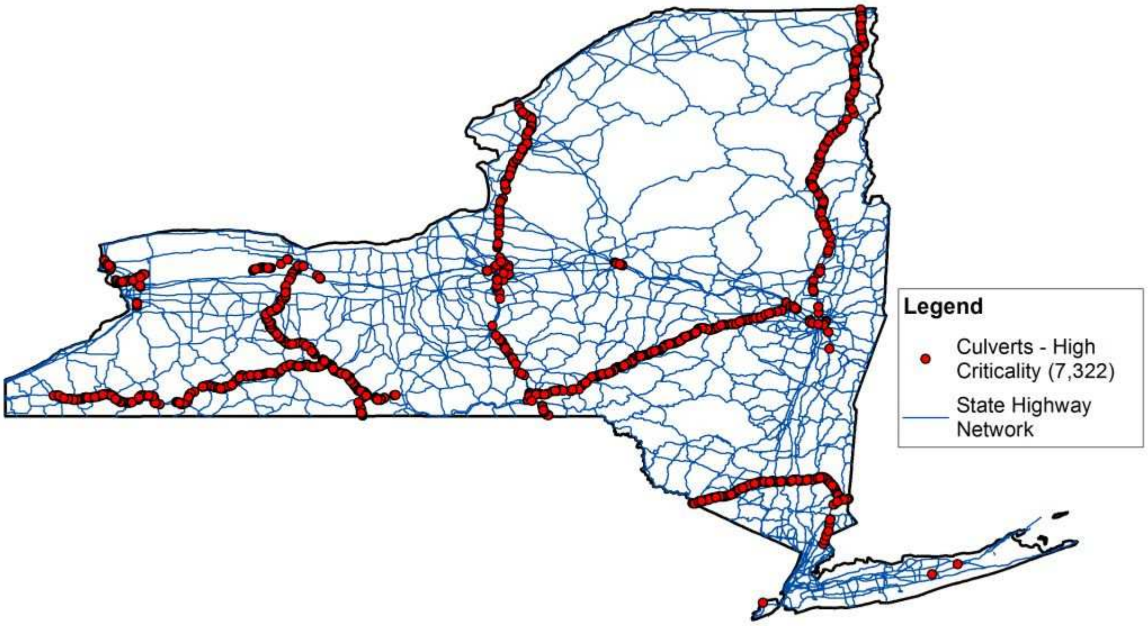


Figure I.6 New York Combined Criticality Index = 3 (High)

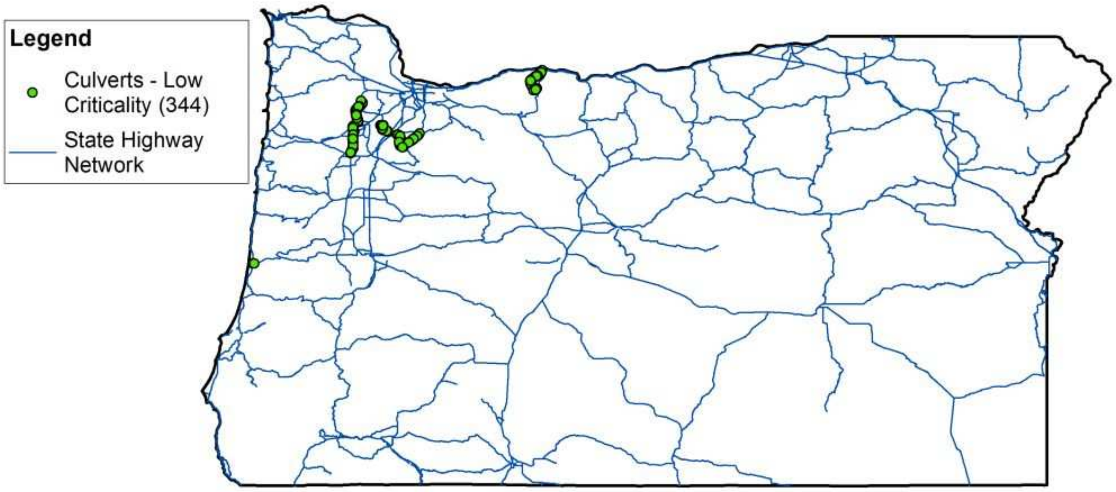


Figure I.7 Oregon Combined Criticality Index = 1 (Low)

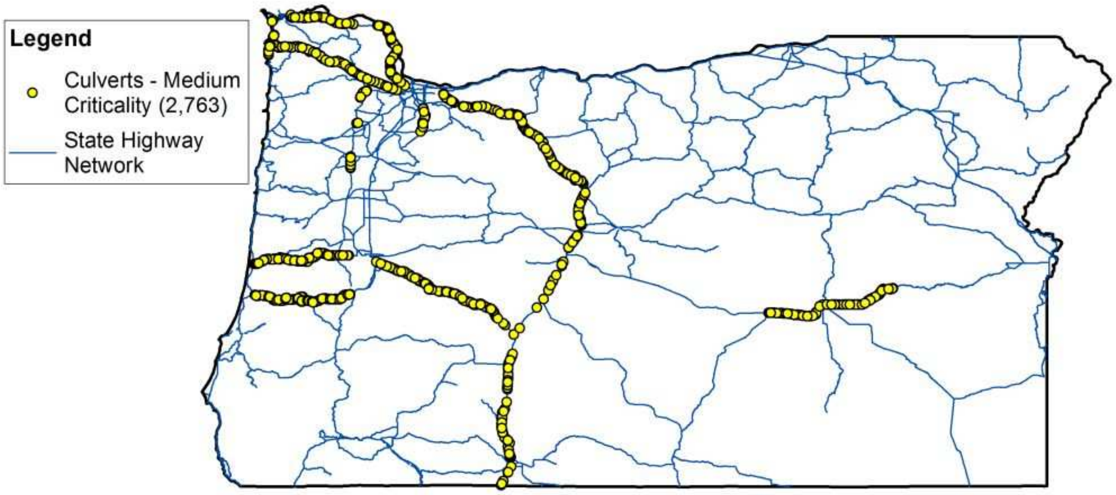


Figure I.8 Oregon Combined Criticality Index = 2 (Medium)

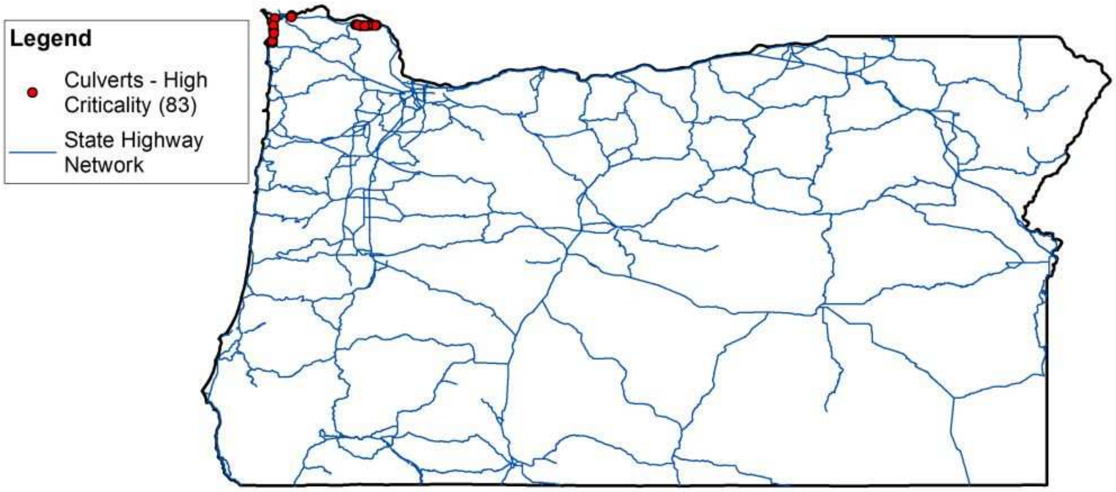


Figure I.9 Oregon Combined Criticality Index = 3 (High)

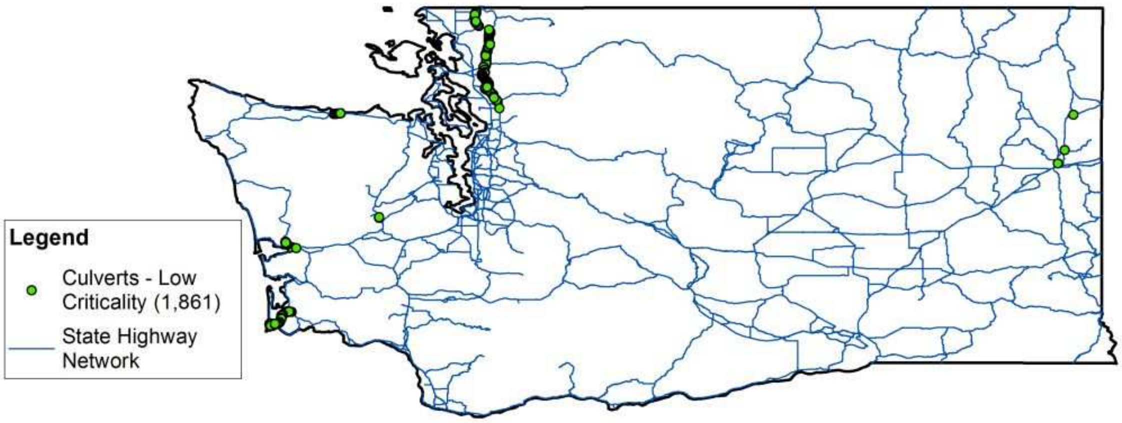


Figure I.10 Washington Combined Criticality Index = 1 (Low)

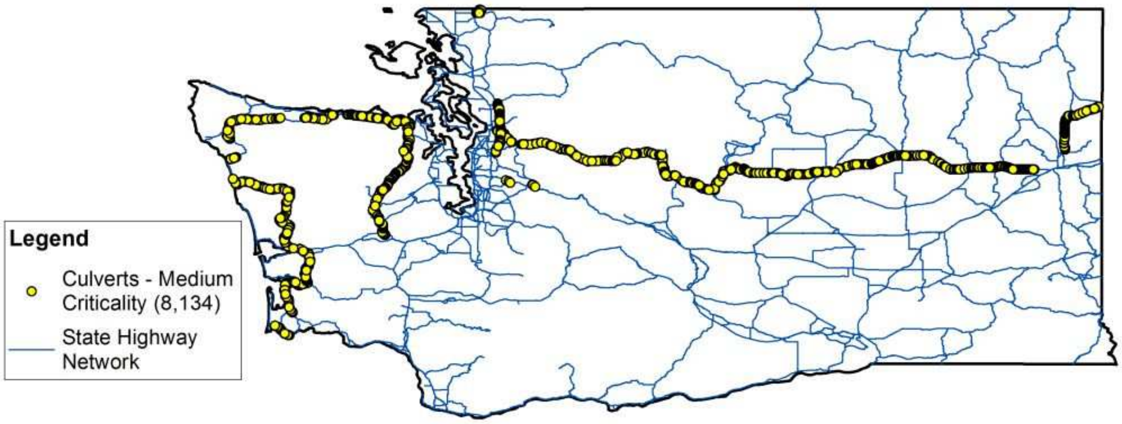


Figure I.11 Washington Combined Criticality Index = 2 (Medium)

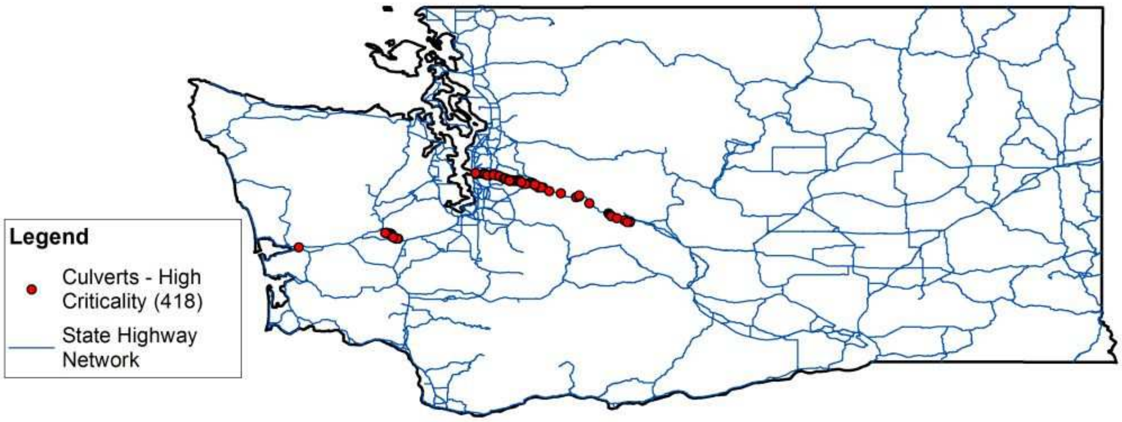


Figure I.12 Washington Combined Criticality Index = 3 (High)

APPENDIX J: CULVERT ASSET PRIORITIZATOIN MAP RESULTS (R-CAP)

