Assessing and Enhancing Transportation Resilience for the State of Iowa

Final Report
October 2020

BRIDGE ENGINEERING CENTER

IOWA STATE UNIVERSITY

Institute for Transportation

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16. Abstract

Flooding, as a predominant destructive hazard, leads to significant direct damage to physical road infrastructure and causes noticeable indirect losses to the communities that rely on the road network. Therefore, it is important to understand the degradation of the network caused by floods to help decision makers and transportation asset managers take adequate preventive measures for floods while preparing for consequences of possible failures.

The goal of the sequence of phases for this project was to develop a system-level resilience framework that can eventually be used as a tool by Iowa Department of Transportation (DOT) engineers to optimize the pre-event mitigation and post-event recovery strategies and prioritize investments while ensuring that the transportation system is capable of absorbing shocks, adapting to changing conditions, and rapidly recovering from disruptions.

The team worked on defining and validating appropriate procedures that will form the cornerstones of resilience assessment and enhancement strategies customized for Iowa's highway transportation network.

The objectives of this systematic research effort, as documented in this report, were as follows:

- Define resilience goals or targets (e.g., functionality level after disruptive flood events)
- Understand system characteristics (e.g., resolution level on the network)
- Characterize disruption scenarios (e.g., extreme flood at various locations on Iowa road network)
- Estimate the consequences of failures (e.g., level of physical loss, traveler delay, economic loss, loss of accessibility)
- Find optimized solutions for possible mitigative impacts, especially in hotspot regions using an actual case study region

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ASSESSING AND ENHANCING TRANSPORTATION RESILIENCE FOR THE STATE OF IOWA

Final Report
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EXECUTIVE SUMMARY

Flooding, as a primary destructive hazard, leads to significant direct damage to physical transportation infrastructures and causes noticeable indirect losses to the communities that rely on the transportation network. This highlights the need to understand the effect of network functionality degradation caused by flood-induced damages, its potential socio-economic impact on the communities served by the transportation infrastructure, and provide decision makers and planners with a holistic tool that allows for development of pre-event mitigation and post-event response plans.

For this purpose, this report defines the requirements for achieving resilience in transportation infrastructure through three inter-related components:

- Understanding the extent to which the system is capable of absorbing the stresses caused by flooding and providing potential alternative routes to alleviate the extra pressure on the system due to damaged roads, bridges, or both
- Understanding the uncertainties associated with the hazard intensity and frequency and the potential for failure of the assets regardless of level of mitigation strategies and planning for rapid recovery of the assets to their target operational levels
- Having the plans, contracts, and resources available to use the "window of opportunity" provided failure to build to better and higher standards to assure long-term resiliency of the system

This project specifically addressed the first item and developed a holistic multi-scale resilience index (MRI) considering flood hazards by synthesizing geographical damage recognition, topological functionality analysis, network operation evaluation, and traffic-user loss estimation (which involves a big part of the methodology in Chapter 3). This integrated model was applied in a real-world Iowa highway network, mainly revealing that a given intensive flood occurrence with different mitigation actions may result in a variety of post-event disruptions in the transportation network. To assist asset owners in developing more reasonable prevention and recovery plans, the MRI that was developed presents both visible, multi-denominational flood consequences and an overall post-event transportation-system robustness indicator.

This project was unique in that it applied the developed MRI in two different case study projects that provide fundamentally different challenges and highlights the robustness of the methodology developed:

- Iowa Department of Transportation (DOT) District 6 primary system
- IA 21 primary and secondary road network

The first case study represents the applicability of the developed MRI on a large-scale network with all possible complications and scenarios of flooding exposed by the flood basins, highlighting the applicability of the developed framework as a robust means to identify hotspots

and provide network-level perspective on the potential improvements required while handling the complexities associated with a large and complex system.

The second case study implements the MRI in the context of benefit/cost analysis for a smaller network, representing project-level usage for the MRI. In this case, the benefits and costs associated with the implementation of mitigation strategies were accounted for using the developed MRI.

This systematic effort is expected to eventually be integrated into a project prioritization tool (PPT), which the Iowa DOT is currently developing, and help optimize and prioritize investments while enhancing resiliency of the system in the long run. The PPT development team is considering different factors in decision making for ongoing and future DOT investments. The discussions with the project technical advisory committee and the PPT development team provided a clear path for the implementation of the MRI as a factor in the decision-making process. It is expected that the current infrastructure developed for the PPT provides an excellent basis for the MRI to be developed and ran as an add-on module to the PPT.

The team also foresees adding to the holistic nature of the MRI by including the other two components to achieve resilience: developing a methodology to assess the recovery rate of the damaged assets based on the extent of damage observed in them and using the framework as a means to prepare for potential failures (for those assets that were not mitigated) such that they are re-built to sustain future events of similar scale. On the first component, without consideration of the extent of damage and rate of recovery, the whole nature of resilience would not be achieved.

1. INTRODUCTION

1.1. Motivation and Significance

Following the requirements of the Moving Ahead for Progress in the 21st Century Act (MAP-21), each state is required to develop a risk-based asset management plan for the National Highway System (NHS) to improve or preserve the condition of the assets and the performance of the system (23 U.S.C. 119(e)(1), MAP-21 § 1106). One of the challenges of incorporating risk (and resilience) with asset management is the lack of a standard framework to identify and prioritize critical assets, and to quantify the impact of threats.

MAP-21 requires the enhancement of safety, infrastructure condition, system reliability, economic vitality, and environmental sustainability and also the reduction of traffic congestion and the number of project deliveries. Implementing resilience, on the other hand, aims to design a system that can stay functional or return to functionality in a rapid manner when an operational disruption or an extreme event occurs. Considering resilience during the decision-making process for short- and long-term investments ensures that the performance measures are met in a more optimized and targeted manner.

The Iowa Department of Transportation (DOT) is planning to include resilience indices as a factor for planning and investment purposes. The goal is specifically to integrate the developed resiliency measures under this project into their project prioritization tool (PPT).

One of the key measures used to evaluate the performance of transportation networks is to identify the extent of disruptions, where transportation network elements, including nodes and links, are disabled, degraded, or destructed either randomly or intentionally, hindering mobility and traffic flow. Some major questions that must be answered in such cases are as follows:

- How vulnerable are the network components to disruption?
- What are the potential consequences of a disruption scenario?
- What types of methodologies are suitable for the evaluation of the potential vulnerability of the system?
- How will different disruption scenarios impact the socio-economic aspects of the community?
- What measures are available to the engineers and planners to estimate the resilience of the system?
- How do these resilience enhancing measures perform?
- How can decision makers craft strategies to enhance resilience with confidence that the strategies will hold during everyday disruptions or when a disaster strikes?

1.2. Research Goal and Objectives

To address all of the listed questions and concerns, the project goal was to define and validate appropriate procedures that will form the cornerstone of resilience assessment and enhancement

strategies customized for Iowa's highway transportation network, especially considering the severe floods Iowa has suffered in recent years.

The objectives of this systematic research effort were as follows:

- Define resilience goals or targets (e.g., functionality level after disruptive flood events)
- Understand system characteristics (e.g., resolution level on the network)
- Characterize disruption scenarios (e.g., extreme flood at various locations on Iowa road network)
- Estimate the consequences of failures (e.g., level of physical loss, traveler delay, economic loss, loss of accessibility)
- Find optimized solutions for possible improvements

To address these objectives, the project team first developed a multi-scale resilience index (MRI) consisting of methods for quick resiliency assessment through topological vulnerability measures and the more intensive social-economic analysis, which could directly show the improvement performance under different pre- and post-even resilience enhancement measures.

Two approaches were considered to implement the developed MRI:

- Consider a large network of transportation assets and assess the developed MRI under different flood scenarios with various return periods

  Iowa DOT District 6 was chosen given it has experienced major disruptions due to multiple flood events in recent years, and it was found to be a suitable case study to prove the significant serviceability reduction of the transportation network and to identify the effective resilience measures when facing floods, as covered in Chapter 3.

  This case study proves that the developed resilience measures provide an appropriate approach to assess the resiliency of a large network of assets and could assist with narrowing down the selections for future improvements and investments at a higher level of decision making.

- Consider a smaller segment of a vulnerable network with a fewer number of projects in such a way that more detailed decisions could be made in terms of increasing the robustness of the vulnerable assets

  For this purpose, the roads and bridges of the IA 21 transportation network were considered as the case study in Chapter 4. This segment of roads has been overtopped with flood waters multiple times in recent years and, as such, provides the perfect test bed to conduct a detailed study on the possible mitigation strategies and for a cost-benefit analysis using the resilience measures developed under this project.

To sum up, the ultimate goal of this project is to develop a system-level resilience framework that can eventually be used by Iowa DOT engineers as a layer in their **project prioritization tool** to help optimize and prioritize investments while ensuring that the transportation system is capable of absorbing shocks, adapting to changing conditions, and rapidly recovering from disruptions.

2. LITERATURE REVIEW

2.1. Social-Economic Impacts of Floods

Flooding can affect many aspects of a community's standard of living. Damage to infrastructure, such as residential, industrial, agricultural, and commercial facilities, can affect an entire area's economic health and growth. The transportation network provides residents with access to all of the necessary facilities in their communities and is a major catalyst for economic growth and also stability. The transportation network creates avenues for increasing the effectiveness and efficiency of business and industries including agriculture, manufacturing, tourism, and real estate. However, if the network cannot support the growth or demands of the community around it, it can cause problems for communities without adequate infrastructure.

Bridges and roads are vital to a community's economy and well-being. Roadways with excess water covering a portion of them decrease the level of service and can increase the hours of traffic delays due to increased congestion (Zimmerman and Faris 2010). If flood waters flow completely over roadways, making them impassable, traffic delays are dramatically increased due to the detours around the closed road sections. Bridges that are closed for safety or completely washed away cause major issues for communities. These can create significant detours for residents and workers or even cut them off from supplies and safety. Public transportation such as buses and trains can also be affected by flooded waterways and may not be accessible to the community.