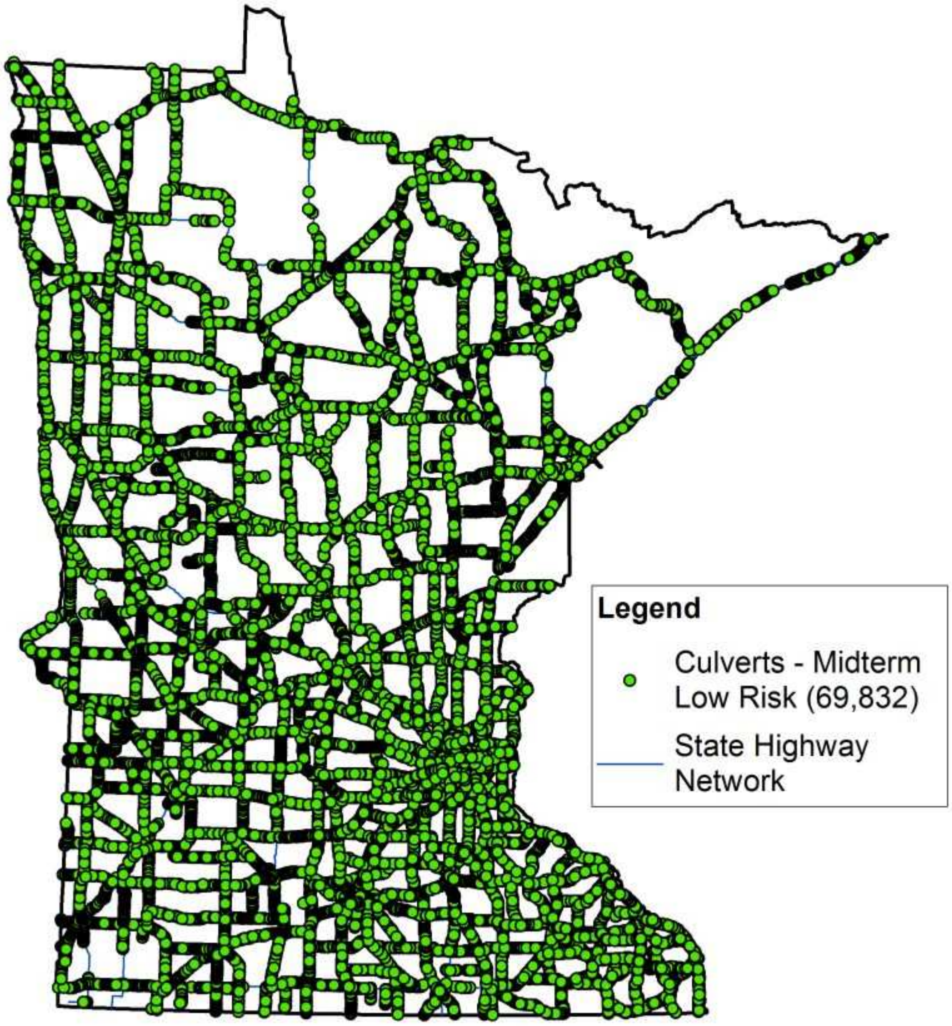


Figure J.1 Minnesota R-CAP Index (Method 1) = 1 (Low Risk), Mid-Century

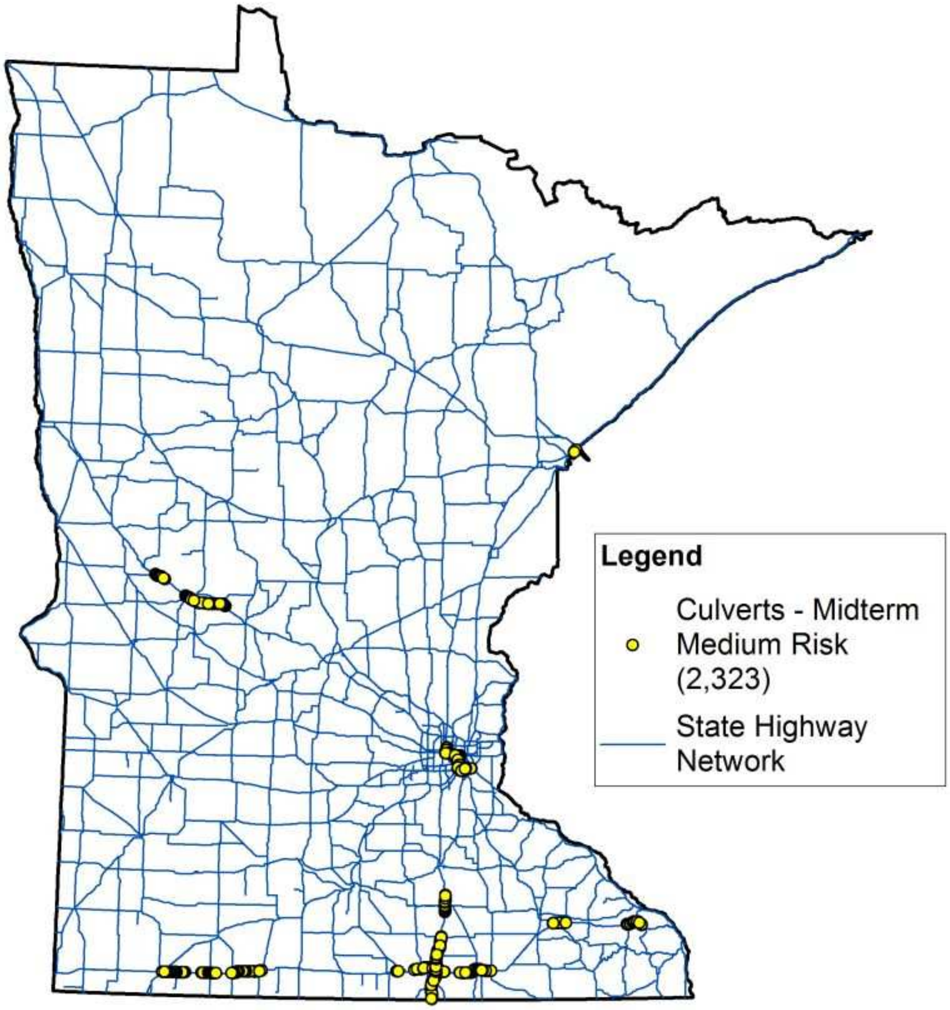


Figure J.2 Minnesota R-CAP Index (Method 1) = 2 (Medium Risk), Mid-Century

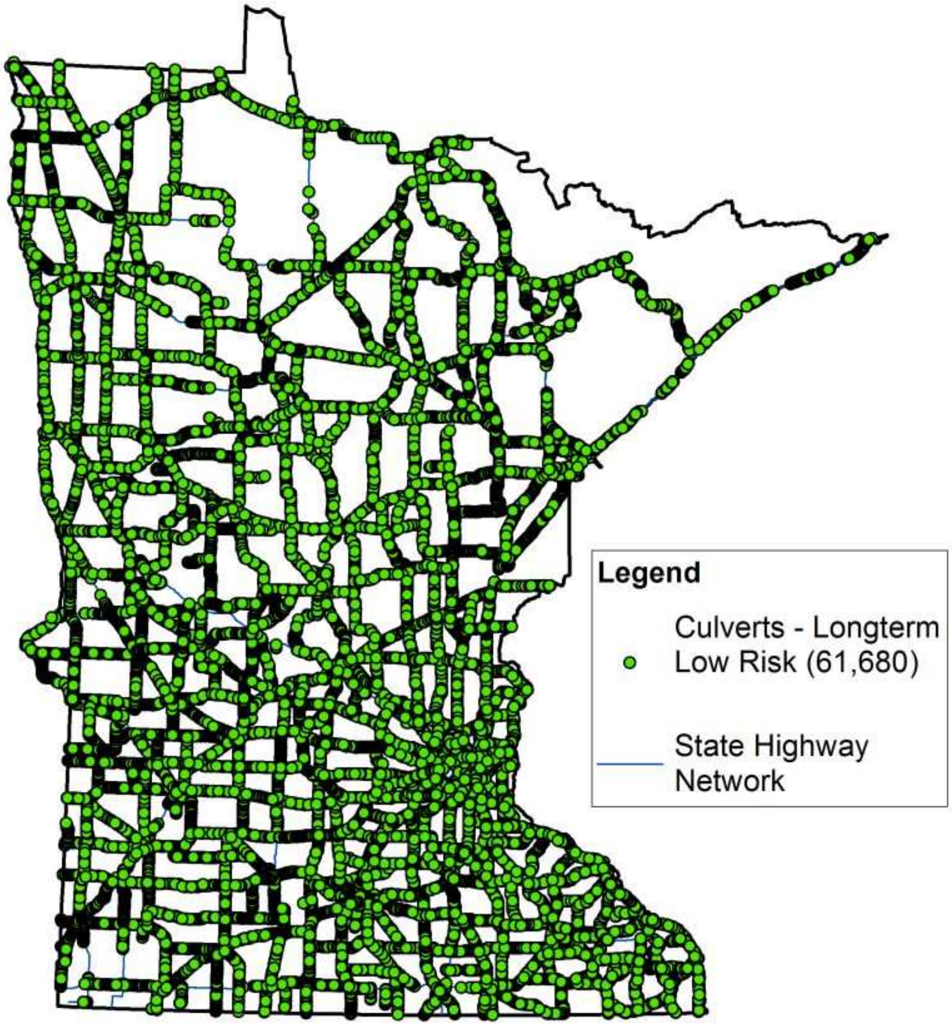


Figure J.3 Minnesota R-CAP Index (Method 1) = 1 (Low Risk), End-Of-Century

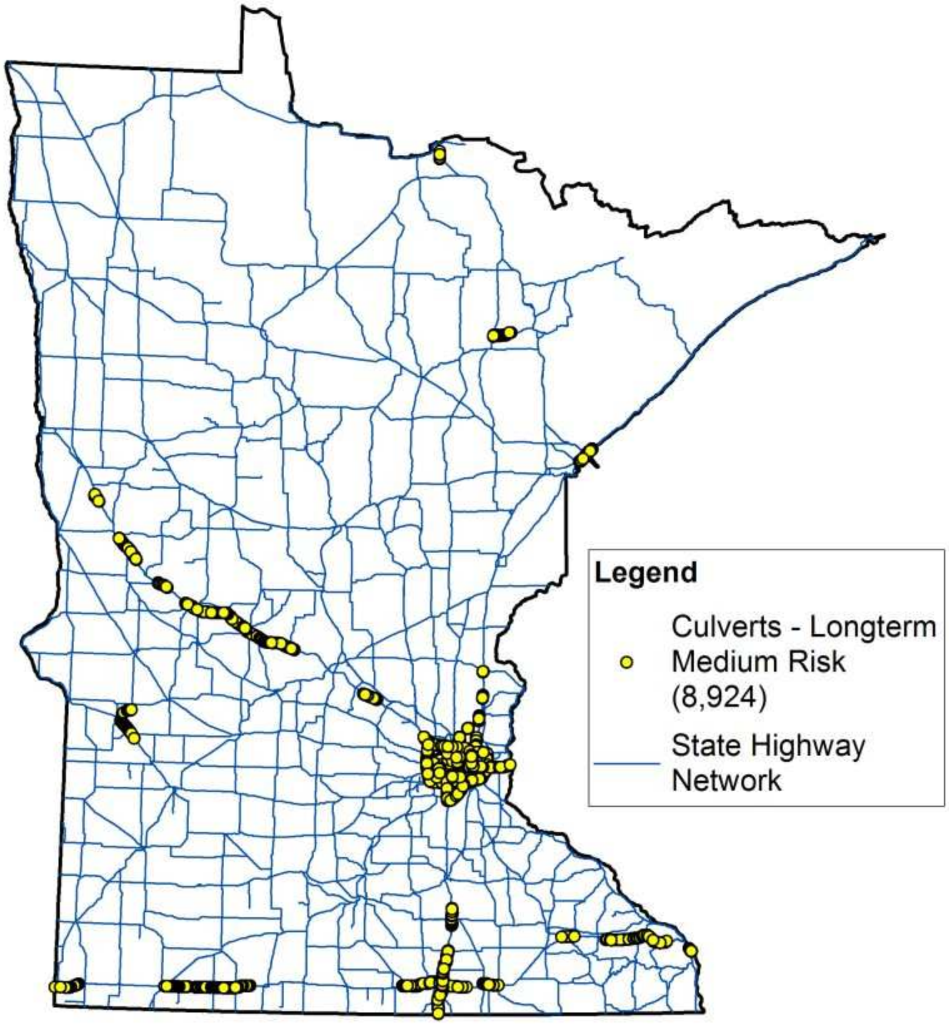


Figure J.4 Minnesota R-CAP Index (Method 1) = 2 (Medium Risk), End-Of-Century

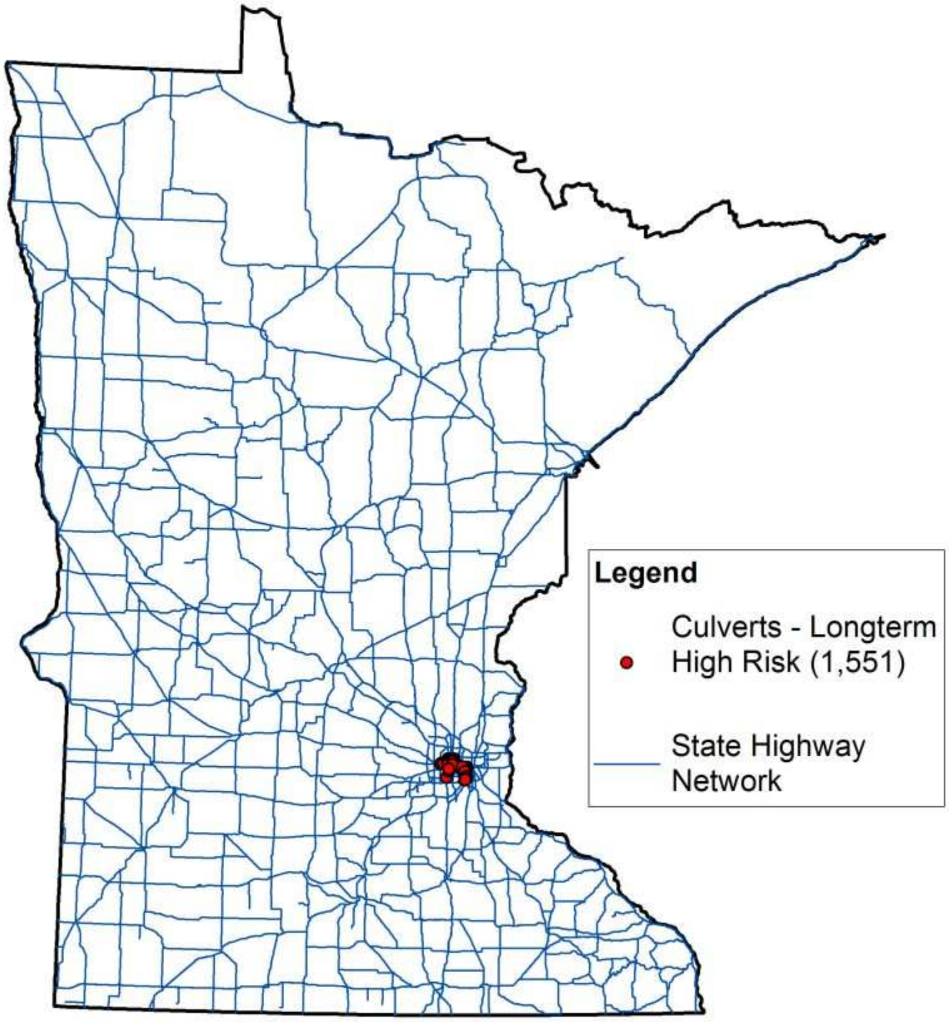


Figure J.5 Minnesota R-CAP Index (Method 1) = 3 (High Risk), End-Of-Century

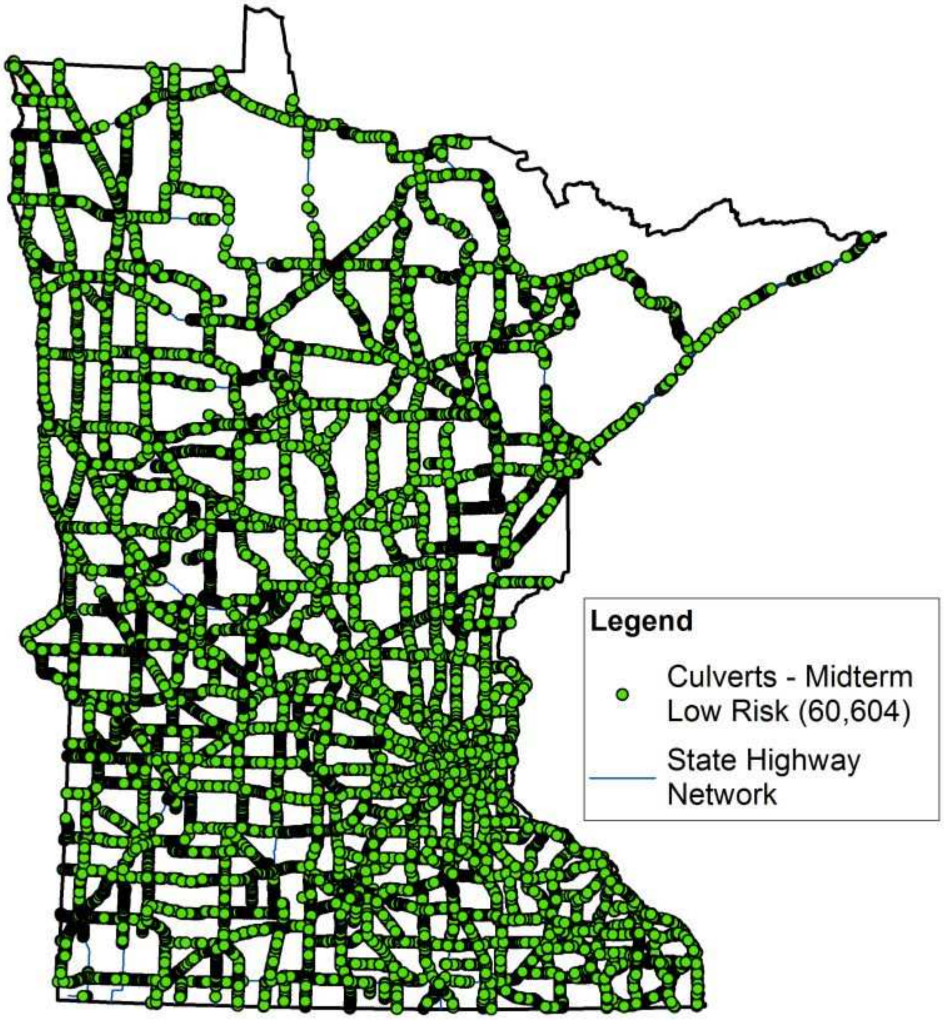


Figure J.6 Minnesota R-CAP Index (Method 2) = 1 (Low Risk), Mid-Century

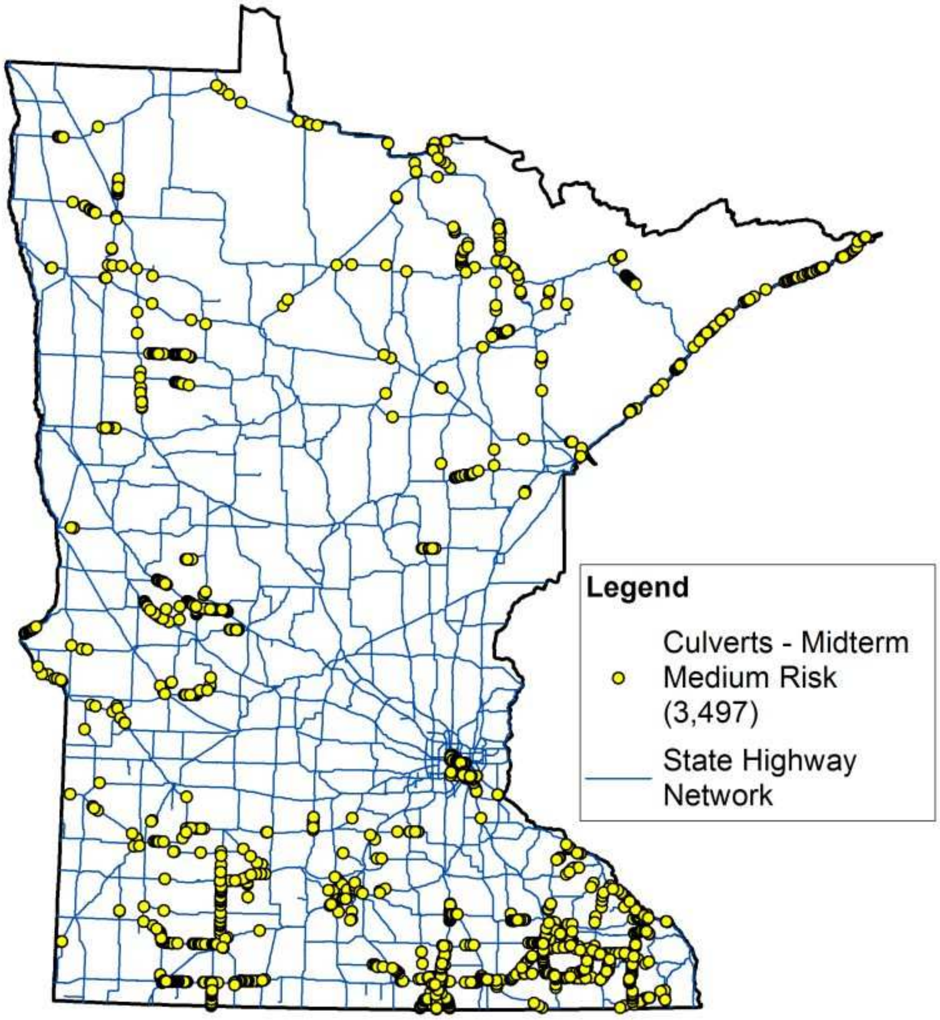


Figure J.7 Minnesota R-CAP Index (Method 2) = 2 (Medium Risk), Mid-Century

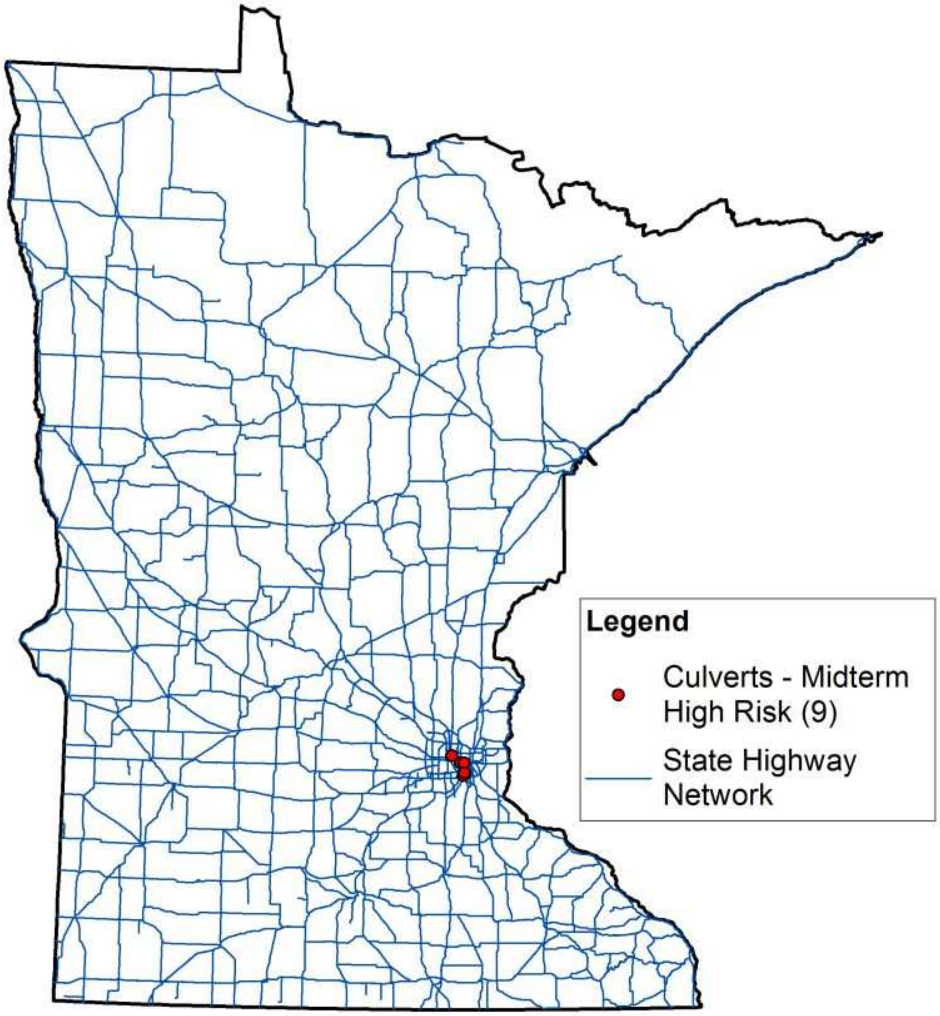


Figure J.8 Minnesota R-CAP Index (Method 2) = 3 (High Risk), Mid-Century

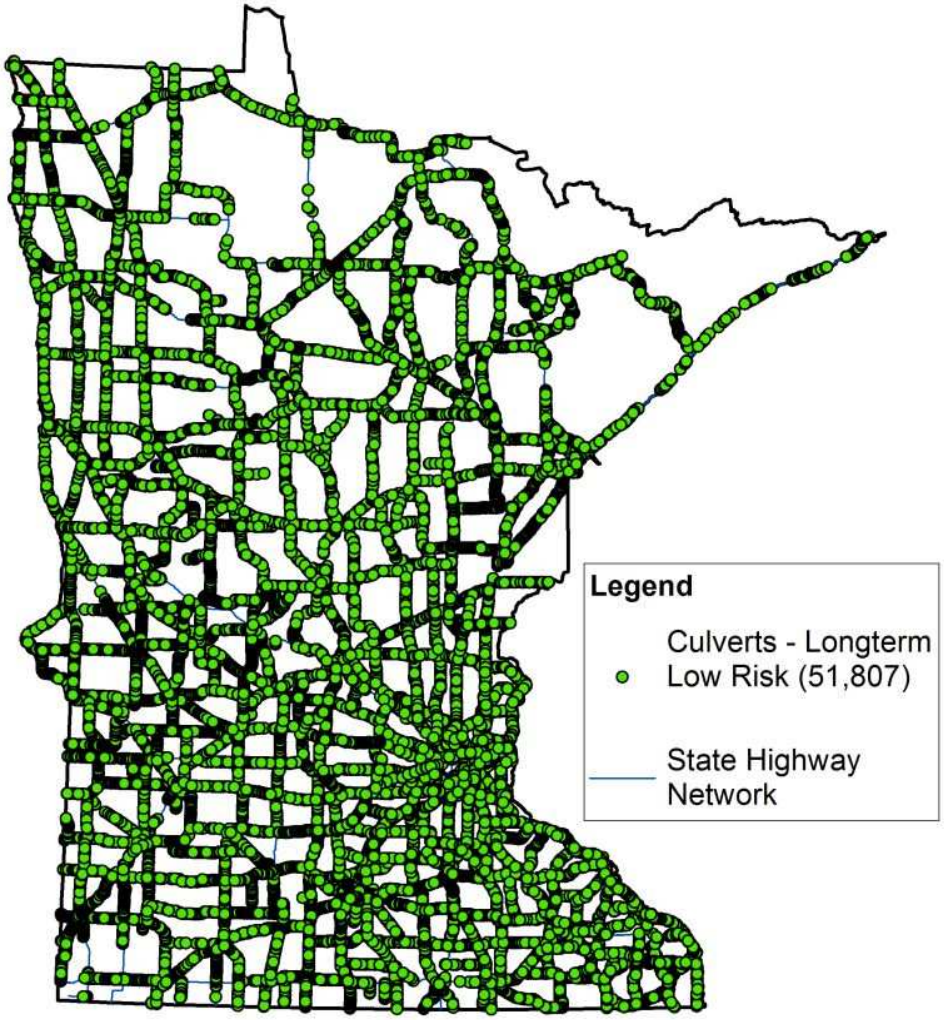


Figure J.9 Minnesota R-CAP Index (Method 2) = 1 (Low Risk), End-Of-Century

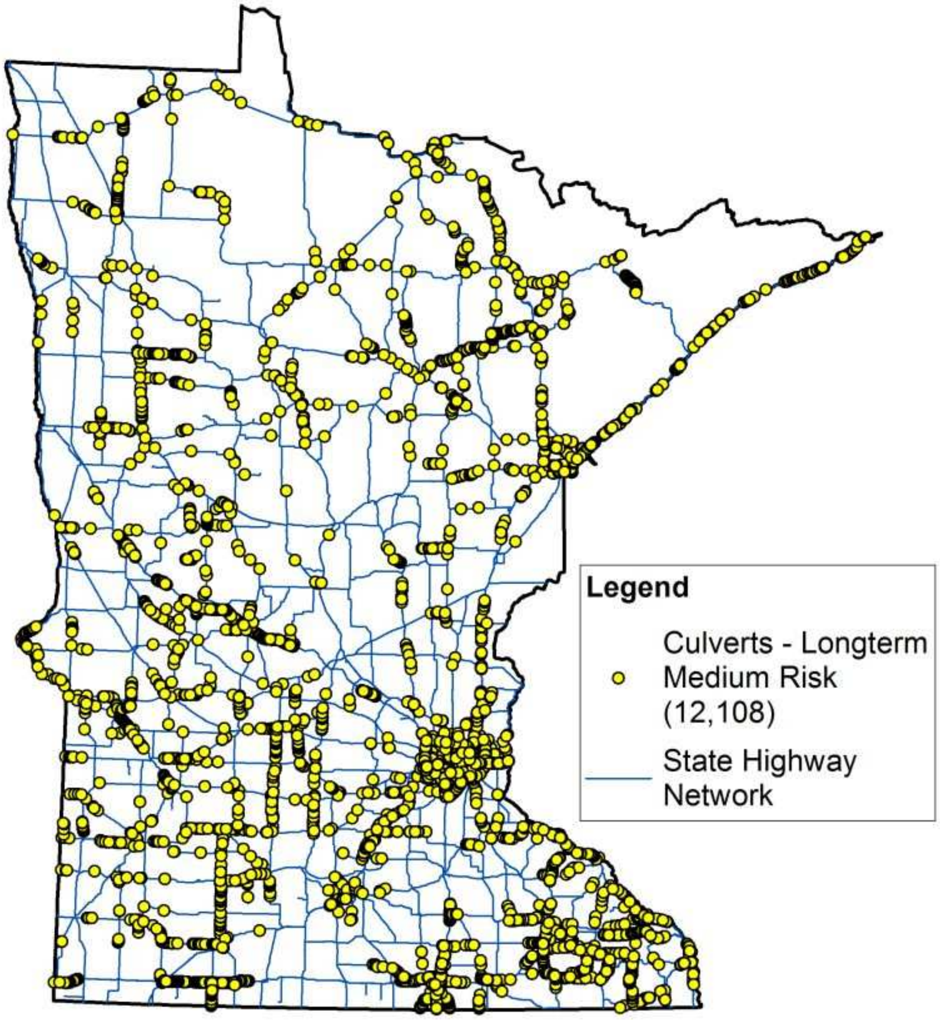


Figure J.10 Minnesota R-CAP Index (Method 2) = 2 (Medium Risk), End-Of-Century

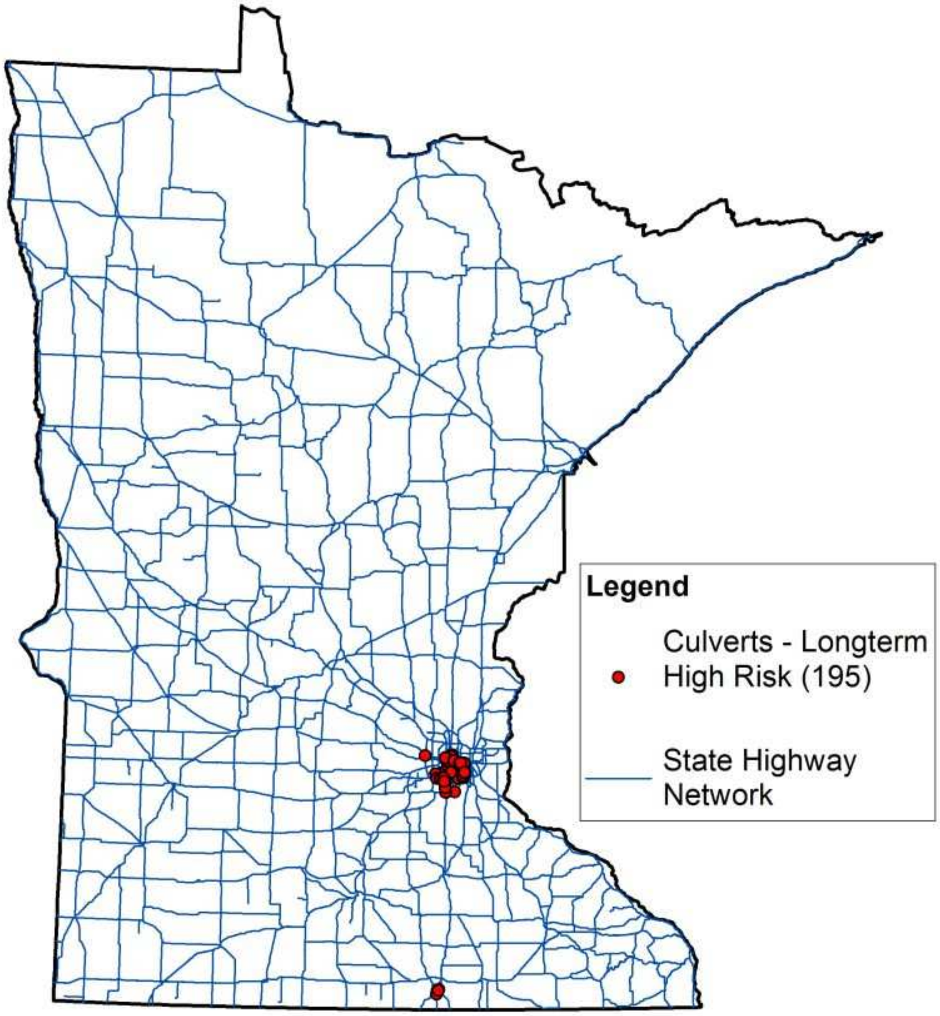