A large part of the economy in rural Iowa communities is based on farming. Flooding can negatively affect the well-being and the financial welfare of farmers and also impact the economy of the state. If there is heavy flooding in the spring during the planting season, farmers struggle to get crops planted because service roads are muddy or even unusable. This shortens the growing season and negatively affects the quality of the crops in the fall. If flooding happens during the fall, closer to harvest, farmers can struggle to get crops from the fields and to market if roads are washed out. This includes many Midwest farmers that sell their corn to ethanol plants or their soybeans to biodiesel plants. Semi-trucks need to be able to transport crops and livestock from farms to production facilities. If roads are impassible due to floods, farmers lose revenue.

Access to roads and bridges and to basic institutions such as schools, hospitals, police stations, and fire stations can be severely impacted if roads and bridges are damaged or destroyed. The aftermath of flooding has a larger impact because movement in and out of these areas are inundated by the lack of connectivity due to the damaged transportation network, which in turn will affect the socio-economic stability of the community.

2.2. Adverse Damages to Transportation Infrastructure

Flooding can have major effects on infrastructure such as roadways and bridges. Racing floodwaters can greatly impact the transportation network by decreasing bridge stability and

strength integrity. Bridges can be affected by flooding through scour, undercutting of bridge abutments, debris impact, uplift, and overtopping.

Scour affects piers and abutments by eroding soil away from foundations and creating a weaker and structurally unstable connection. Flood waters can uproot trees, move other large objects, and wash them downstream. These objects can impact bridge piers or the superstructure depending on how deep the waterway is from the flood. As flood waters rise, bridges experience increased buoyancy due to a greater portion of them being submerged under water. If the waters reach the superstructure, the buoyancy affect is magnified greatly, because the water pushes against the larger surface area of the underside of the roadway. If a bridge stays structurally sound through all of the forces, the water can eventually overtop the bridge and flow across the top (Kalendher et al. 2014).

Meanwhile, the road network of the United States is very complex and necessary for the general population to travel every day. Roads in lower elevations or in coastal regions are usually at the most at risk for damage due to flood waters. Flood waters beside roads in ditches can erode the soil and undercut the road pavement creating a dangerous driving surface. This can also occur if culverts under roads are not large enough to adequately let floodwater flow through. Flood waters can also wash out unpaved roads in rural communities making the roads impassable and unusable.

2.3. Hazard Analysis Efforts

Floods are most commonly caused by extreme rainfall events. Rivers can surge and urban roadways can flood due to lack of drainage capabilities.

This description of events starts with intensity-duration-frequency (IDF) relationships. These relationships can describe the frequency of a rainfall intensity occurring given a specific time interval. Usually, the precipitation levels are averaged (and otherwise known as "aggregated"). New methods are used to create IDF curves to try to predict how rainfall will change in the future.

One study, by Mirhosseini et al. (2013), gathered historical precipitation data and future projections from data centers and generated IDF curves using six different projections. The six projects were not identical; however, overall, they could conclude that rainfall durations of less than 4 hours are expected to slightly decrease or stay the same. The more extreme events are not so conclusive. Three projections show an increase in rainfall intensity for a 12-hr rainfall and three projections predict a decrease. This shows how unpredictable the intensity or duration of rainfall events can be.

Projected weather trends are difficult to indicate, but most people agree that extreme weather events have increased due to climate change. Unfortunately, as previously discussed, urbanization has increased developments in hazard-prone areas, which leads to more flooding events due to decreased drainage capabilities.

In light of this, after the floods of 2008, Iowa established the Iowa Flood Center (IFC). The goal was to increase research into flood events and increase awareness through high quality mapping models. There are statewide 1D floodplain delineation and 1D/2D coupled models for urban flood maps. This benefits Iowa by creating a single comprehensive set of maps for the entire state to use.

The Iowa Department of Natural Resources (DNR) began collecting new elevation data of all streams using laser imaging, detection and ranging (LiDAR) since the 2008 floods. The IFC has created a few libraries of flood inundation maps for communities. The data are carefully organized according to communities instead of by watersheds or administrative divisions. This information can provide an individual city an idea of the extent of flooding based on a predicted river stage. Predicting which areas are at risk for a flood can help city planners and leaders work to protect their cities (Gilles et al. 2012).

To provide access to the flood inundation maps and a large amount of other information, the Iowa Flood Information System (IFIS) was created. This is a web-based platform at the IFC that provides communities information such as rainfall conditions, stream-flow data, watershed and river characteristics, and other visualization tools. IFIS users can look at the past 10 days of data with weather conditions as well as a time-series graph of data taken every 15 minutes from sensors. This interactive site also gives flood conditions, forecasts, rainfall, and other visual data. This data center is also able to provide any member of the public access to a vast amount of information related to weather and the risks of floods (Demir and Krajewski 2013).

2.4. Vulnerability Analysis

Vulnerability in the transportation system is defined as the susceptibility to disruptions due to incidents such as floods or other extreme hazards that can negatively impact society through reductions in road network serviceability (Berdica 2002). Vulnerability can be analyzed from a few perspectives.

First, there are the vulnerabilities of the physical network itself. Incidents cause damage to the physical components of the network resulting in the closure of some segments and rebuilding and restoring activities.

Second, and maybe most importantly, is the reduced accessibility from the discontinuities in the function of the network due to the physical incidents. Accessibility defined for the transportation network concerns the opportunity and mobility for people to engage in daily activities with ease. Mobility within the network is described as the effectiveness of connecting separate locations as well as the extent to which people can make use of the transportation system.

Last, the more vulnerable the network is, the greater the risk for disasters. Risk is the probability that an incident will occur and the consequences once that event has taken place. This section focuses on the first part of that definition: vulnerability.

The literature discussing the vulnerability of the transportation system has increased rapidly in the past two decades. There are a couple perspectives on vulnerability (Berdica 2002). One is a societal view and how an individual living in a community will be affected if exposed to the disruption. The second is on the technological side of the system and looks at the probability that the physical elements will be disrupted and how that can affect society. This report focuses on the technological perspective.

2.4.1 Bridge Vulnerability

The most critical elements of the transportation network are identified by analyzing where disruptions would be the most severe. For example, it could be a bridge that provides access to a city across a body of water or a road link that, if disrupted, could affect a large region around it. Bridges are vulnerable to a number of flood-induced, hydraulic factors, including water pressure, scour, corrosion, and the impact of debris.

A study by Wardhana and Hadipriono (2003) analyzed data from more than 500 bridge failures between 1989 and 2000. The authors found that bridges are most vulnerable to several flood-induced hydraulic factors including water pressure, scour, corrosion, and the impact of debris. More than 50% of the failed bridges studied were the result of hydraulic factors. The ages of the failed bridges ranged from those still under construction to 157 years, with a mean of 52.5 years.

Debris accumulation is one of the sources of bridge vulnerability. The accumulation of debris can result in increased water velocity that could result in higher flood levels, higher water pressure on the bridge components, and potentially higher scour depths. In addition, if water depths greatly increase upstream, the water could flow into the nearby floodplains or over manmade levees, damaging the surrounding area.

The uplift forces on a bridge due to water or entrapped air can counteract the bridge weight and potentially lift a bridge and cause it to wash downstream. Most of the early studies on this occurring were laboratory experiments using a horizontal plate. Tests using waves of different heights and periods were conducted to find uplift pressures and drag forces. Some plates were fully submerged, and others were varying distances above the water.

Following all of these simplified experiments, a study by Douglass et al. (2006) found that limited experiments had been done using modern wave-generating models and modern highway bridge geometries. This study estimated wave loads on bridge decks using a new empirical equation.

Sheppard and Marin (2009) developed a theoretical model for wave loadings on horizontal structures by extending and modifying previous models to include bridge superstructure shapes and environmental conditions near coastal bridges. The model can be used for any area if the information and laboratory equipment needed is available to calculate empirical coefficients.

A study by Xiao et al. (2010) studied the effects of uplift on the Biloxi Bay Bridge in Mississippi in three cases—just above the water, half submerged, and fully submerged—based on the maximum surge elevation of Hurricane Katrina. The fully submerged simulation bridge deck had the largest uplift force at 137% of the bridge span weight. By using the data from the hurricane, the simulation indicated that the bridge deck was lifted for 20–30% of a single wave period, which means the bridge was moved by a combination of vertical and horizontal wave forces.

Scour is another major source of vulnerability in bridges over waterways. It alters static and dynamic characteristics of bridges and may lead to excessive deflections and induce maximum actions in the structural members (Klinga and Alipour 2015, Shang et al. 2018, Fioklou and Alipour 2019). Different types of scour include local scour, general scour, and aggradation/degradation (Ettema et al. 2003).

Benedict (2016) collected observed scour data from South Carolina and developed hydraulic models for each site to investigate which hydraulic conditions caused the scour. Hydraulic data that were generated was used to compute theoretical scour using methods from Evaluating Scour at Bridges by Arneson et al. (2012). Most theoretical scour depths exceeded the observed scour depths. The variables that influenced abutment scour the most were embankment length, geometric-contraction ratio, approach velocity, and soil cohesion. It was also observed that, as the embankment length and geometric-contraction ratio increase, the amount of scour also increases.

Once the likelihood of different types of vulnerability is identified for a bridge site, the flood fragility functions can be developed to assess the likelihood of failures under different scenarios. A flood fragility curve is derived by running repeated structural analysis on a bridge and analyzing the structural responses using analysis software. Structures can be analyzed using material parameters, occupancy state, foundation parameters, and others to objectively evaluate the risk for the structure. However, this method has rarely been used for evaluating bridges subjected to scour and other hydrodynamic forces (Lee et al. 2016, Kim et al. 2017, and Ahamed et al. 2018).

2.4.2 Road Vulnerability

Deteriorating pavements can be accelerated by high saturation. The pavements can lose capacity for transferring traffic loads through damaged intralayer bonding due to saturation, leading to slippage cracking, potholes, and rutting (Leng et al. 2008). Flowing debris that slides along the top of the pavement can smooth the pavement leading to texture loss (Kreibich et al. 2009). The debris can also clog and cover the pavement surface.

A study in Iowa after the Missouri River floods in 2011 analyzed many sites where flooding occurred (Vennapusa, et al. 2013). The researchers detailed the damages sustained and the repairs necessary to fix the damage at the time. In situ falling weight deflectometer (FWD) measurements from flooded and non-flooded areas on aggregate roads showed significant statistical differences in most road segments. The researchers conducted repeated tests over

several months and half of the road segments were still significantly different while the others recovered.

This study showed that post-flood events require in situ testing to help characterize field conditions. The California bearing ratio (CBR) of the base layer was approximately the same, but the ratio for the subgrade material was 10 times higher in non-flooded areas than in flooded areas on a hot-mixed asphalt (HMA) pavement. On a portland cement concrete (PCC) pavement segment, longitudinal cracks were observed in areas where the subbase layer was washed out.

Water velocity was found to be a significant factor in structural damage to road infrastructure. The increased water loads, along with debris, can put stress on the roadway leading to uncertainty of structural integrity after a flooding event. As the frequency of flooding events increases and the pavement bounces back and forth from normal to saturated, this can quickly deteriorate the roadway.

A study by Helali et al. (2008) investigated an area that was flooded by Hurricane Katrina. Part of the area was flooded for weeks, and another part had higher traffic loads due to flooded roadways being unusable. The roads that were flooded had larger deflection values indicating a reduced structural condition. The researchers also used historical network condition data provided by the Pavement Management System (PMS) to estimate the pre-Katrina road conditions and used extensive field testing to evaluate the post-Katrina road condition; they observed similar deflection changes indicating flood damage.

Another study analyzed short-term post flood characteristics (Sultana et al. 2016). The authors concluded that once the pavement becomes saturated from the flood, if it does not dry out, the pavement will never regain its original strength from when it was originally built. This causes more problems for areas that are repeatedly flooded. However, if pavements can survive through the flood and traffic when the pavement is saturated, there was evidence that the pavement regains strength during dry weather periods. However, ideas are mixed on how long pavements can last in water before they are considered structurally damaged, which requires further study.

A study in 2017 concluded that thin surface pavements could have irreversible damage from short flooding durations (Mallick et al. 2017). The layer permeability of the HMA and pavement thickness can significantly affect the critical timetable for road damage. Thicker and less permeable layers, which are recommended to be made with a fine gradation asphalt binder, could be used to slow the ingress of water that will cause damage into the pavement. Roads in coastal regions are particularly vulnerable according to this study, because pavement strength can drastically be affected after 6 hours of inundation.

2.5. Consequence Analysis

Transportation networks are designed based on many factors, but two of the most important are capacity and free-flow speed. In theory if vehicles traveling on the roads can continue driving the posted speed limit, there will be no congestion other than at peak travel times. However, due to

weather events, the free-flow speed decreases, traffic congestion increases, and the effectiveness of the transportation network decreases. The following studies can be categorized as those relating rainfall to road capacity loss, those relating rainfall to vehicle speed limits, and those relating rainfall to driver delay and congestion.

Various studies have investigated the relationship between traffic volumes and congestion due to weather events such as rainfall. A study by Hranac et al. (2006) found that any amount of rainfall decreased capacity on average by 10–11% in Minneapolis-St. Paul, Baltimore, and Seattle. Brilon and Ponzlet (1996) concluded a 12–47% reduction for any rate of rainfall.

Other studies separated losses by the rate of rainfall. Ibrahim and Hall (1994) found a capacity reduction of 14–15% for rainfall falling at rates greater than 0.25in/h. Smith et al. (2004) concluded that rainfall falling at rates between 0.001 in/h and 0.25 in/h caused a capacity reduction of 4–10%. Reductions of 25–30% were concluded for rainfall falling at rates greater than 6.4 mm/h. A study based in Virginia concluded that rain falling at 0.01–0.25 in/h decreases capacity by 4–10%, and it decreases by 25–30% when rain falls at a rate faster than 0.25 in/h (Smith et al. 2004). Another study in Minneapolis-St. Paul by Agarwal et al. (2005) concluded average capacity reductions of 1–3%, 5–10%, and 10–17% for trace, light, and heavy rain conditions, respectively.

Chung (2012) created a method to quantify non-recurrent congestion as a function of precipitation and the time of that precipitation. The study compared the rate of speed traveled during rainfall to the normal traveling speed of that area at that specific time of day, such as peak morning flow. This method could be used for any areas with that available traffic information.

A few studies have specifically studied the effect of rainfall on vehicle speeds. Smith et al. (2004) studied the Hampton Roads region of Virginia and found that any rate of rainfall will decrease the operating speeds by 5–6.5%. A study in the UK by Hooper et al. (2014) concluded that there is no obvious relationship between vehicle speeds and precipitation other than speeds decrease once it starts raining.

Other studies were able to differentiate between rates of rainfall. Ibrahim and Hall (1994) concluded that speed reductions of 1.9–12.9 km/h occurred if rain fell at rates between 0.25–6.4 mm/h, and increased to 4.8–16.1 km/h if rain fell faster than 6.4 mm/h. Kyte et al. (2000) had larger decreases in free-flow speed with a range of 14.1 to 19.5 km/h speed reduction as well as a 31.6 km/h decrease for heavy rainfall.

Hranac et al. (2006) found that the free-flow speed due to light rain (<0.01 cm/h) decreased 2–3.6 % on average in their study of Minneapolis-St. Paul, Baltimore, and Seattle. Heavier rain decreased the free-flow speed by 6–9%. Agarwal et al. (2005) concluded that free flow speed decreased 1–2%, 2–4%, and 4–7% for trace, light, and heavy rain, respectively, in Minneapolis-St. Paul.

For the investigated factor of driver delay on highways due to heavy rainfalls or floods, Stern et al. (2003) did a study in Washington, DC, and found that precipitation increased travel time by 11% during peak-period traffic and 3.5% during off-peak periods. Suarez et al. (2005) did a study in the Boston metro area and used flooding and traffic information from 2003 to simulate a 100-year flood and 500-year flood and compared it to projected 2025 values. The riverine flooding increased the total vehicle miles and total hours traveled, while coastal flooding decreased the number of total trips taken. In the base setup before the flooding scenarios, there were more trips in 2025 and more vehicle miles traveled in 2025 due to an increase in population. However, the increase of vehicle miles traveled after the flooding scenarios was actually less in 2025 even though the population was higher. This could be due to more traffic links in the network that would allow a larger amount of shorter traffic routes to be taken.

2.6. Resilience Analysis

Murray-Tuite (2006) breaks down transportation resilience into 10 dimensions: redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, and the ability to recover quickly. The study used an event in Washington, DC, to test the methods to measure different types of resiliency. It focused on providing metrics for the final four dimensions of resiliency given there were no widely accepted measurements of resilience.

Adaptability can be measured by how certain lanes, such as special-use lanes, are used after an incident. Mobility is measured in a handful of ways including evacuation time, response vehicle travel times, queue length, average queueing time per vehicle, amount of time that traffic is traveling at speeds slower than its posted speed limit, and the volume to capacity ratio. Safety usually refers to the number of crashes that occur, but the number of fatalities per mile of roadway could be used. Recovery is related to the time, budgetary resources, and outside assistance necessary to restore the network to an acceptable degree. The recovery variable is very case specific because it depends on the extent to which the transportation network elements have been damaged.

Research on transportation network resilience measures is increasing; however, a unique agreed-upon approach is yet to be found due to the complexity and volatility of the actual network. For this report, the authors integrated the following studies to analyze the Iowa network under flood events.

Ash and Newth (2007) tested a network for cascading failures. Each node was given capacity characteristics and, when it was removed, the data were distributed to the adjacent nodes. The study randomly changed which node was removed, so it could test many different setups. The algorithm searched for network characteristics that were associated with robustness. In other words, it looked at how the network was organized where the removed node had the smallest effect on the network around it.

Attoh-Okine et al. (2009) pursued creating a resiliency index for urban infrastructure. Using belief functions, the study was able to use subjective and independent information to measure how changes in the infrastructure can affect the resiliency index.

Alipour and Shafei (2015 and 2016) developed a network of bridges and used time-dependent fragility curves to assess the vulnerability of each bridge. Then, they integrated the developed fragility functions into a model of the transportation network represented by network theory and flow-based models to assess the resiliency of the transportation network. Different measures, such as direct costs associated with the replacement of the damaged bridges, indirect cost associated with longer travel times, and opportunity costs were considered.

In another study, Testa et al. (2015) developed a topology-based framework to study the vulnerability of the New York City road system to storm surge. In this study, two approaches were considered: a scenario-based approach that assessed the vulnerability to different storm surge scenarios and a random series of scenarios to assess the damageability of the network when the nodes are randomly removed.

In a more recent studies, Zhang and Alipour (2020a, 2020b, 2020c) assessed the vulnerability of a network of bridges and roads to failures and used an optimization algorithm to replace the bridges in such a way that would improve the bridge vulnerability scores within the network while minimizing the costs associated with the direct replacement (or improvement of the bridges) and indirect costs associated with the required closures.

Twumasi-Boakye and Sobanjo (2018) created a computational approach for evaluating the resilience of transportation networks. The study used bridge closure scenarios to compare how those closures indicate resiliency of the network. Data were initially gathered to see how the network operated with the bridges in place. Then, one by one, the impact of each bridge closure on the network was investigated. The importance of each bridge was represented by its reliability index value. Each high impact area could be highlighted so decision makers would know where to look for upgrades and rehabilitation. While a few different methods exist for use of resiliency metrics, studies using these methods in realistic transportation networks are lacking.

3. PROOF OF SERVICEABILITY REDUCTION OF FLOODED IOWA NETWORK

3.1. Introduction

A transportation network is an imperative entity used to increase local economic development, and extreme weather events, such as floods, negatively impact the performance of the transportation network. Rising and rapidly flowing flood waters can damage and close bridges and sections of roads. Direct costs from repairs to roads and bridges are expensive and can be financially demanding. Every link in the transportation network that is unusable due to flooding decreases serviceability and efficiency in the system. Detours are created where available but require more time to reach their destinations. In areas with less redundancy, trips may be canceled, because there is no possible path to certain destinations. The indirect losses from the dysfunctionality of a transportation network can accumulate quickly putting economic stress on local communities.