Figure J.11 Minnesota R-CAP Index (Method 2) = 3 (High Risk), End-Of-Century

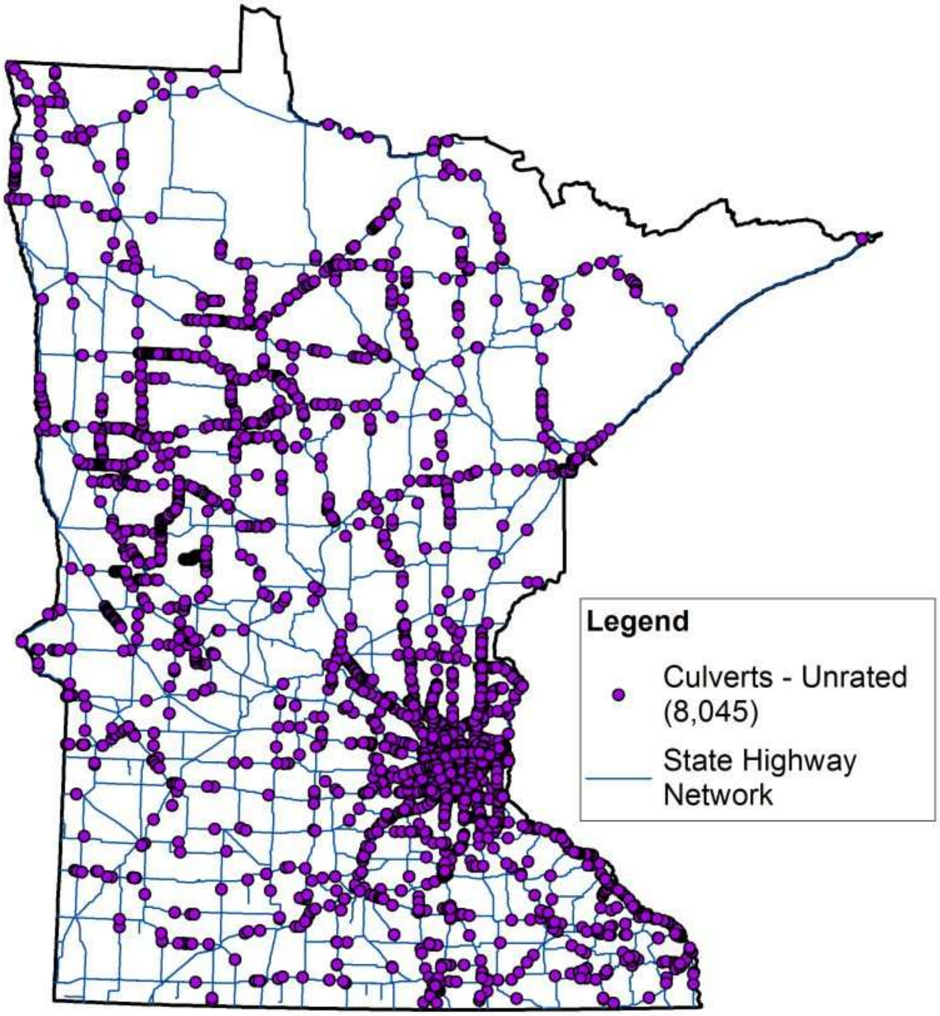


Figure J.12 Minnesota R-CAP Index (Method 2), Overall Condition Unrated

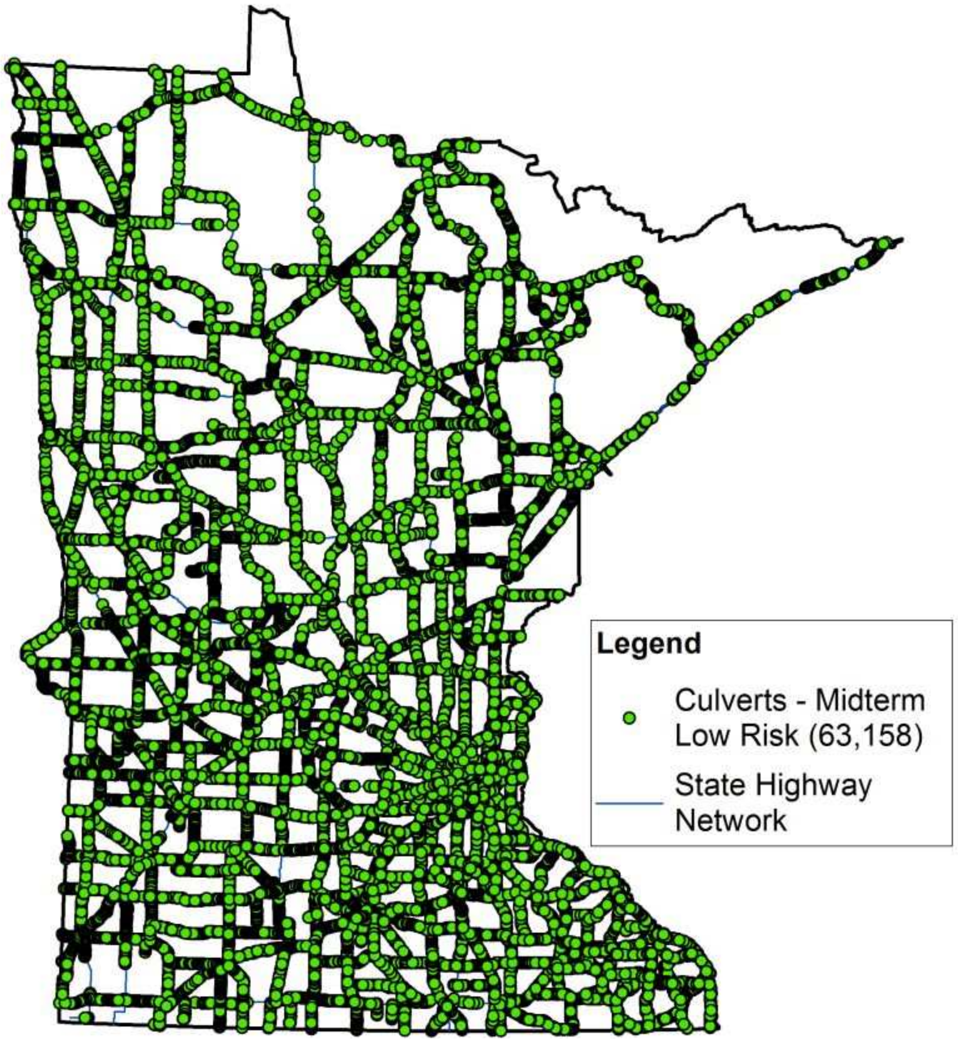


Figure J.13 Minnesota R-CAP Index (Method 3) = 1 (Low Risk), Mid-Century

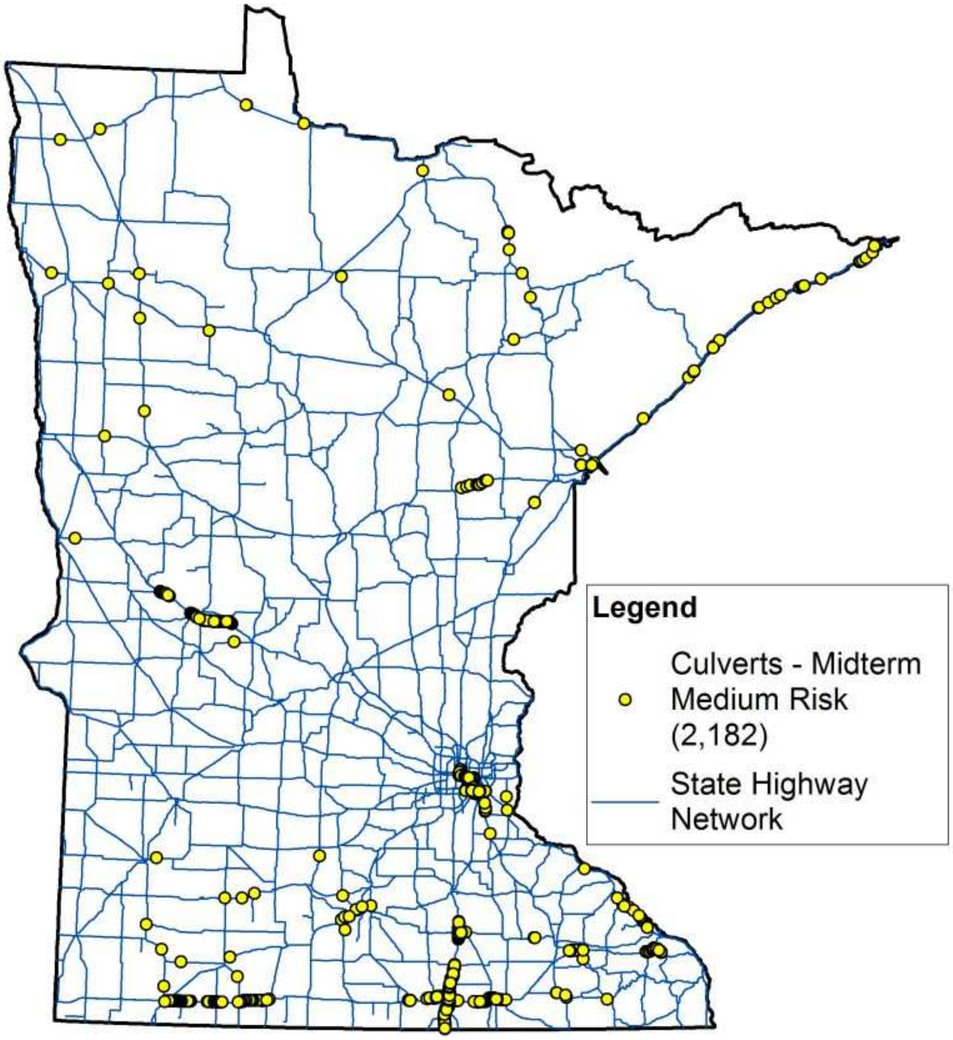


Figure J.14 Minnesota R-CAP Index (Method 3) = 2 (Medium Risk), Mid-Century

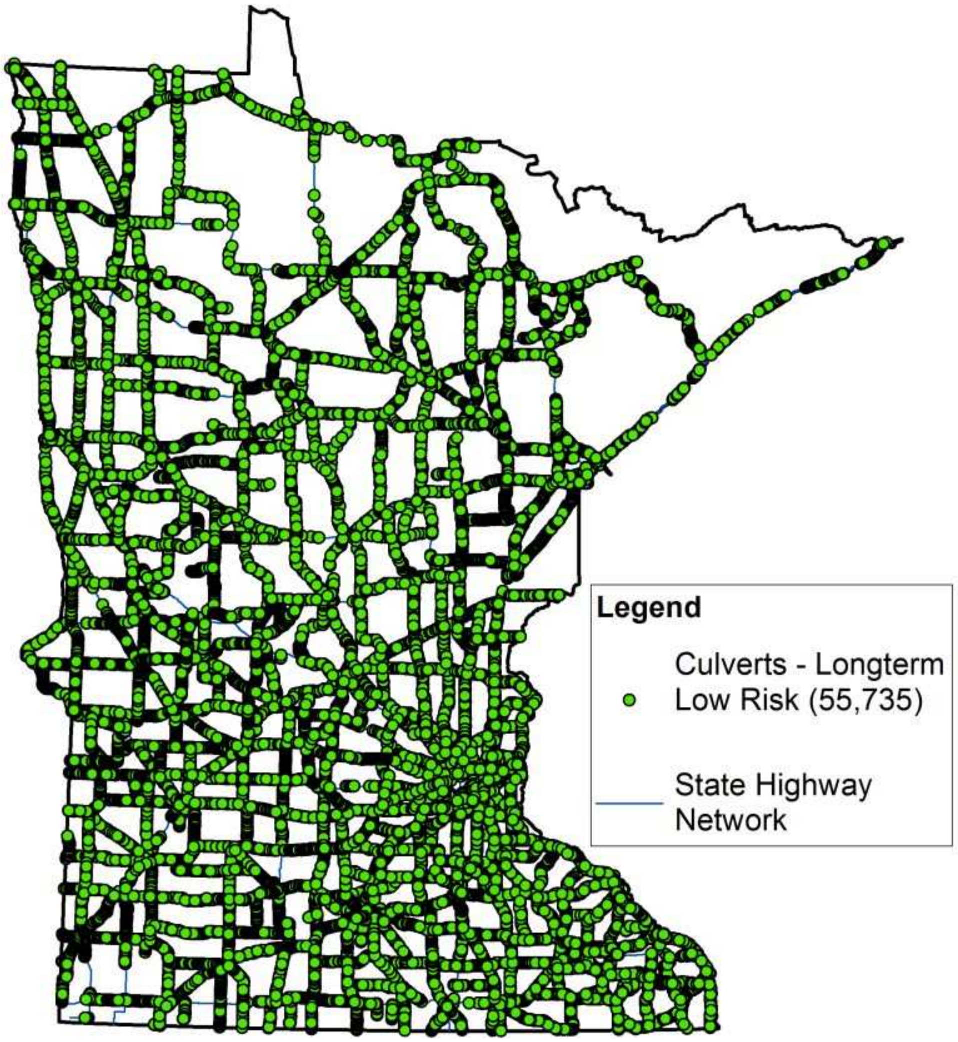


Figure J.15 Minnesota R-CAP Index (Method 3) = 1 (Low Risk), End-Of-Century

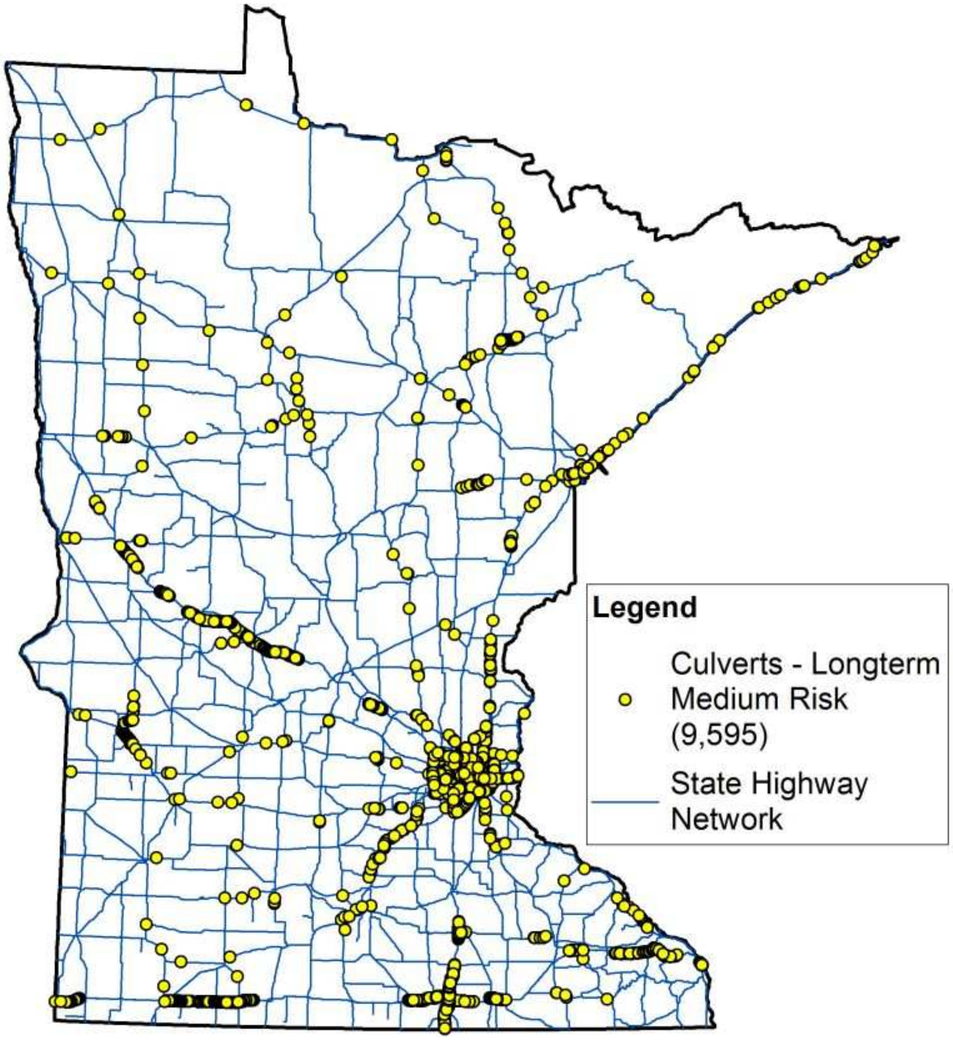


Figure J.16 Minnesota R-CAP Index (Method 3) = 2 (Medium Risk), End-Of-Century

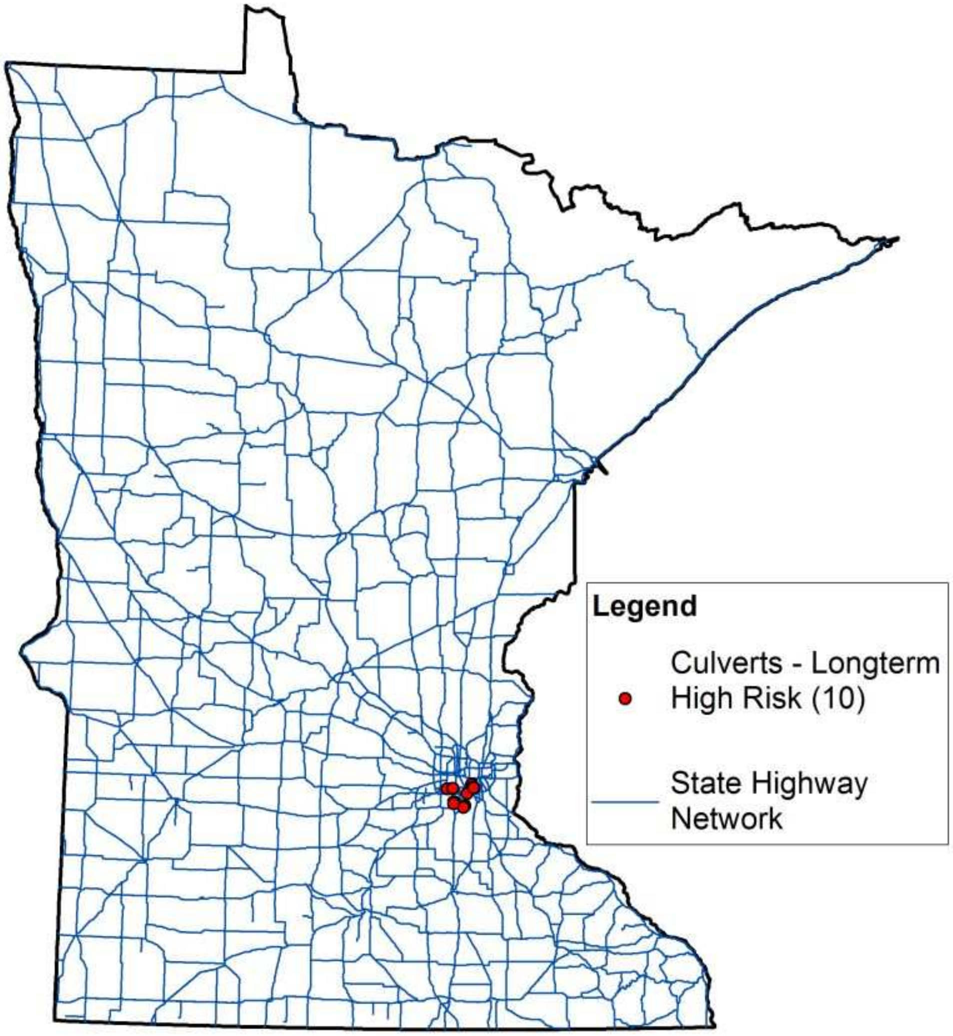


Figure J.17 Minnesota R-CAP Index (Method 3) = 3 (High Risk), End-Of-Century

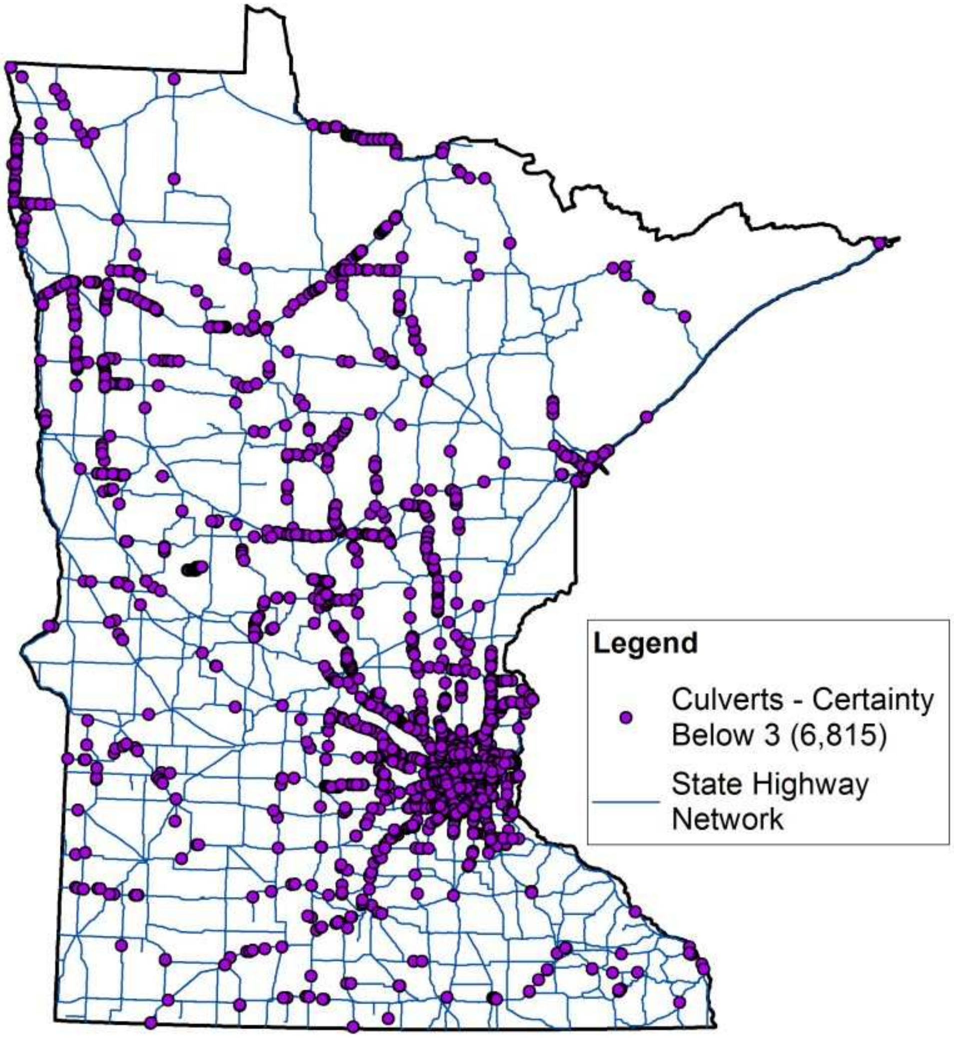


Figure J.18 Minnesota R-CAP Index (Method 3), Certainty Rating Below 3

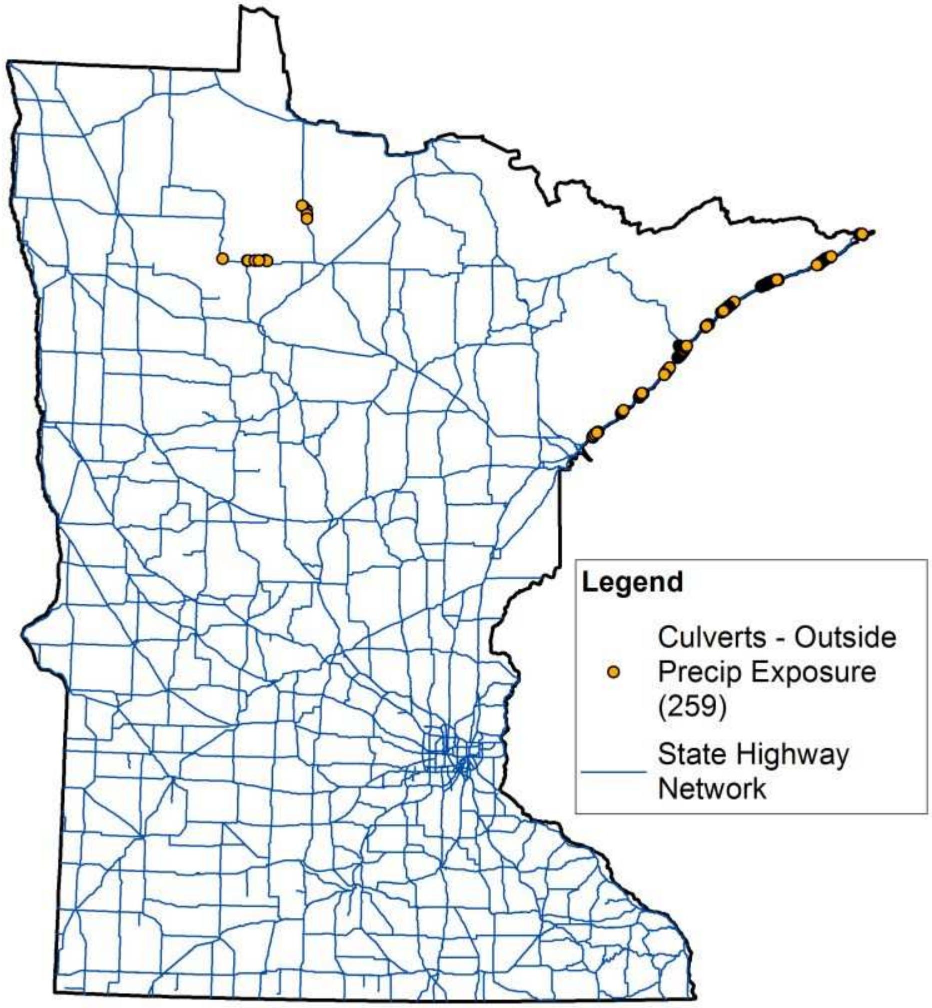


Figure J.19 Minnesota No R-CAP Index, Outside of Precipitation Exposure Area

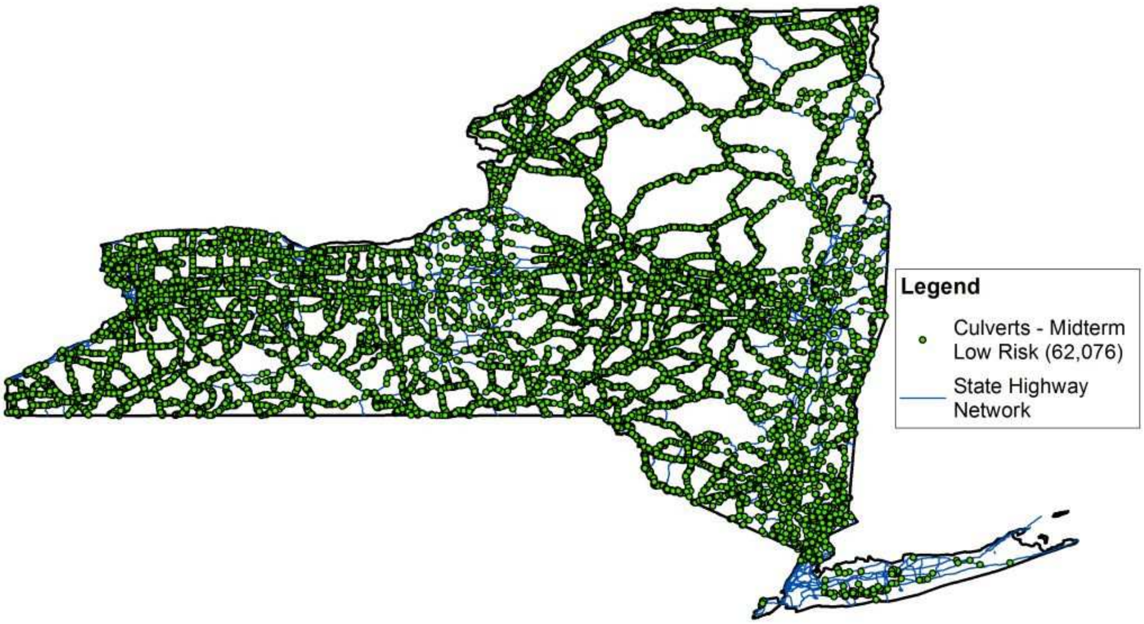


Figure J.20 New York R-CAP Index (Method 1) = 1 (Low Risk), Mid-Century

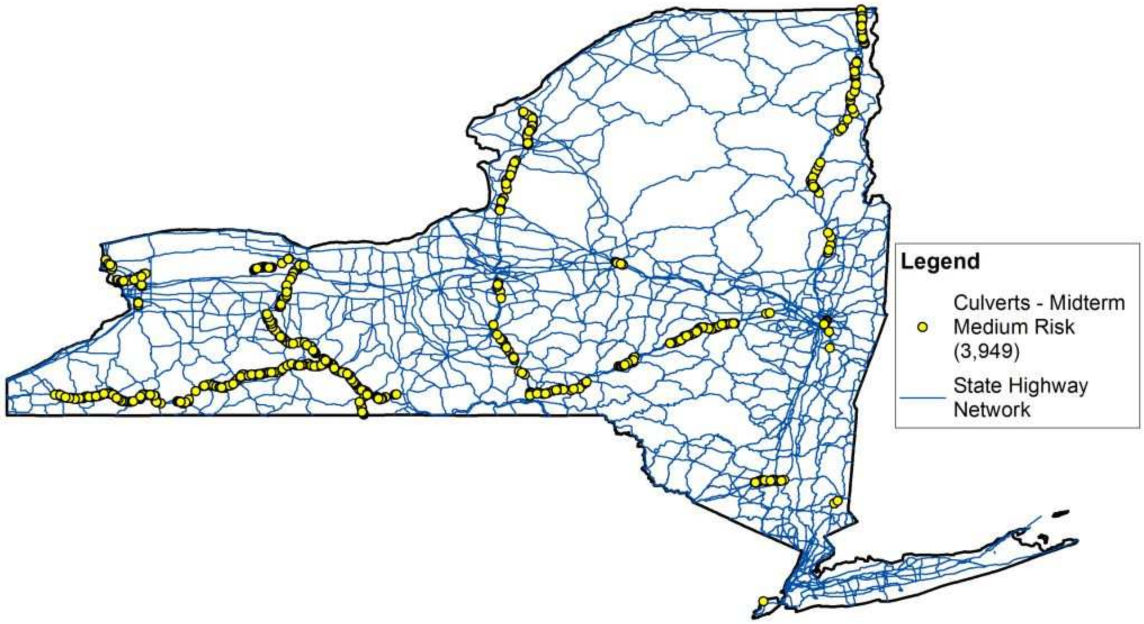