There are many characteristics that can be used to describe a transportation network and its performance capabilities. New studies are using a wider range of analyses to find a better overview of how floods affect transportation network performance and resiliency.

This chapter proposes a holistic framework that integrates flooding hazards with the vulnerability analysis of transportation road infrastructures, topologic risk analysis, and flow-based risk assessment. The vulnerability analysis of infrastructures provides the extent of closure on roads and bridges. The topologic risk analysis, based on graph theory, provides immediate information on the network characteristics that could be linked to instantaneous connectivity measures. The flow-based risk assessment computes the entire network traffic time via the user equilibrium model to assess user losses due to increased traffic time. Finally, the developed framework is used to assess the risks for a segment of the road system when facing flooding events with various return periods such as 2, 50, 200, and 500 years.

It is expected that the integrated framework and network performance measures will inform a clear reduction of results from flood hazards. The following study is a great example showing quantitatively how flooding affects a road network.

3.2. Case Study

The case study here uses the primary road system from eastern Iowa (in Iowa DOT District 6) to make a quantitative statement on the resiliency of the network against inland flooding (Zhang et al. 2018, Zhang and Alipour 2019). Twelve counties with two major cities, Cedar Rapids and Iowa City, are included in the roadway segments. The network is comprised of 4,599 nodes, 7,512 links, and 603 state-owned bridges. The Iowa DOT provided information on this roadway system, which included a total traffic demand of 33,704,389 trips.

Historical flooding data and geographical data were collected and embedded into the analysis of the road network. The area tested has experienced multiple severe floods in the last decade that have negatively affected the agricultural business and daily operations of the traffic network.

The goal of creating the model was to quantify the status of damages on roads and bridges across the transportation network. The input information considered for this part of the study was as follows: flood events are random with a specific flood return period; when a road floods, the capacity is zero, traffic demand does not significantly change, and network users are informed on which detours are available and will use these detours to travel to their destinations. These assumptions made it easier to decide which components are affected and unusable.

The main hazard used to predict whether roads or bridges were damaged was flood water depth. A road was considered as closed if the water rose above its surface, and a bridge was considered as closed if the water reached the lower beam level. Figure 3.1 illustrates the process of estimating the closures at a network level and the vulnerability-analysis process for a 50-year flood event.
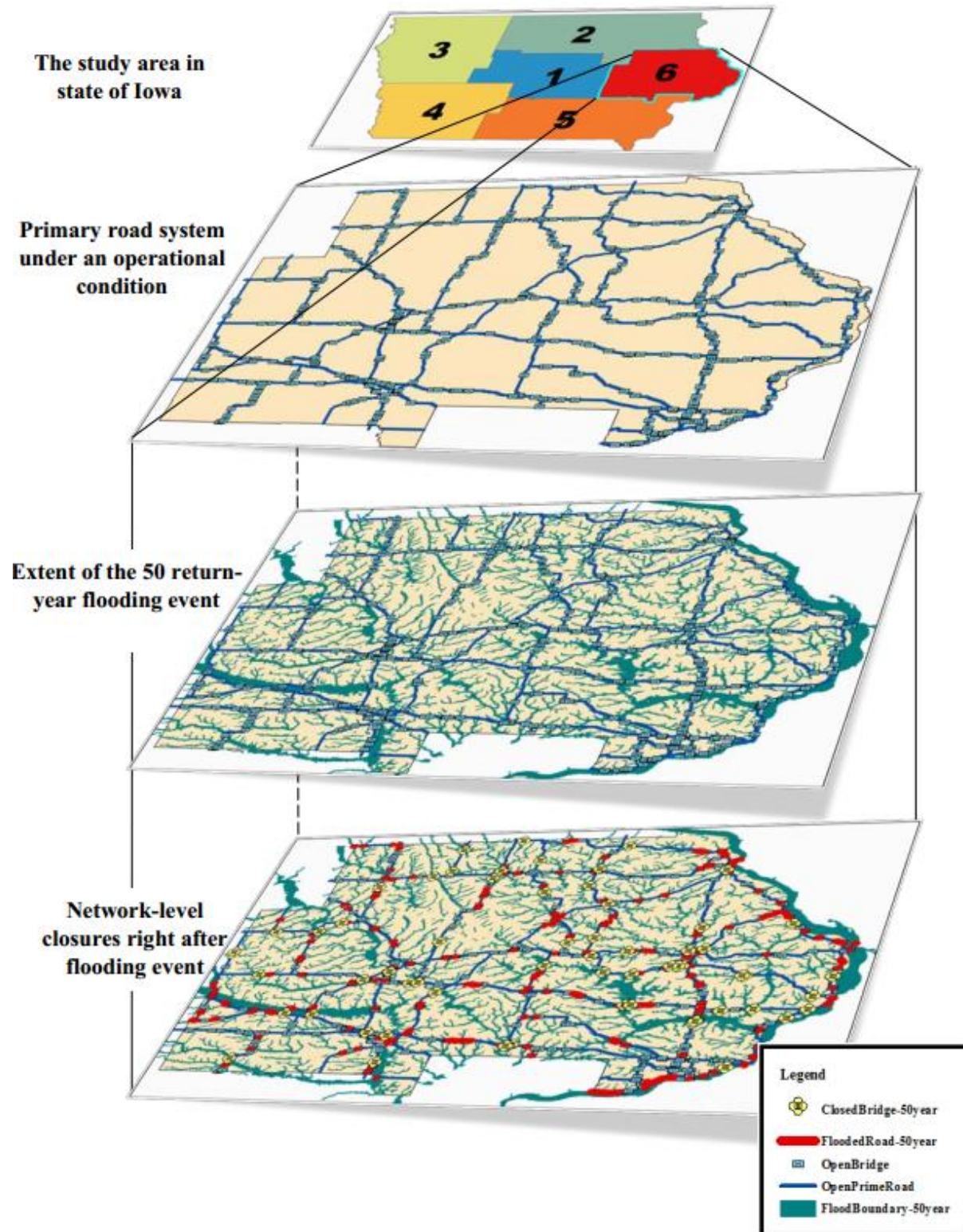
Figure 3.1. Example of network-level closure after a flood with a 50-year return period in the primary road system of Iowa DOT District 6

The study area in state of Iowa

Primary road system under an operational condition

Extent of the 50 return-year flooding event

Network-level closures right after flooding event

Legend

⊕ ClosedBridge-50year

▬ FloodedRoad-50year

▭ OpenBridge

— OpenPrimeRoad

▬ FloodBoundary-50year

3.3. Topological Methodology

As a first-step analysis approach that does not require a significant amount of time, the risk of losing traffic network functionality can be quantified using a topological analysis. Road networks consist of nodes and links, which, based on their location and connectivity, can be used to quantify resilience to extreme events. The connectivity of a road network is described as the ease of movement on links between nodes. If the network is interrupted by a link failure and the flow can easily be reestablished on another path, it shows the redundancy of a network. These are two important characteristics to have in a road network, and three topological properties were used in this study to represent these characteristics.

The first topological property is nodal degree. This is the average number of links passing through each node across the network. A node, i, could have incoming links from other nodes to i and other outgoing links from i to other nodes. The nodal degree of node i is the average of the sum of incoming links to node i (d_i^{In}) and the sum of outgoing links (d_i^{Out}) from node i. The average nodal degree of the entire network with N nodes is calculated using equation (3.1).

$$d_{avg} = \frac{1}{2N}\sum_{i=1}^{N}(d_i^{In} + d_i^{Out}) \tag{3.1}$$

Clusters are the second indicator of network connectivity. A network with many clusters will have a higher performance value as a system, because cluster coefficients measure local link density. The equation calculates the connectivity of the neighboring nodes of a given node. A neighboring node in this calculation has a link connected to node i. The average cluster coefficient of the network is calculated by determining the average of all the local cluster coefficients. This value will be between 0 and 1 and expresses the degree to which the neighborhood is connected. The closer that value is to 1, the more interconnected a network is. This cluster indicator is calculated using equation (3.2).

$$C_{avg} = \frac{1}{N}\sum_{i=1}^{N}\frac{2L_i}{(\frac{d_i^{In}+d_i^{Out}}{2})(\frac{d_i^{In}+d_i^{Out}-1}{2})} \tag{3.2}$$

The third and final indicator is related to the shortest path. SP_{ij} measures the shortest traveling distance between node pairs, i and j. The average shortest path, P_{avg}, is the average shortest distances of all origin-destination pairs in the network. The smaller it is, the better the network will perform. The calculation is in equation (3.3).

$$P_{avg} = \frac{1}{N(N-1)}\sum_{i=1,i\neq j}^{N}\sum_{j=1,j\neq i}^{N}SP_{ij} \tag{3.3}$$

The maximum number of links in a network can be defined as follows: a link must exist that connects each node to all the others, |N|(|N|-1).

3.4. Flow-Based Methodology

A flow-based analysis uses data, such as traffic, flow speed, and travel time, to find the total of all traffic times on every link in the network. Indirect loss computations after large flooding events are imperative to know how badly floods are affecting the network. The method used for this analysis is a four-step model using traffic generation, traffic distribution, mode choice, and traffic assignment.

The traffic assignment is accomplished after the traffic generation and distribution data are collected. The traffic demands are allocated so that every link flow is maintained at link capacity. The traffic time on the routes used must be less than the travel time it would take to use the next shortest route, which is known as Wardrop's first principle. The algorithm uses link free flow travel time, link traffic volume, link capacity, and traffic flow from node to node. The capacity is adjusted based on the various disruptions to represent the level of closures to bridges and roads from flooding events.

3.5. Network Performance Measurement

Given the large scale of the network and the large traffic volume, the total traffic time or delay of a network cannot properly represent the extent of the impact under different flooding scenarios. To address this issue, a performance measure was used at a network level, P_{net}, to normalize the indirect transportation losses to each traffic flow. The average travel time per traffic flow under the fully operational network is T_{flow}^0 and the average travel time per traffic flow after a flood event with a k-return period is T_{flow}^k. The losses of the network functionality can be defined as the ratio of the travel delay per flow under hazards to the operational travel time per flow. Based on this, the remaining network functionality after extreme flooding, P_{net} can be deemed as the result of the complete network functionality minus the loss on traffic time per traffic flow. Equation (3.4) shows this performance measure calculation and helps show the impact that a flood event has on network performance.

$$P_{net} = 1 - \frac{T_{flow}^k - T_{flow}^0}{T_{flow}^0} \tag{3.4}$$

3.6. Discussion of Results

The goal of analyzing the case study network was to show to what extent flooding impacts the transportation network. Flood events with return periods of 2- to 500-years were considered. Under the considered scenarios, the number of roads closed increased from 49 to 292, and the number of closed bridges went from 31 to 116. The flood water depth averaged between 4 and 7 feet for all flooding events and reached a maximum of 24.79 feet in the 200-year flood event. Figure 3.2 presents the sample network after each flooding scenario in addition to closed assets and flood water depths data.

16
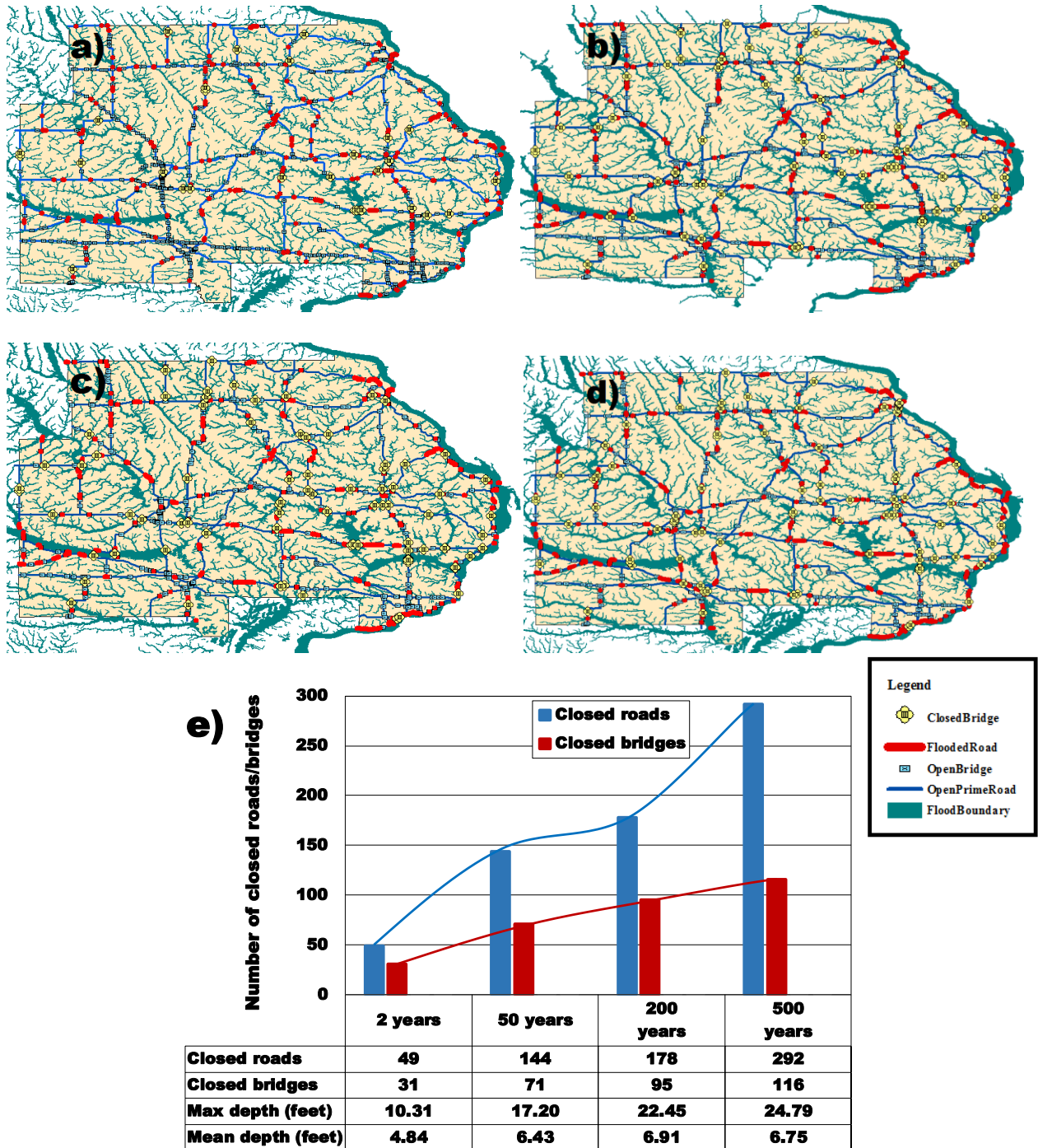
Figure 3.2. Damaged network maps and closure information under flooding scenarios: (a) return period of 2 years, (b) return period of 50 years, (c) return period of 200 years, (d) return period of 500 years, and (e) aggregated data under different flooding events

This study went on to examine the extent of damages on the network topologically after estimating the obvious physical damages. Table 3.1 shows the topological data for the network for each flood event.

Table 3.1. Values of topographical indices under different flooding events

Flooding years	No flood	2 years	50 years	200 years	500 years
d_{avg}	0.0252	0.0250	0.0249	0.0248	0.0244
$D^{0.1}{}_{avg}$	0.0023	0.0022	0.0019	0.0017	0.0011
C_{avg}	3.76×10^4	3.76×10^4	3.76×10^4	3.76×10^4	3.24×10^4
$Tr^3{}_{num}$	3,899	3,835	3,702	3,673	3,522
P_{avg}	0.3988	0.3974	0.3952	0.3966	0.4006
SP_{num}	3,888,348	869,636	327,71 4	388,103	250,838

The nodal degree decreased as the flood events intensified, which describes slow loss of node connections. The more lost links, the greater the possibility that a node is completely disconnected from the network. The cluster coefficient did not vary much during the analysis, which means that most clusters are formed right away after minor flood events. The residual shortest paths decreased as flood events intensified, which is counterintuitive. The paths should increase because detours are usually longer given that they must go around a flooded area. However, many links could be cut off completely, and, consequently, there is no path to the destination. This implies there are complete disconnections of some origin-destination pairs within the network.

The study also calculated indirect losses due to the simulated flooding events. The average travel time for the fully functional network was 0.4584 hours and increased up to 22% for the 500-year flood event. The average delay of traffic increased after every flood event to a maximum of 0.0989 hours per flow. The last indirect loss measurements analyzed the increase of bridge and road closures and the rate of performance loss. The road and bridge closures increased from 0.69% after the 2-year flood to 4.21% after the 500-year flood. A 17.7% decrease in performance after the 500-year flood was the maximum loss for this analysis. The indirect transportation losses are shown in Table 3.2, and the performance loss values are presented in Figure 3.3.

Table 3.2. Characteristics of indirect transportation losses under different flooding events

Flooding years	No flood	2 years	50 years	200 years	500 years
Travel time per flow (hour)	0.4584	0.5411	0.5459	0.5492	0.5573
Traffic delay per flow (hour)	0	0.0827	0.0875	0.0908	0.0989
Transportation performance (P_{net})	100.0%	84.7%	84.0%	83.5%	82.3%
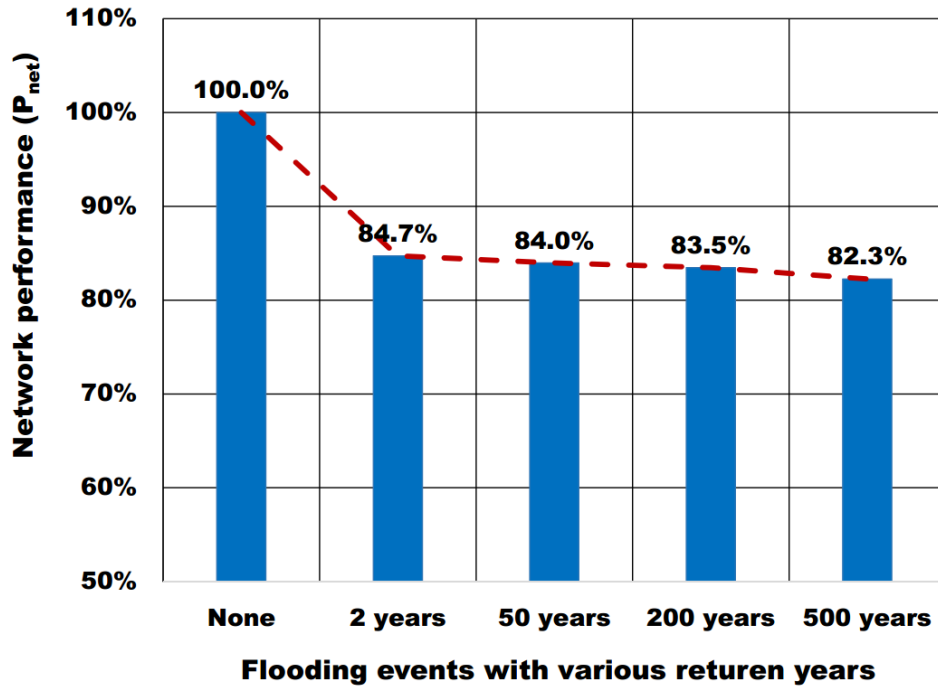
Figure 3.3. Performance loss for the network after flood events

This study illustrates the accumulated significance of indirect losses when closures due to flooding take place in the network. Comparing to directly presenting the easily estimated closure duration due to sustained damaged, this study developed the evaluation approach to illustrate the accumulated significance of indirect losses right after overtopping occurs in the network. To prevent such socio-economic losses in the network, there needs to be specific attention to the mitigation strategies that will minimize the likelihood of flood-induced closures.