Figure J.21 New York R-CAP Index (Method 1) = 2 (Medium Risk), Mid-Century

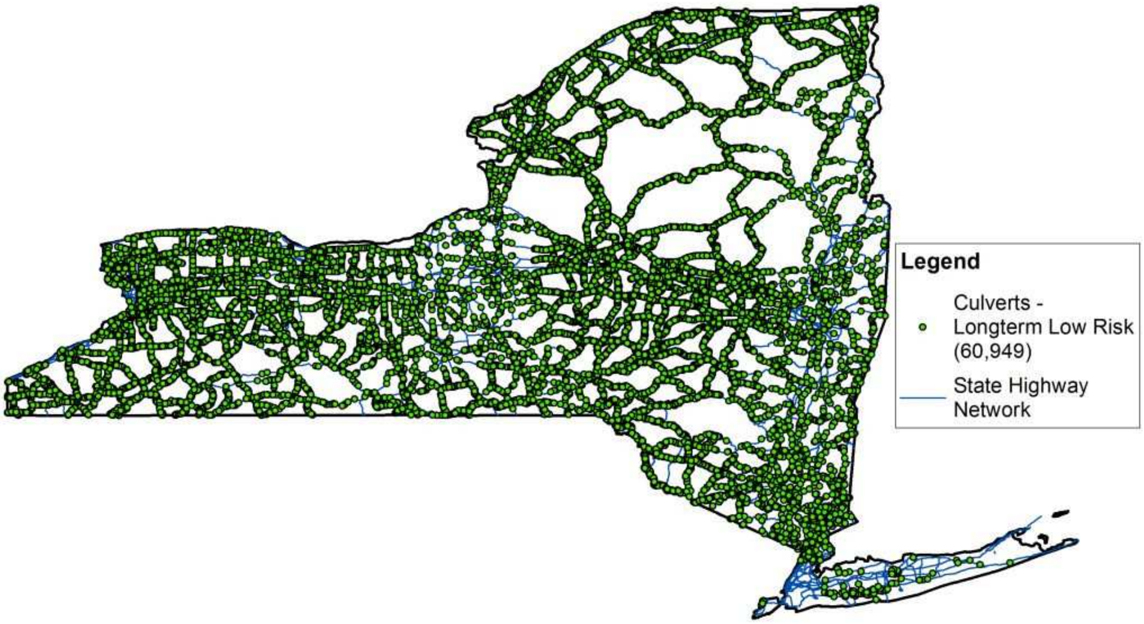


Figure J.22 New York R-CAP Index (Method 1) = 1 (Low Risk), End-Of-Century

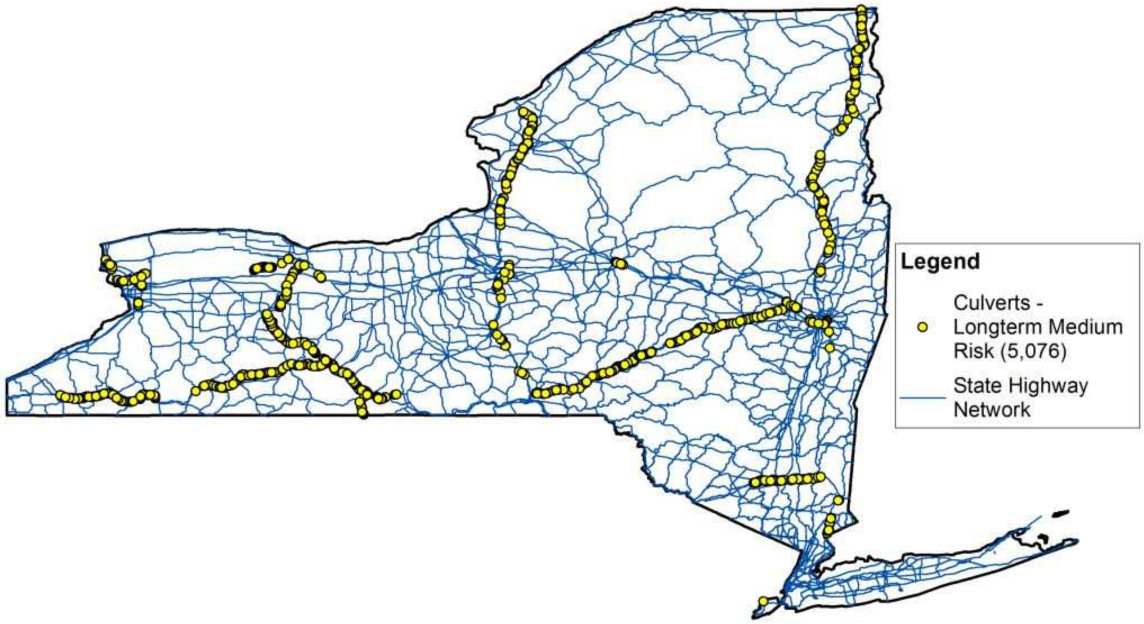


Figure J.23 New York R-CAP Index (Method 1) = 2 (Medium Risk), End-Of-Century

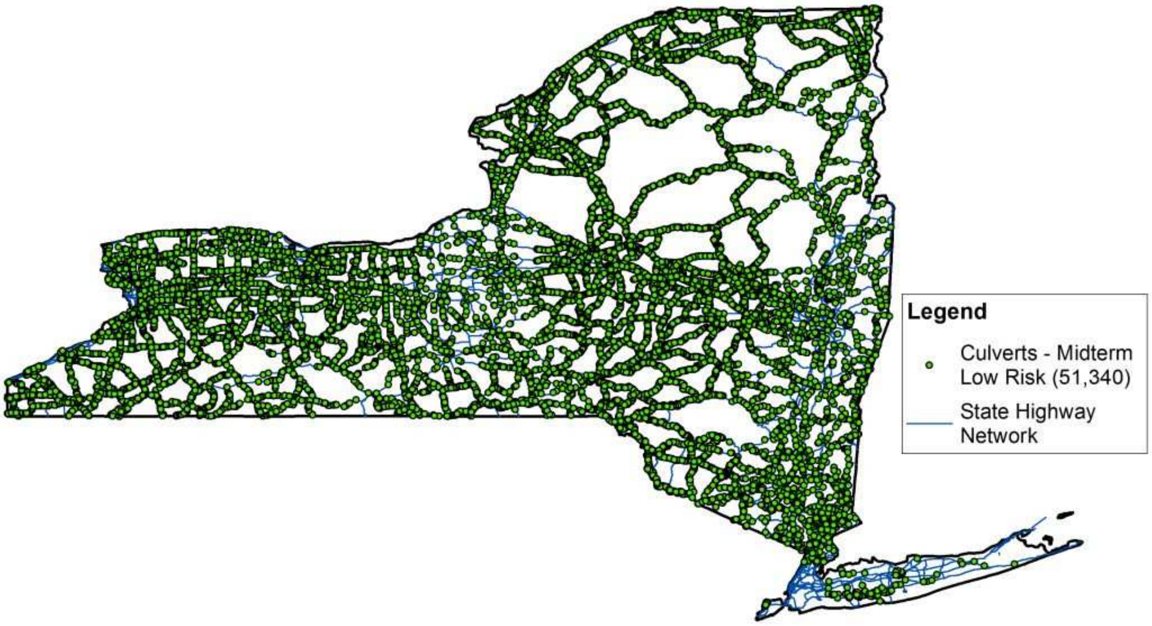


Figure J.24 New York R-CAP Index (Method 2) = 1 (Low Risk), Mid-Century

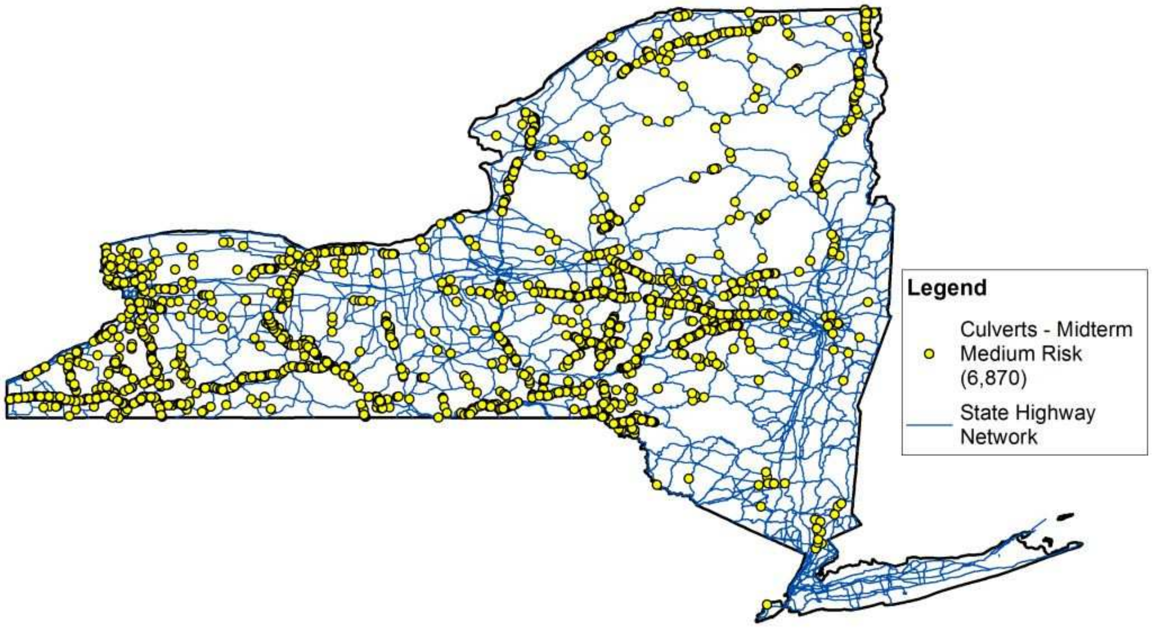


Figure J.25 New York R-CAP Index (Method 2) = 2 (Medium Risk), Mid-Century

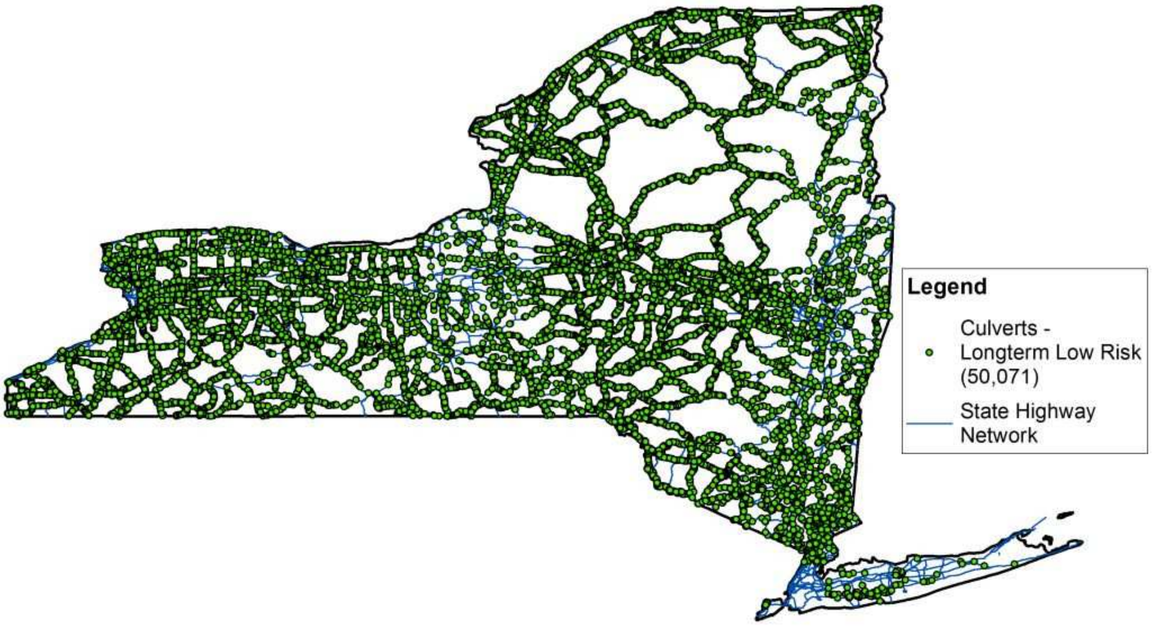


Figure J.26 New York R-CAP Index (Method 2) = 1 (Low Risk), End-Of-Century

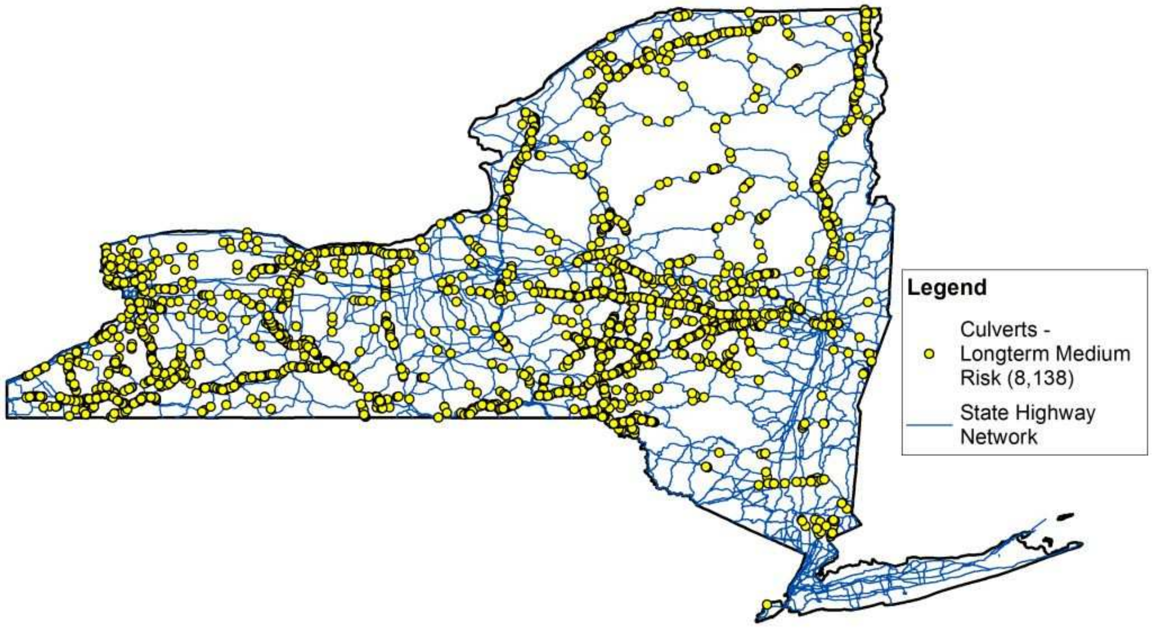


Figure J.27 New York R-CAP Index (Method 2) = 2 (Medium Risk), End-Of-Century

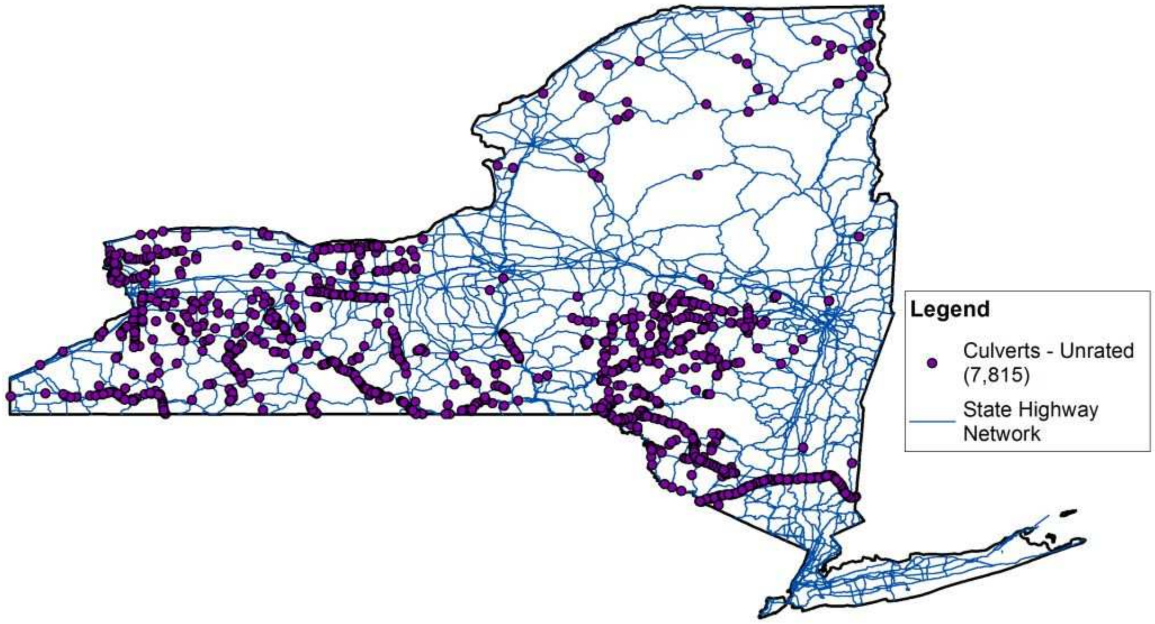


Figure J.28 New York R-CAP Index (Method 2), Overall Condition Unrated

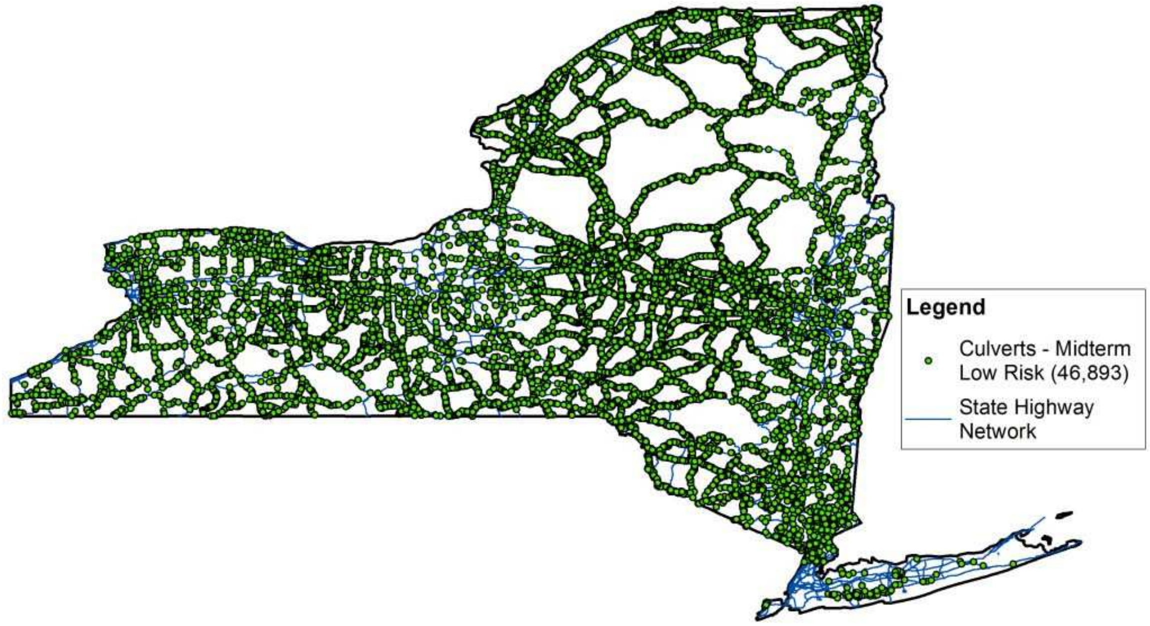


Figure J.29 New York R-CAP Index (Method 3) = 1 (Low Risk), Mid-Century

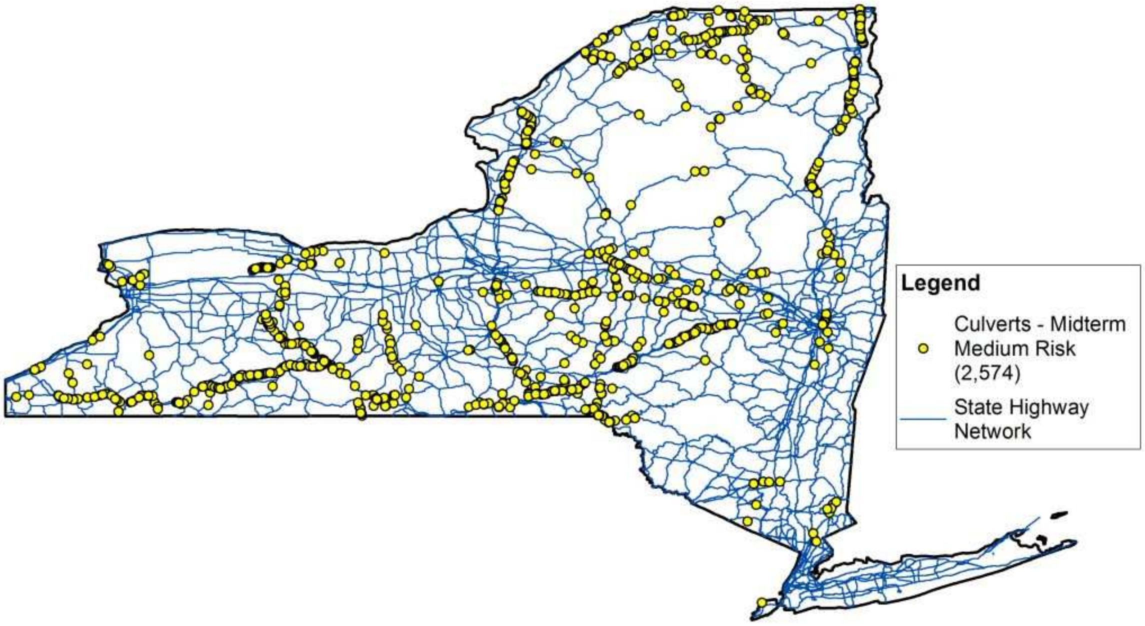


Figure J.30 New York R-CAP Index (Method 3) = 2 (Medium Risk), Mid-Century

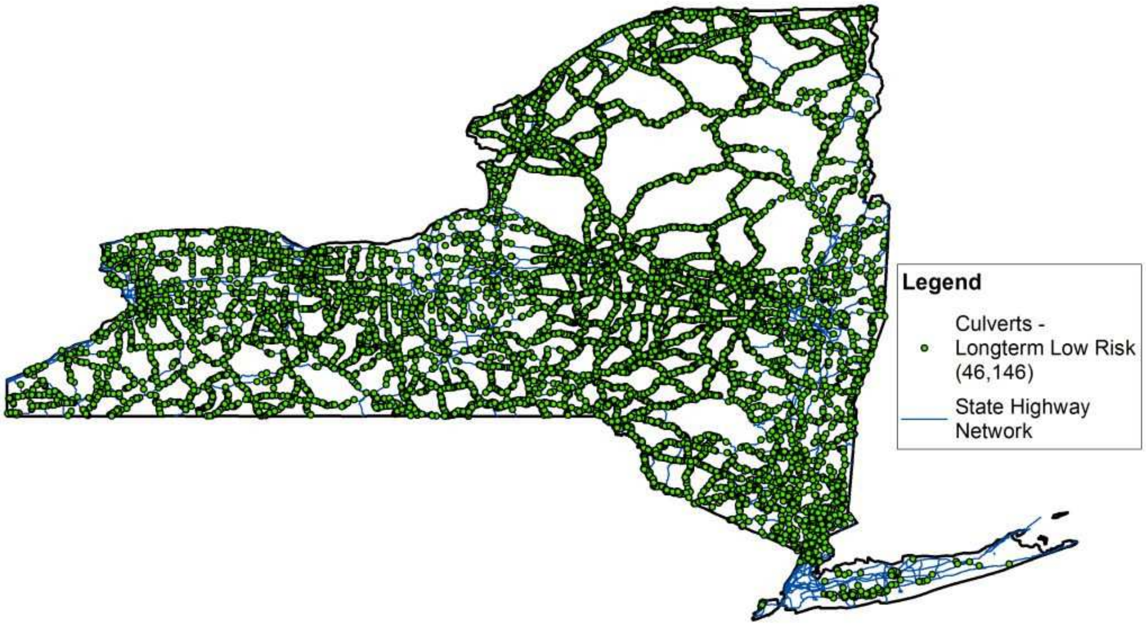


Figure J.31 New York R-CAP Index (Method 3) = 1 (Low Risk), End-Of-Century