This is the focal point of the case study analysis considered in Chapter 4. The accumulated significance of indirect losses are important for this specific report, because it will use many of the same measurements that were calculated for this study. However, the direct costs of rebuilding the assets and the indirect costs of lost trips and time also need to be considered to complete a robustness assessment (Chapter 4).

The focus for this study was to show that performance is negatively affected by flooding events. It is important to provide more attention to this problem and to have a measured approach to understanding the short- and long-term of flood-induced closures in transportation networks transportation network.

This project provides a meaningful and easy-to-implement procedure to evaluate the likelihood of damages to the transportation network due to flood events, estimate the direct and indirect losses associated with such closures, and use the results as a tool to prioritize different projects while considering the long-term implications of mitigation efforts on the life cycle of assets considering the likelihood of flood events.

4. MULTI-SCALE RESILIENCE ASSESSMENT FOR FLOODED IOWA NETWORKS

4.1. Introduction

We can divide resilience into three major components:

- Capacity to absorb the shocks induced by flooding events either by having characteristics that make the transportation network less vulnerable to flood events (such as higher elevation of roads and bridges and scour mitigation strategies in bridges, to name a few) or by providing alternative routes to potentially vulnerable roads and bridges

- Capacity of the Iowa DOT and local authorities to restore the functionality of the network in the shortest possible time after flooding events, to reduce the recovery time with pre-defined plans, ready-in-place contracts, and human and instrument resources ready to be deployed (and potentially using strategies such as accelerated bridge construction) (Zhang and Alipour 2020c)

- Capacity to plan for the failures with the goal of benefitting from the window of opportunity provided by the failures to build to a better standard in such a way that the vulnerability of the transportation asset to future events of similar or even higher scales is reduced in the long term

To the authors of this report, it is only by consideration of all of the abovementioned major components that any DOT (including the Iowa DOT) can achieve a pathway to complete resiliency.

This project, as the first phase of a multi-tiered project, was specifically focused on the first of the three components mentioned above. If a transportation network is robust, it has the ability to absorb the shocks imposed by events such as floods by not only enhancing its capacity to combat the adverse effects of floods but also by providing alternative routes to those closed segments.

Contrary to most of the available studies that just account for the development of methods and strategies to either assess the likelihood of closures or assess the impact of improvement strategies to individual assets of the system in silos, this study introduces a holistic resilience assessment approach that not only is capable of assessing the vulnerabilities to the multiple physical transportation assets but also account for the extent of transportation robustness, considering its redundancy (i.e., the capacity to provide alternative routes).

This project also went one step further toward similar studies, by characterizing the socio-economic impact of closures through the characterization of the extent of traffic delays and their associated costs. Noting that this characterization of such costs is conducted right after the flooding event occurs and does not include the potential longer disruption to the transportation network due to the recovery efforts that fall under the purview of the second major component mentioned above, that is a focus for future studies.

A few methods that capture specific measures for analysis after an extreme flood event have been used to measure robustness in recent years. However, the methods fail to capture the entire scope of damages caused by an event as large as a flood.

For example, a community could have two floods that have the same overall flood stage height but could behave in very different ways. One could occur and recede very quickly and the other could recede over a long period of time. The assets would have nearly the same vulnerabilities for each flood, but the flood's impact could be felt with different magnitudes. The same bridges and roads would be closed, but they would be closed for a longer period of time if the flood recedes slowly. Therefore, the indirect losses for a community would be much greater depending on the delays and canceled trips.

This chapter develops a composite multi-scale transportation-system robustness model considering flood hazards by synthesizing geographical damage recognition, topological functionality analysis, network operation evaluation, and traffic-user loss estimation (which involve a big part of the methodology in Chapter 3). This integrated model was applied in a real-world Iowa highway network, mainly revealing that a given intensive flood occurrence with different mitigation actions may result in a variety of post-event disruptions in the transportation network. To assist asset owners in developing more reasonable prevention and recovery plans, the developed multi-scale resilience index (MRI) presents both visible, multi-denominational flood consequences and an overall post-event transportation-system robustness indicator.

The MRI can also be used to see if the mitigation methods improve the MRI of the networks compared to the no-action strategy. Figure 4.1 illustrates the overall methodology of this study.
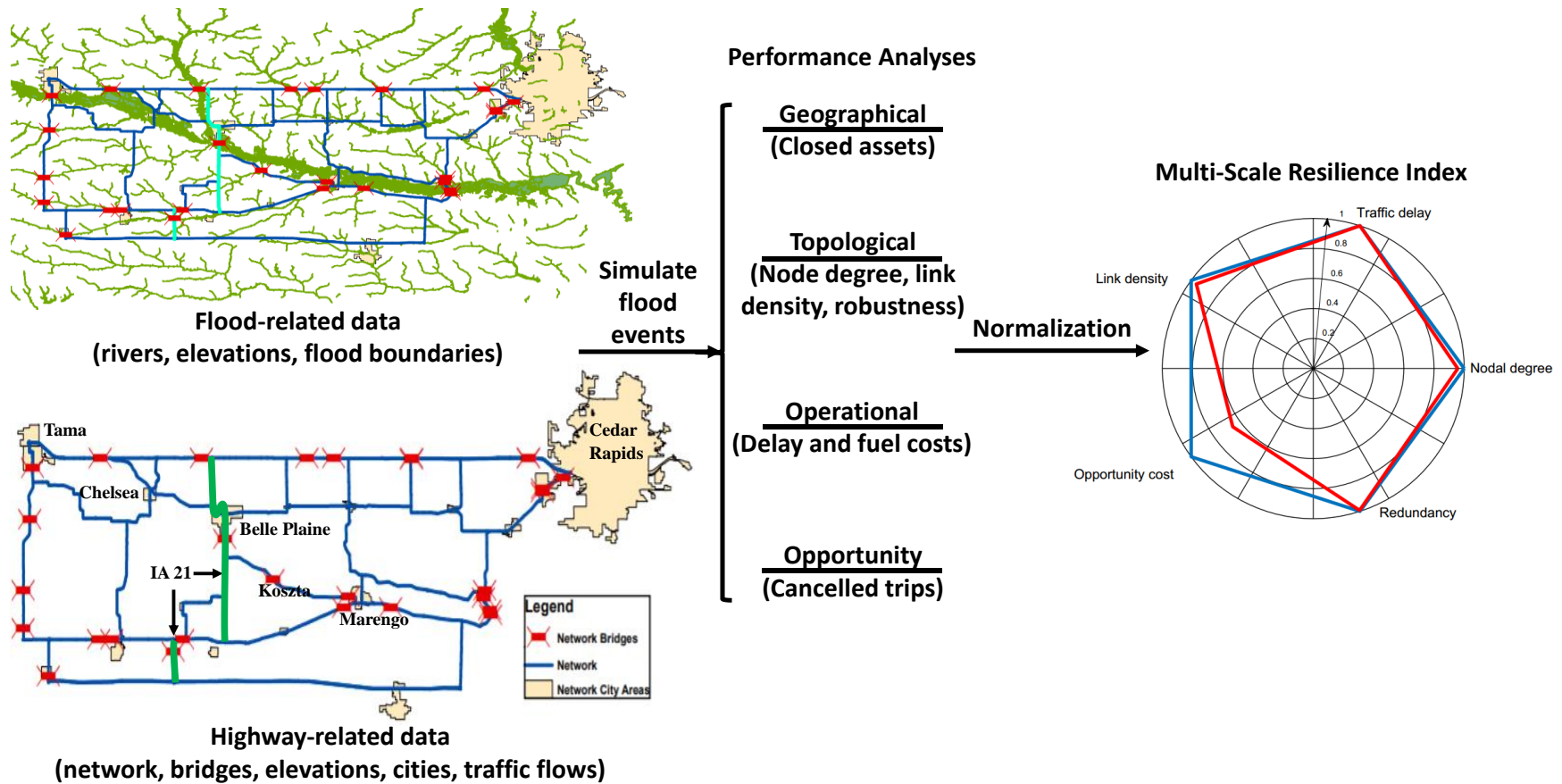
Figure 4.1. Flow chart illustrating the multi-scale resilience index methodology of this study

4.2. Multi-Scale Resilience Index

There is a challenge for researchers to create a common approach to analyze transportation networks for their flood resiliency. One method currently used is to examine flood water depths at asset locations. A bridge or road is considered unusable once the flood water has risen above the road height or the height tolerance of a bridge. However, there is not a single available universal criterion for bridge tolerances given the uniqueness of each bridge structure. Therefore, surveying historical flood data from local agencies is a viable approach to provide better estimates of the vulnerability of the system.

A transportation network consists of roads and intersections that can be represented as a graph created with links and nodes. Graph theory can be used to quantify robustness of a network by comparing indices calculated for pre- and post-flood functionality of the network Three indices can be used to measure network robustness: node degree, link density, and path redundancy.

A node degree calculation is the sum of all incoming and outgoing links on that single node. To make this a characteristic that describes the entire network, the number of links connected to each individual node is averaged across the system. This parameter was described in section 3.3 as d_{avg} and is illustrated in Figure 4.2.

Figure 4.2. Example of a node with two incoming links (red arrows) and two outgoing links (blue arrows)

Network-level link density is the ratio of the total number of links to the maximum number of links if every node is directly connected with every other node in the system, *N(N-1),* where *N* is the number of nodes. This value is measured between 0 and 1. A network is considered very sparse and not robust if the link density value is close to 0 and is considered more robust if the value is closer to 1. Figure 4.3 presents a simple example of a perfect link density of 1.
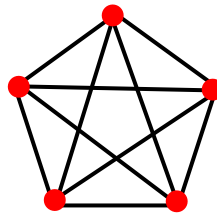

Figure 4.3. Simple example of network with a network-level link density of 1

The total number of links is equal to the maximum number of links possible.

Because floods usually damage a section of the entire transportation network, a residual network remains to satisfy travel demands with alternative routes, although, of course, these do not reflect

the most economic set of initial paths. Therefore, the extent to which a damaged network could reflect the greatest number of alternate paths is a necessary reflection of network robustness or structural strength.