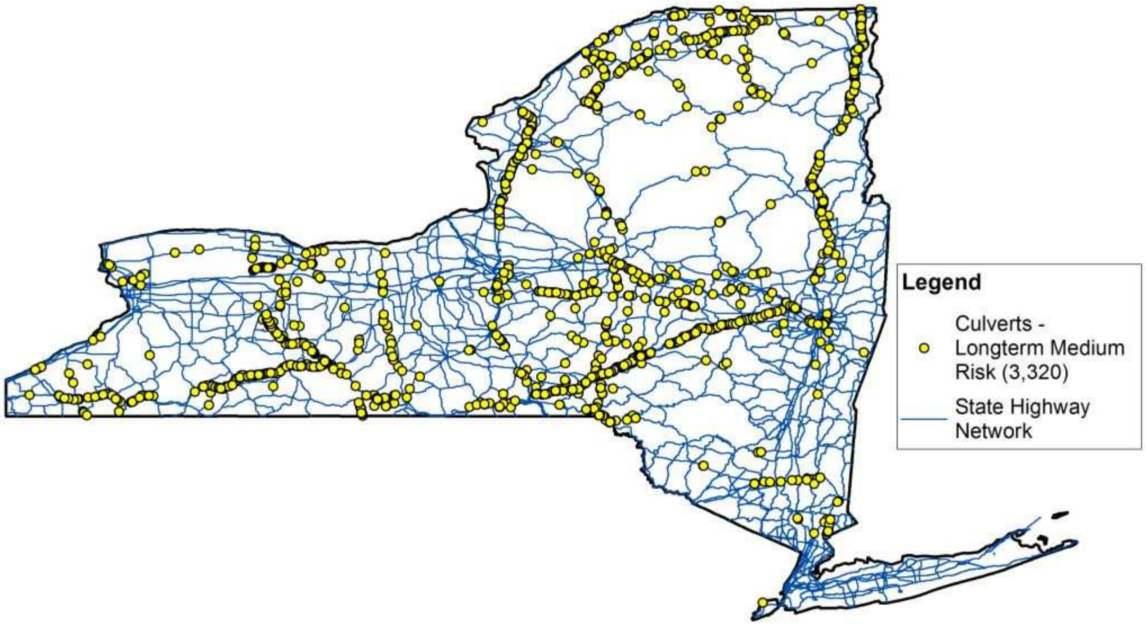


Figure J.32 New York R-CAP Index (Method 3) = 2 (Medium Risk), End-Of-Century

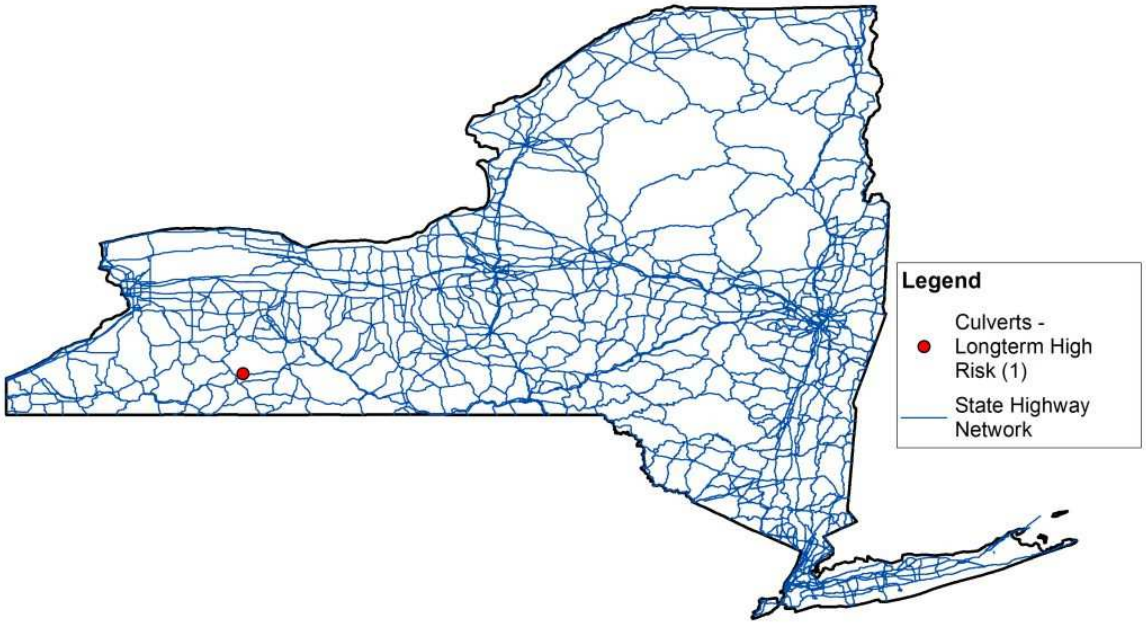


Figure J.33 New York R-CAP Index (Method 3) = 3 (High Risk), End-Of-Century

Figure J.34 New York R-CAP Index (Method 3), Certainty Rating Below 2

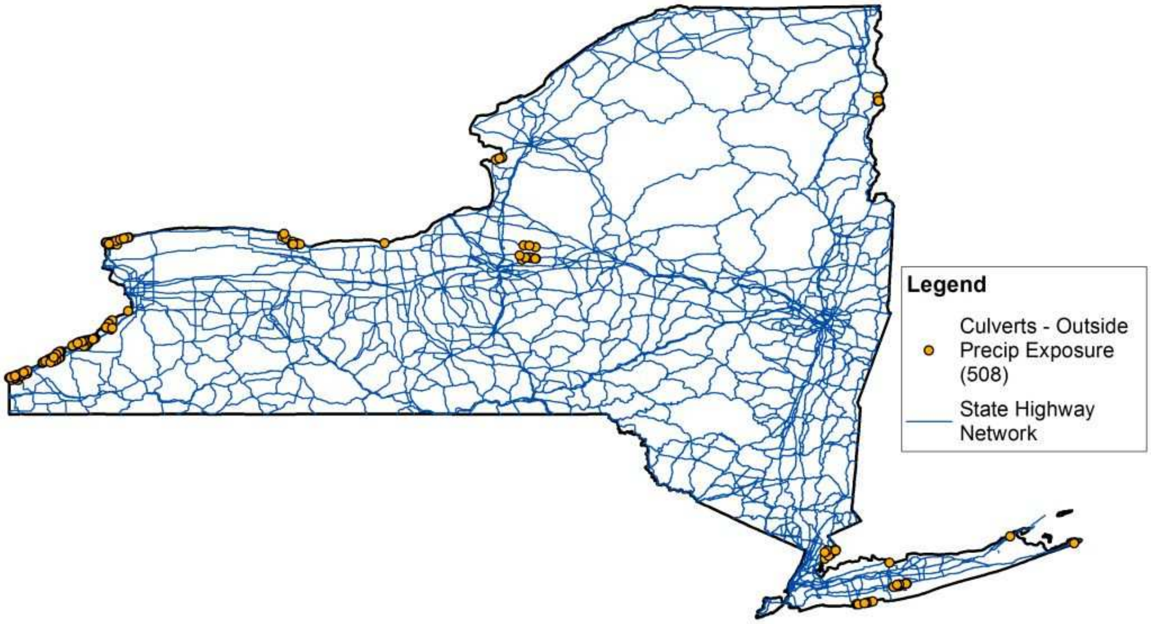


Figure J.35 New York No R-CAP Index, Outside of Precipitation Exposure Area

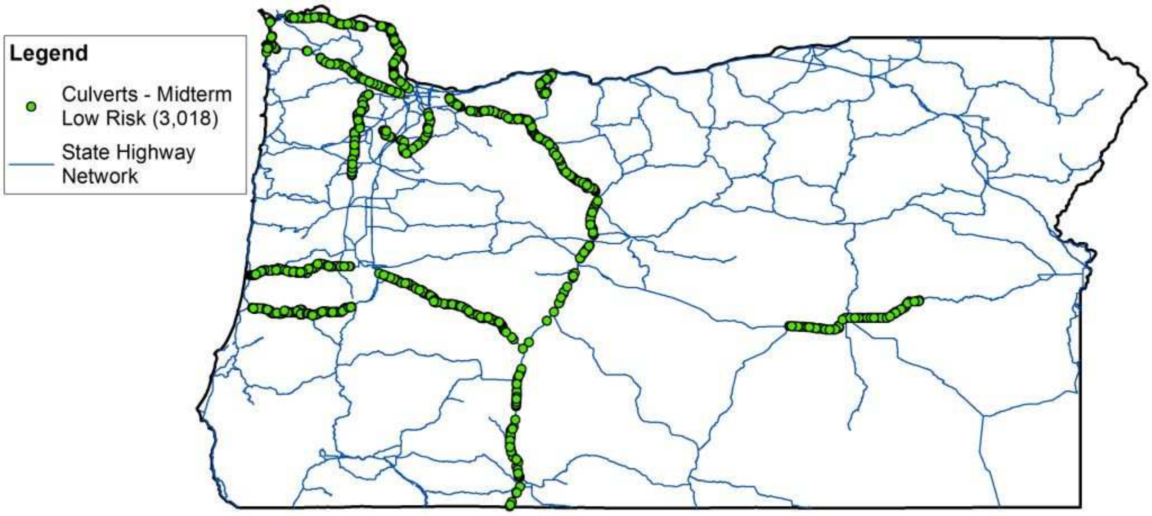


Figure J.36 Oregon R-CAP Index (Method 1) = 1 (Low Risk), Mid-Century

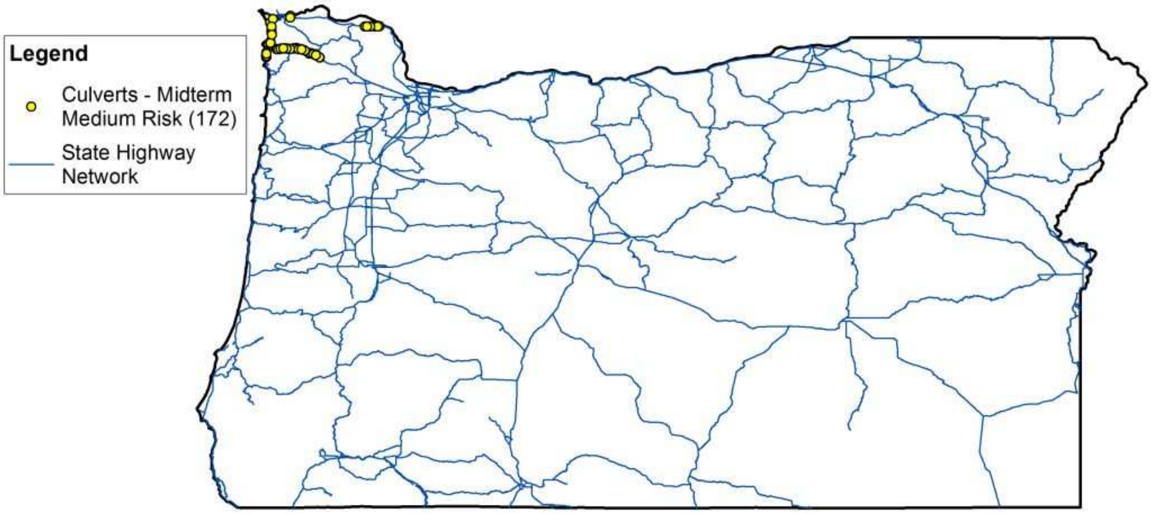


Figure J.37 Oregon R-CAP Index (Method 1) = 2 (Medium Risk), Mid-Century

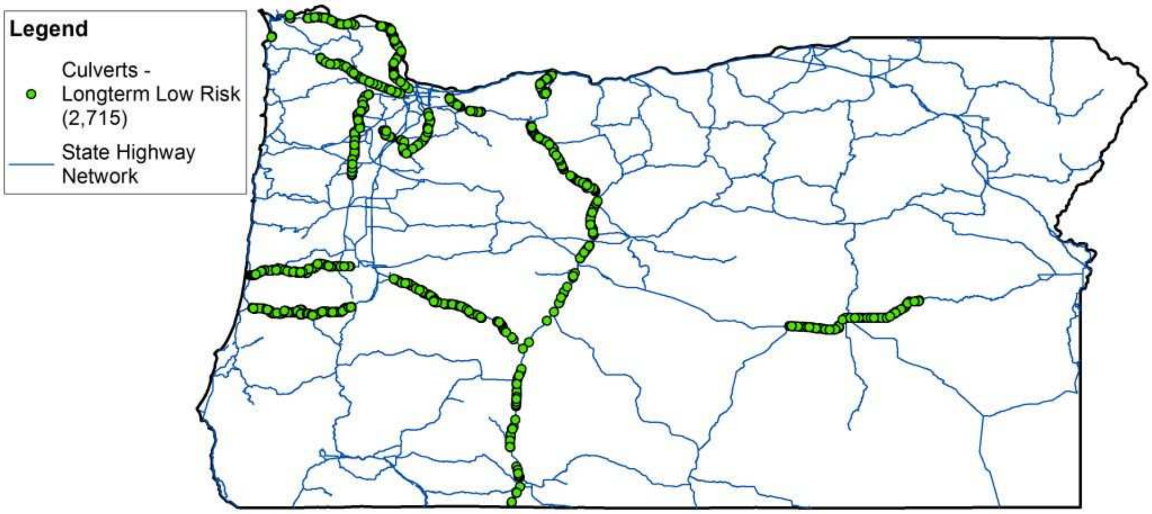


Figure J.38 Oregon R-CAP Index (Method 1) = 1 (Low Risk), End-Of-Century

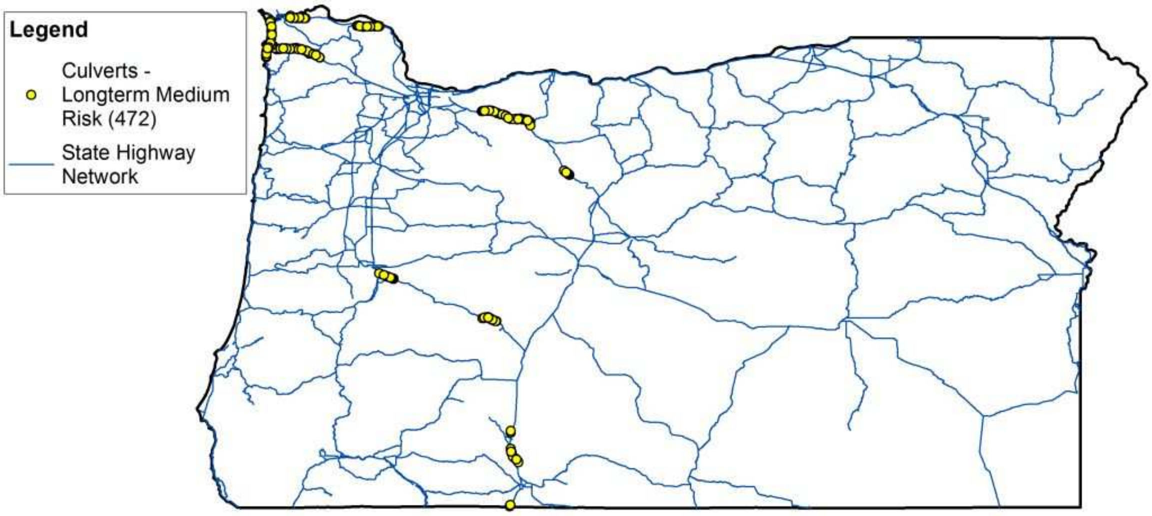


Figure J.39 Oregon R-CAP Index (Method 1) = 2 (Medium Risk), End-Of-Century

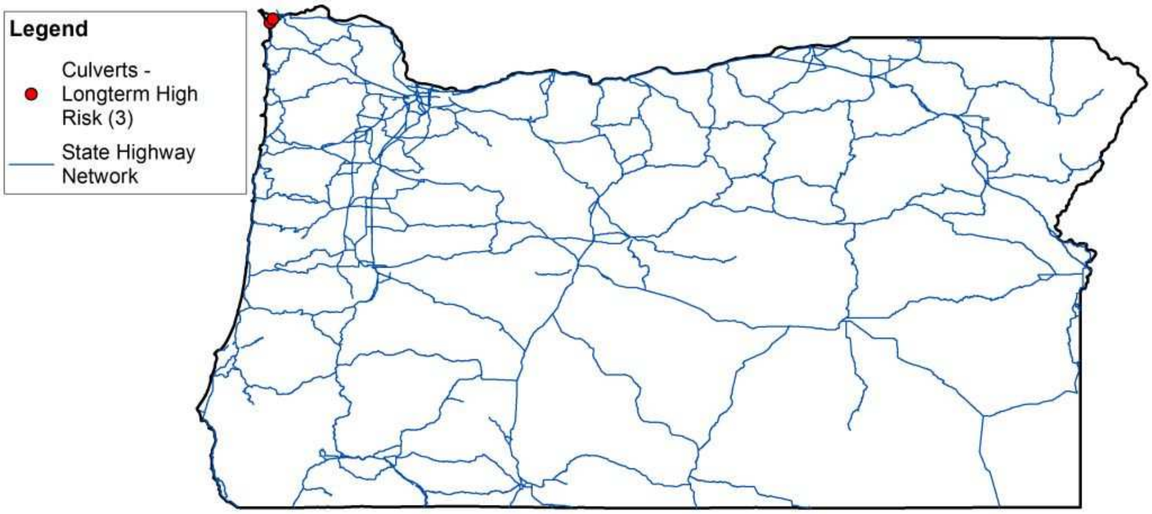


Figure J.40 Oregon R-CAP Index (Method 1) = 3 (High Risk), End-Of-Century

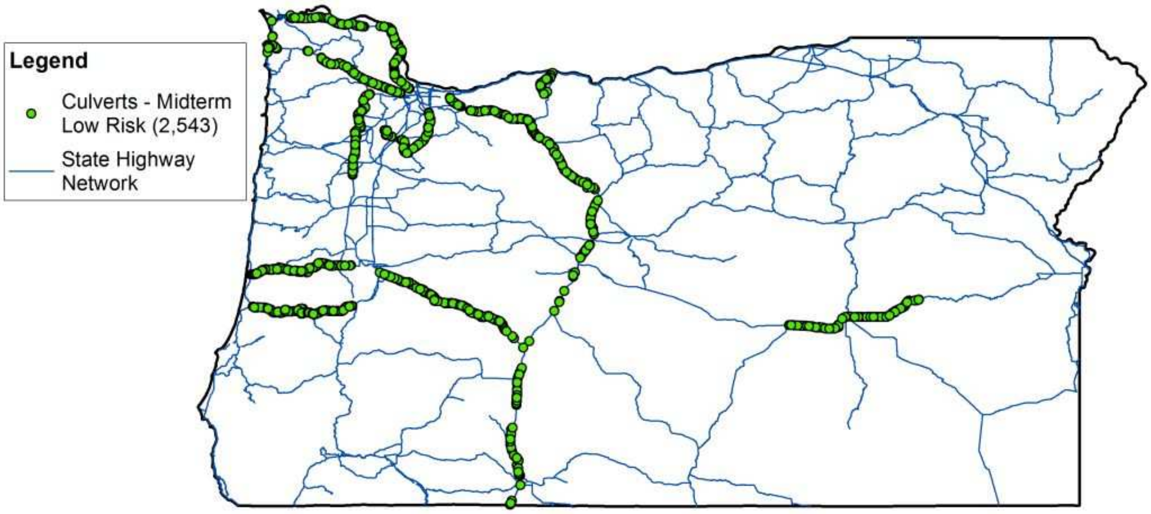


Figure J.41 Oregon R-CAP Index (Method 3) = 1 (Low Risk), Mid-Century

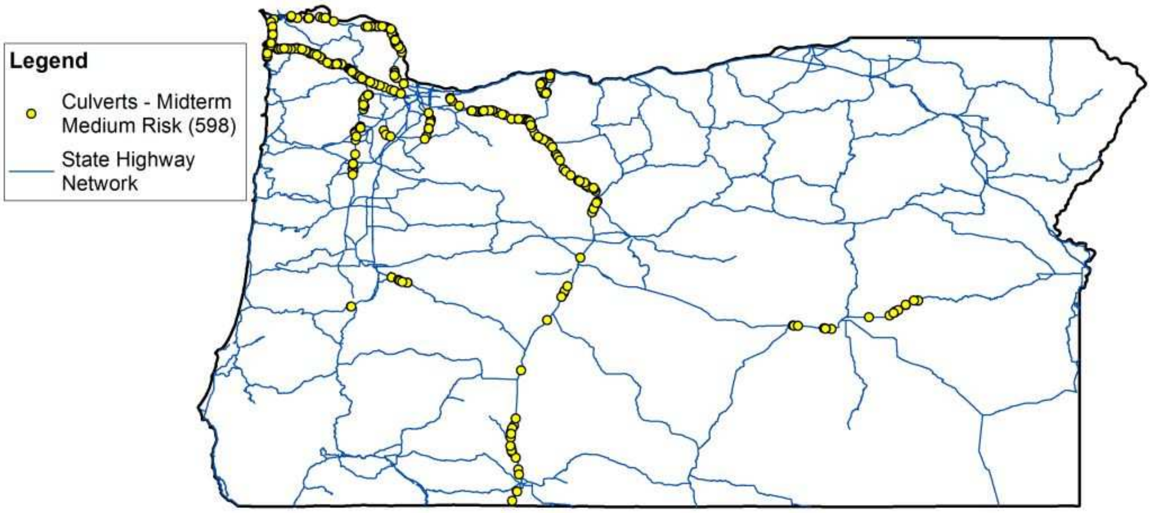


Figure J.42 Oregon R-CAP Index (Method 3) = 2 (Medium Risk), Mid-Century

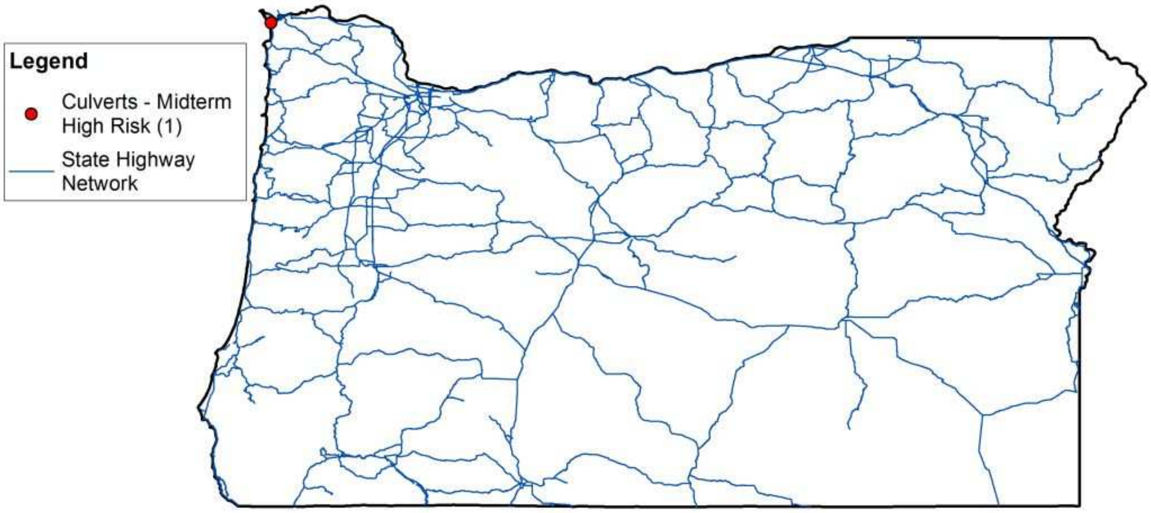


Figure J.43 Oregon R-CAP Index (Method 3) = 3 (High Risk), Mid-Century

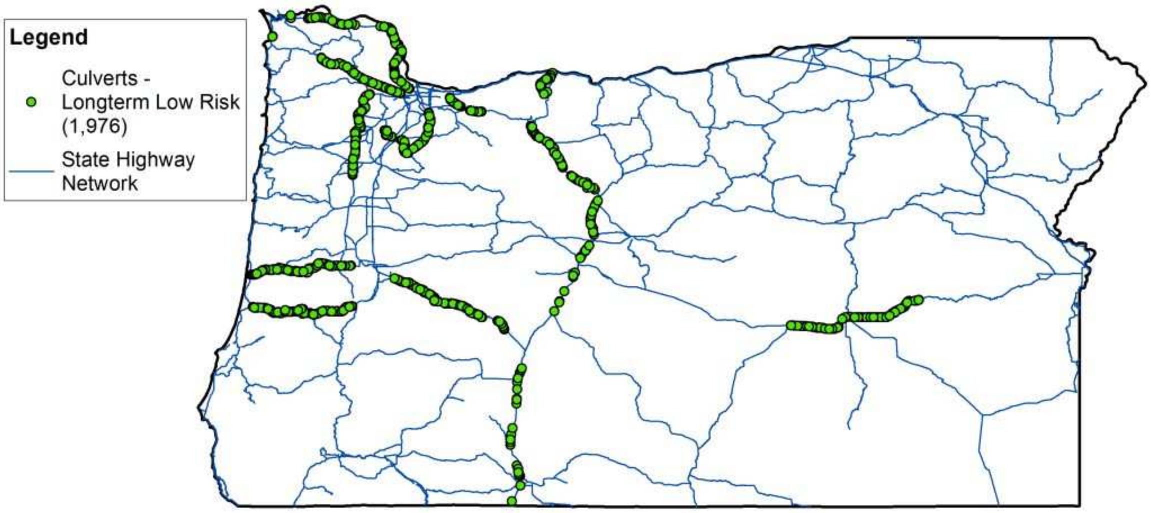


Figure J.44 Oregon R-CAP Index (Method 3) = 1 (Low Risk), End-Of-Century

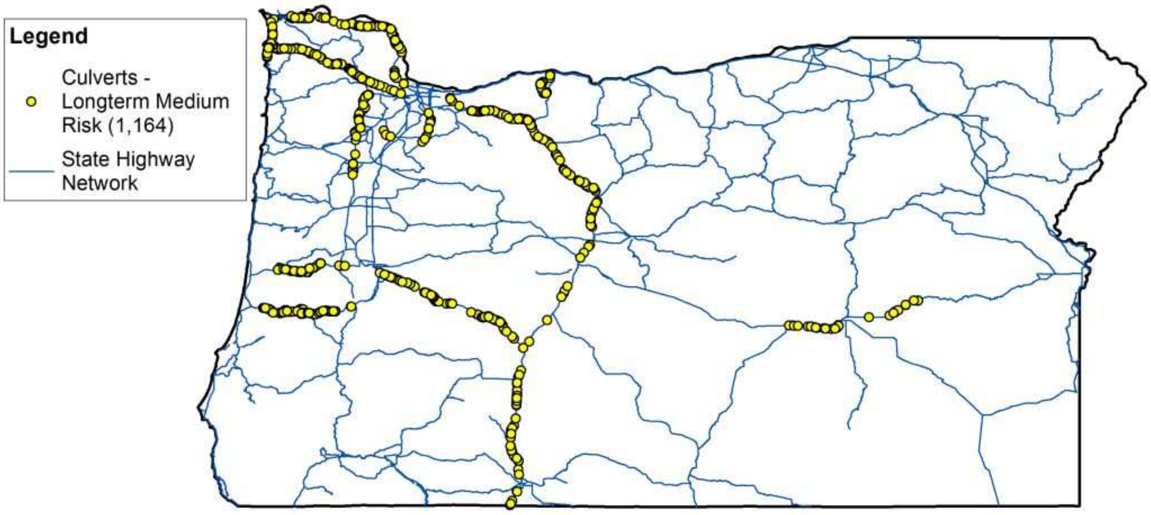


Figure J.45 Oregon R-CAP Index (Method 3) = 2 (Medium Risk), End-Of-Century

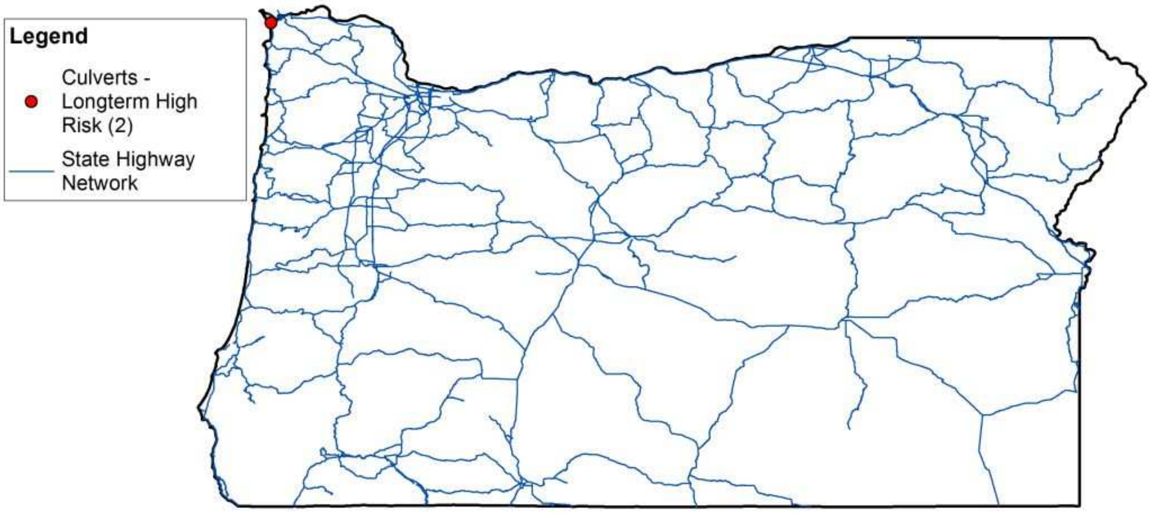


Figure J.46 Oregon R-CAP Index (Method 3) = 3 (High Risk), End-Of-Century

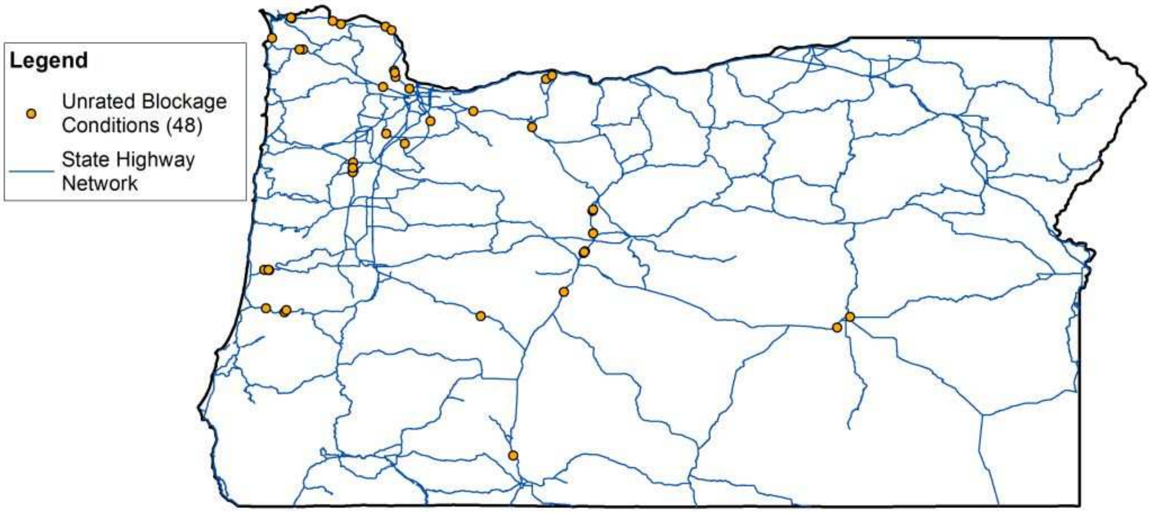


Figure J.47 Oregon R-CAP Index (Method 3), No Rated Blockage Conditions

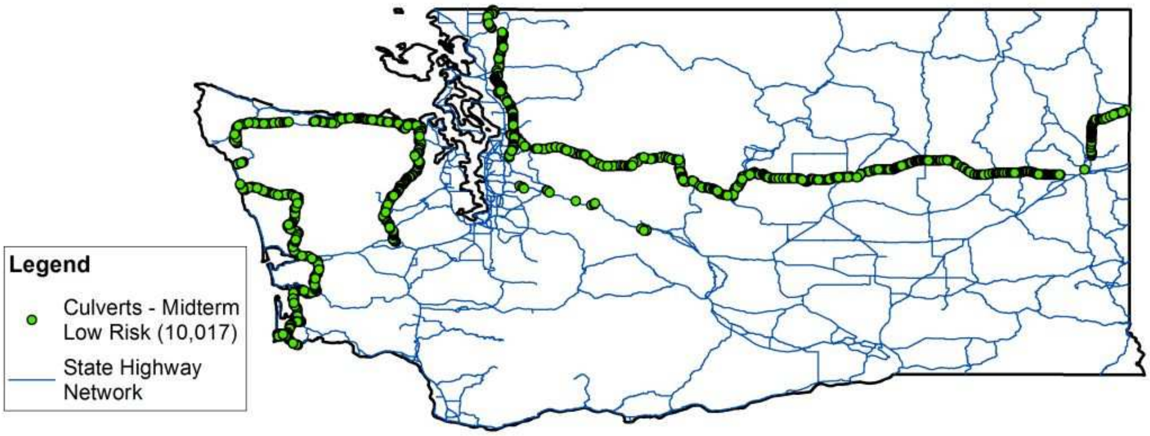


Figure J.48 Washington R-CAP Index (Method 1) = 1 (Low Risk), Mid-Century

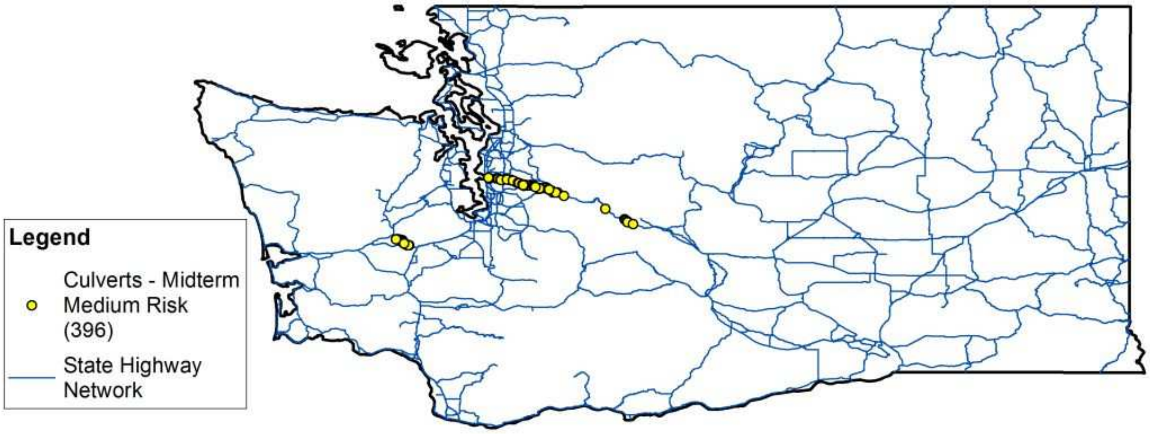


Figure J.49 Washington R-CAP Index (Method 1) = 2 (Medium Risk), Mid-Century

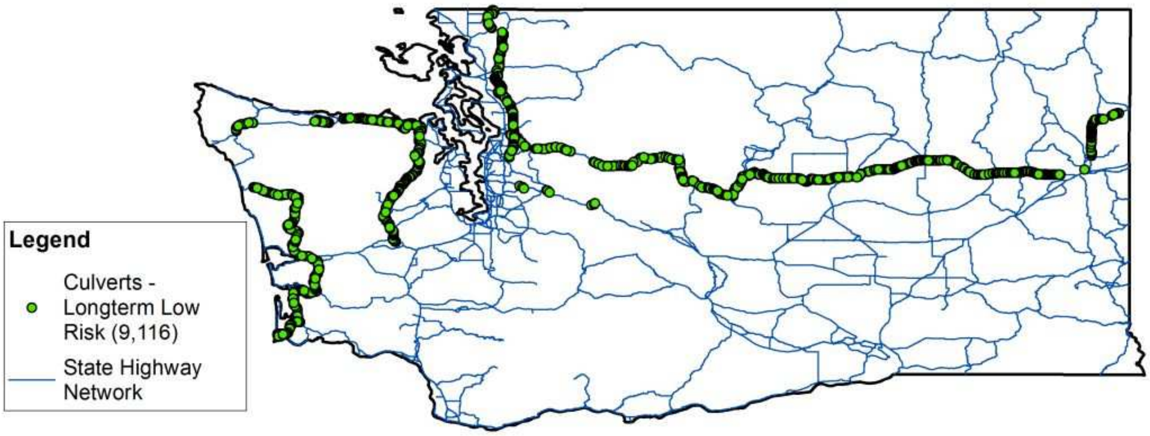


Figure J.50 Washington R-CAP Index (Method 1) = 1 (Low Risk), End-Of-Century

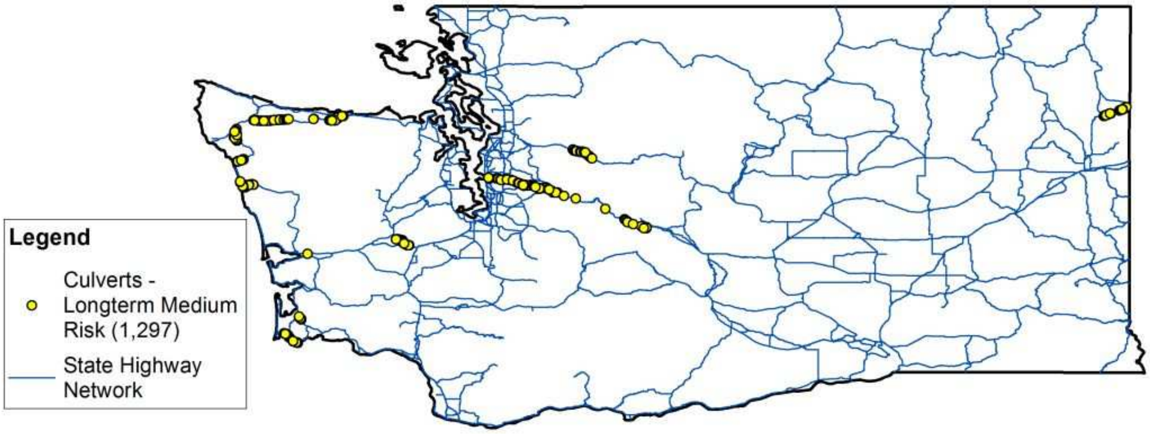


Figure J.51 Washington R-CAP Index (Method 1) = 2 (Medium Risk), End-Of-Century

APPENDIX K: CULVERT ASSET PRIORITIZATION TABULAR RESULS - COMPARISON OF VULNERABILITY METHODS