The redundancy ratio, Re_{graph}, is a measurement that reflects the number of alternate paths a road user could take after a flooding event. This ratio quantifies all available routes from one node to all its neighbors' neighboring nodes. It represents a comparison between the original network and the network post-event and is calculated by dividing the number of available paths from every node to its neighbors' neighboring nodes post-flood by the number of available paths from every node to its neighbors' neighboring nodes pre-flood. Figure 4.4 provides a visual representation of this.
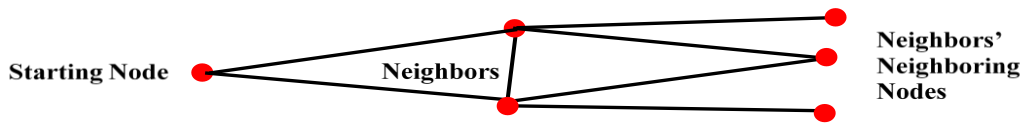
Figure 4.4. Paths used to calculate the redundancy ratio

The formulation is presented in equation (4.1), in which all parameters with the prime mark represent the flooded network and parameters without the prime superscript mean a daily operational traffic network.

$$Re_{graph} = \sum_{i' \in N'} \sum_{j' \in V'(i)} path(i',j') / \sum_{i \in N} \sum_{j \in V(i)} path(i,j) \tag{4.1}$$

where $V(i)$, $V'(i)$ are the set of neighbors' neighbor nodes of node i. $path(i,j), path(i',j')$ are paths from node i to j under operational and flooded conditions, and N is the set of nodes.

This characteristic can be very insightful for a large network with many damaged assets. The three indices—node degree, link density, and redundancy—are calculated for the fully operational network as well as for after a flood event scenario. The closer the post-event values are to the pre-event values, the more robust the network is with respect to traffic network connectivity.

Network operations can also be analyzed through the interaction of road capacity, traffic flow, and vehicle speed. These parameters minimize traffic travel time through optimal network performance. However, when flood events occur, these parameters can severely affect travel time with non-recurrent traffic delay and the indirect economic losses from those delays. The economic losses attributed to traffic delays post-flood are calculated only from the remaining trips and traffic demands. This cost is calculated from possible vehicle maintenance and added fuel expenditures from congestion or long detours and the additional labor costs.

Another indirect cost from floods is the canceled trips that cannot be completed because portions of the network are closed, resulting in long detours that would render the trips either unrealistic

or virtually impossible. These lost opportunities for businesses can become costly depending on the severity and length of the closures. This study characterizes these losses as the opportunity cost. The total indirect cost for a flood event is the sum of the delay cost and the opportunity cost.

The proposed MRI helps to determine how much a flood disrupts a network and community. For the average nodal degree, link density, and network redundancy, normalization is the division of their values by the values under operational network conditions and then taking those times their weights of importance, as shown in equation (4.2).

$$\text{N}(Deg_{avg}/\text{Density}/\text{Re}_{graph}) = W_{Deg_{avg}/\text{Density}/\text{Re}_{graph}}(Value'/Value^0) \tag{4.2}$$

As before, the prime superscript reflects the occurrence of floods and the zero superscript reflects daily transportation operations. The weight value in Equation (4.2) equals 1 in common conditions where the related parameters act with the same importance as all of the others in an MRI radar chart. This weight can range from 1 down to 0 with the lower value corresponding to the heavier change/influence in the MRI chart. For instance, $W_{Deg_{avg}} = 0$ means the decision-makers want to enhance the influence of the average nodal degree to a very severe condition where the flood has made a complete disfunction of the network's nodal topological feature. However, such an extreme weight value should be carefully treated with a series of support data. Formulizations in equations (4.3) through (4.5) are the normalization of traffic-delay losses, traffic-trip reduction, and opportunity costs, reflecting the resistance or residual ability of the network serviceability.

$$\text{N}(L_d) = 1 - (1 + W_{L_d}) L_d'/L_d^{wc} \tag{4.3}$$

$$\text{N}(D_{red}) = 1 - (1 + W_{D_{red}})D_{red}'/\sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}} D_{(i,j)}^o \tag{4.4}$$

$$N(L_{opp}) = 1 - (1 + W_{L_{opp}})L_{opp}'/L_{opp}^{wc} \tag{4.5}$$

where L_d^{wc} is the network-level traffic delay losses when all roads reflect a 50% traffic time increase, considered as the worst situation. Similarly, L_{opp}^{wc} is the worst-situation opportunity loss when all traffic trips have been removed by floods. Weights in equations (4.3) through (4.5) also stand for the magnified effect of losses. These weights should be nonnegative and ensure $\text{N}(L_d/D_{red}/L_{opp}) \geq 0$. For instance, $0 \leq W_{L_d} \leq (L_d^{wc}/L_d' - 1)$. Here, 0 is the common condition where the related parameter acts with the same importance as the other parameters in the MRI. When $W_{L_d} = (L_d^{wc}/L_d' - 1)$, it magnifies the loss induced by the flood event to the most adverse situation such that traffic delay is thought to be reaching the lowest value of network serviceability that would be characterized as no resistance to traffic delay, $\text{N}(L_d) = 0$. Other values in the weight domain are conditions where this parameter is not reaching the most extreme conditions but has some effect on decision making.

In summary, the developed algorithm provides decision makers with the opportunity to weight different measures considered in the MRI differently depending on how they'd like to go about prioritizing their decisions. This is a great feature of the developed MRI given it can be tuned to the local needs of the transportation agency or agencies.

In this chapter, all weights are set in their default conditions. After setting up the radar chart and the associated weights, MRI can be calculated as the percentage of the area within the red line (flooded network performance) divided by the area within the blue line (operational network performance) (see equation (4.6) and the previous Figure 4.1).

$$\text{MRI} = Area_{red}/Area_{blue} \tag{4.6}$$

The other two network cases with all of the flooding scenarios are compared to the original network under normal operation. After each flooding scenario is simulated, the network may lose some level of functionality depending on the extent of damage to its assets. Additionally, mitigation methods, such as pre-event infrastructure maintenance, can be applied to the network to reduce the operational and economic losses.

The developed MRI provides a holistic overview of the network vulnerabilities, availability of alternative routes, and potential socio-economic impacts on the communities served by the transportation assets. With adjusting the weights of different measures, decision makers and planners can specifically focus on different measures impacting the MRI (for example focusing accessibility right after floods, or availability of alternative routes, or economic implications in terms of driver delay costs) or just using similar weighing factors such that they can have a holistic understanding of the state of the network.

The hazard analysis component, allows for either a scenario-based approach (where a specific flood scenario, such as a 100-year flood return on the Iowa River, is considered) or a life-cycle analysis using multiple floods with their associated return periods. These capabilities provide a very robust framework for DOT decision makers and planners to identify hotspots under different scenarios of flooding and implement an MRI in their project prioritization tool in such a way that it informs better decisions for the long-term resiliency of the Iowa DOT primary system.

4.3. IA 21 Case Study

While the MRI provides a robust means to holistically study the resilience of a large system, it is also applicable in applications with a more focused nature. In this part of the study, the developed MRI framework was applied on a smaller road network and used for benefit/cost analysis of the pre-event mitigation strategies considering the larger impacts closures could have on the communities this roadway serves. For this purpose, IA 21 was considered.

IA 21 is a 97-mile state highway running north-south in east-central Iowa. It begins west of Hedrick at IA 149 and ends in Waterloo at US 20. This area has a history of flooding, and IA 21 has flooded multiple times in recent years (see Figure 4.5).
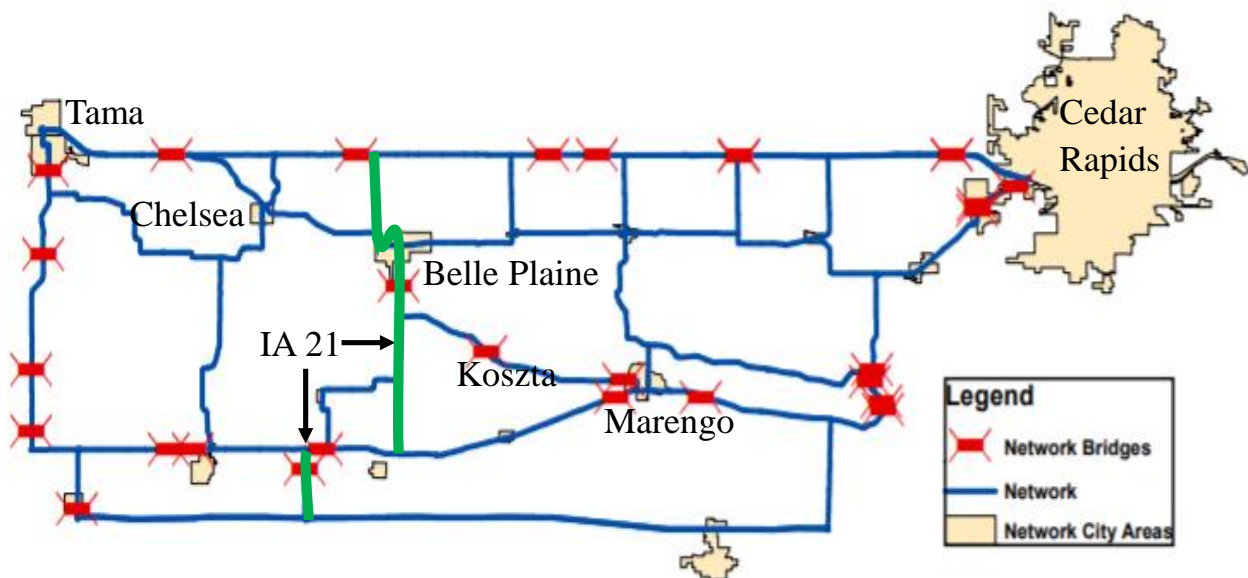

Figure 4.5. Network surrounding IA 21 used to analyze flooding effects

Belle Plaine is a town just to the north of the Iowa River, which flows from the northwest to the southeast. Unfortunately, IA 21 is the only highway traveling south out of Belle Plaine, so when IA 21 floods, travelers must take a large detour around the flooded area.