Table K.1 Minnesota R-CAP Method Comparisons, Mid-Century

Minnesota Mid-Century		Method 2 - R-CAP Index		
		1	2	3
Method 1 R-CAP Index	1	60604	1471	0
	2	0	2026	9
	3	0	0	0

Minnesota Mid-Century		Method 3 - R-CAP Index		
		1	2	3
Method 1 R-CAP Index	1	63158	134	0
	2	0	2048	0
	3	0	0	0

Minnesota Mid-Century		Method 3 - R-CAP Index		
		1	2	3
Method 2 R-CAP Index	1	58861	32	0
	2	1359	2082	0
	3	0	8	0

■ - Upgraded R-CAP Index

▒ - No change in R-CAP Index

□ - Downgraded R-CAP Index

Table K.2 Minnesota R-CAP Method Comparisons, End-Of-Century

Minnesota End-Century		Method 2 - R-CAP Index		
		1	2	3
Method 1 R-CAP Index	1	51807	3335	0
	2	0	7713	41
	3	0	1060	154

Minnesota End-Century		Method 3 - R-CAP Index		
		1	2	3
Method 1 R-CAP Index	1	55735	472	0
	2	0	7932	6
	3	0	1191	4

Minnesota End-Century		Method 3 - R-CAP Index		
		1	2	3
Method 2 R-CAP Index	1	50176	106	0
	2	2997	8870	3
	3	0	184	6

■ - Upgraded R-CAP Index

▒ - No change in R-CAP Index

□ - Downgraded R-CAP Index

Table K.3 New York R-CAP Method Comparisons, Mid-Century

New York Mid-Century		Method 2 - R-CAP Index		
		1	2	3
Method 1 R-CAP Index	1	51340	3920	0
	2	0	2950	0
	3	0	0	0

New York Mid-Century		Method 3 - R-CAP Index		
		1	2	3
Method 1 R-CAP Index	1	46893	726	0
	2	0	1848	0
	3	0	0	0

New York Mid-Century		Method 3 - R-CAP Index		
		1	2	3
Method 2 R-CAP Index	1	43326	202	0
	2	2558	2345	0
	3	0	0	0

▓ - Upgraded R-CAP Index

░ - No change in R-CAP Index

□ - Downgraded R-CAP Index

Table K.4 New York R-CAP Method Comparisons, End-Of-Century

New York End-Century		Method 2 - R-CAP Index		
		1	2	3
Method 1 R-CAP Index	1	50071	4573	0
	2	0	3565	1
	3	0	0	0

New York End-Century		Method 3 - R-CAP Index		
		1	2	3
Method 1 R-CAP Index	1	46146	872	0
	2	0	2448	1
	3	0	0	00

New York End-Century		Method 3 - R-CAP Index		
		1	2	3
Method 2 R-CAP Index	1	42170	249	0
	2	2979	3031	1
	3	0	1	0

▓ - Upgraded R-CAP Index

░ - No change in R-CAP Index

□ - Downgraded R-CAP Index

Table K.5 Oregon R-CAP Method Comparisons, Mid-Century(Left) and End-Of-Century (Right)

Oregon Mid-Century		**Method 3**			**Oregon End-Century**		**Method 3**		
		1	**2**	**3**			**1**	**2**	**3**
Method 1 R-CAP Index	**1**	2543	430	0	**Method 1 R-CAP Index**	**1**	1976	696	0
	2	0	168	1		**2**	0	467	0
	3	0	0	0		**3**	0	1	2

▨ - Upgraded R-CAP Index ░ - No change in R-CAP Index □ - Downgraded R-CAP Index

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