If individuals are traveling to the east, they cannot go through Koszta, because it is usually flooded as well. Network users must travel an extra 20 miles east to go through Marengo. For a western destination, the detour is nearly 30 miles farther west past Tama to find a non-flooded roadway by Montour. The bridge and road by Chelsea are also not usable during a flood event.

Not only do individuals who use this network, including those who work in Cedar Rapids, get stuck with lengthy detours, but businesses in this area are also impacted. Dollars are lost from trips being canceled or delayed due to flooded roadways. Not only are there direct costs to repair the transportation assets, but there are significant indirect costs from delays and lost business opportunities. This is a serious issue that negatively affects the community of Belle Plaine and the surrounding area.

The road network used to analyze the impact of a flood in this area includes roads in five counties and one major city, Cedar Rapids. The network spans from Tama in the northwest across to Cedar Rapids in the northeast and south as far as I-80. There are 744 links and 700 nodes. The network also includes 29 state-owned bridges along the 351 miles of roadway. The list of bridges in the network with locations and building materials is shown in Table 4.1.

Table 4.1. Bridge information for the IA 21 network

No.	Bridge ID	Longitude	Latitude	Material
1	0625.7S030	-92.1497	41.9638	Concrete
2	0627.8S030	-92.1082	41.96375	Concrete
3	0635.8L030	-91.9868	41.96356	Concrete
4	0635.8R030	-91.9871	41.96323	Concrete
5	0654.2S021	-92.2778	41.86684	Concrete
6	4805.4S212	-92.2028	41.81794	Concrete
7	4809.0S151	-91.8638	41.77625	Concrete
8	4809.3S151	-91.8652	41.78202	Concrete
9	4810.4S151	-91.8751	41.79629	Concrete
10	4811.2S151	-91.8732	41.80508	Concrete
11	4811.9S212	-92.0856	41.79704	Concrete
12	4820.3S006	-92.0924	41.78533	Concrete
13	4820.3S006	-92.0196	41.78545	Concrete
14	5722.0S151	-91.7838	41.92296	Steel
15	5722.3S151	-91.7829	41.92672	Steel
16	5724.3S151	-91.7517	41.94061	Steel
17	5745.2L030	-91.8048	41.96425	Concrete
18	5745.2R030	-91.8054	41.96401	Concrete
19	7900.9S006	-92.4536	41.74629	Concrete
20	7903.2S063	-92.5913	41.76035	Concrete
21	7906.3S063	-92.5914	41.80507	Concrete
22	7906.6S006	-92.3435	41.74661	Concrete
23	7940.3S021	-92.3579	41.73183	Steel
24	7997.1S06	-92.5522	41.70217	Concrete
25	7999.8S006	-92.4743	41.74612	Concrete
26	8609.2S030	-92.4716	41.96385	Concrete
27	8612.3S063	-92.5815	41.89075	Concrete
28	8616.7S063	-92.5771	41.95231	Concrete
29	8617.2S030	-92.3141	41.964	Concrete

Iowa DOT staff believe a quarter-mile section of IA 21 needs to be raised about a foot with additional culverts to maintain water flow under the road when a flood event occurs. The solution they recommend is to raise that section of road 2.5 feet to significantly improve the level of service so the road can also be resilient against worse floods. The Iowa DOT provided a concise cost estimate of $2.5 million to raise the grade and pave one mile of highway.

The direct repair costs were compared to the indirect losses of delays and business losses over a period of time. There are three parts to the results. Three analyses were completed to determine when a cost/benefit trade off begins when comparing network performance and construction fees.

Flooding scenarios (for 2-, 5-, 10-, 50-, and 200-year floods) were run using the network in its current state, which is called the **Base case**. The second case analyzes the network after changing every flooded road of the tested network with a water depth less than 2.5 feet to not flooded, which is called **Improved**. This was done to investigate how mitigating additional network roads and increasing the pre-flood construction costs affects the ability to have a positive benefit/cost ratio. The third case analyzes flooding scenarios on the network after mitigating only the sections on IA 21 (and not the entire network) with a flood water depth of less than 2.5 feet, which is called **IA 21 Improved**.

The data necessary to run these simulations were gathered from several sources. Bridge information was found in the Iowa DOT SIIMS database, and other elevation and depth data were added from LiDAR data and also flood stage data from the Iowa Flood Center. Table 4.2 shows the information used and its original data locations.

Table 4.2. Data obtained for the study of IA 21 floods

Information	Data Type	Data Details
Network Connectivity	ArcGIS (.shp)	Nodes (longitude and latitude) and links (polyline)
Transportation Operation	TransCAD (.mtx, .wrk, .dbd)	Transportation district boundary (polyline), OD nodes (longitude and latitude), traffic/TAZ demands (trip matrix), and road capacity (flows)
Floodplain Water Depth and Boundary	ArcGIS (.shp)	Floodwater over Iowa ground (ft)
Iowa Ground Elevation	ArcGIS (.shp)	Earth ground elevation (ft)
Bridge Elevation	SIIMS (.pdf)	Bridge elevation over Iowa ground (ft)

Table 4.3 shows how the individual costs were decided.

Table 4.3. Values of unit costs associated with sections 4.2 and 4.3 in the case study

Cost	Source	Reference Data	Value
C_{car}^d	Iowa DOT 2016, Schrank et al. 2015	• Passenger occupancy = $1.25/car • Congestion cost = $17.67/person/hour • Include costs of fuel, labor, and maintenance	$22.10 ($/hour/car)
C_{tru}^d	Iowa DOT 2016, Schrank et al. 2015	• Congestion cost = $94.04/truck/hour • Include costs of fuel, labor, and maintenance	$94.04 ($/hour/truck)
C_{car}^{opp}	Bureau of Labor Statistics 2019a	• Average full-time weekly earnings = $905	$198.50 ($/car)
	Bureau of Labor Statistics 2019b	• Percentage of employed and unemployed full- and part-time workers are 79.33%, 16.78%, and 3.9%, respectively	
C_{tru}^{opp}	Bureau of Transportation Statistics 2017	• 2015 national shipment weight by truck = 10,776 million tons • 2045 national shipment weight by truck = 14,829 million tons	$14,864 ($/truck)
		• 2015 national shipment value by truck = $11,626 billion • 2045 national shipment value by truck = $18,691 billion	
		• 2019 unit value by truck with annual growth factor = $1,101/ton	
	FHWA 2015	• Two truck weights used = 10 tons and 17.5 tons • Average truck weight = 13.5 tons	

These values were used to calculate the indirect costs when assets are closed for a certain amount of time. In an actual flood event, different roads and bridges could be closed for different periods of time. For this study, the lengths of time that the assets were considered closed depended on which flooding incident was being analyzed. Currently, literature is lacking on the average closure duration of assets based on flood intensity; therefore, the amount of time the assets were closed was assumed as shown in Table 4.4 for the simulations covered in this report.

Table 4.4. Road closure duration assumptions

Flood Scenario	2-Year	5-Year	10-Year	50-Year	200-Year
Closure Duration	5 hours	15 hours	30 hours	3 days	7 days

This information was used in every flood event analysis on all three scenario cases analyzed.

4.4. Results and Discussion

4.4.1. Base Network

The first network case studied was the base network. The base network is the control network, because there is no pre-event mitigation action. The five different flooding scenarios (2-, 5-, 10-, 50-, and 200-year) were simulated on the road network. Figure 4.6 depicts the flooded network after a 2-year flood event.
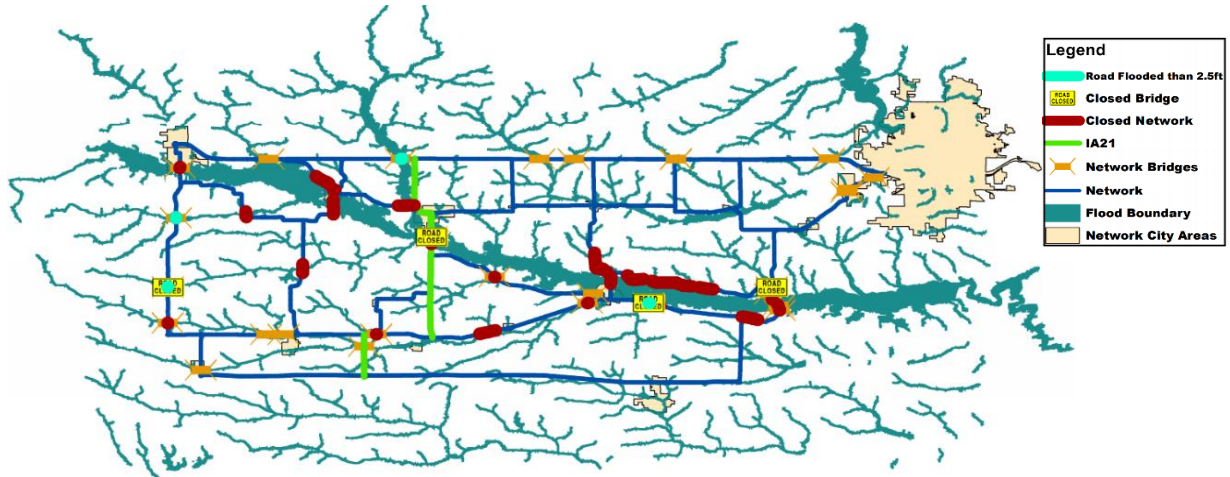

Figure 4.6. Base network flooding after a 2-year event

The other simulated flood events are included in Appendix A. The flooded roadway water depths ranged from 0 to 15 feet deep. The number of roads in a specific flooded water depth are also presented in Appendix A for the base network. As expected, the number of roads and bridges closed from flooding increased as flood intensity worsened. The number of closed roads was documented as individual numbers of links that were flooded on some part of the total roadway link. The network used in this report was provided by the Iowa DOT. For the total studied network, there were 744 individual links.

The closure information for every flood scenario is shown in Table 4.5.

Table 4.5. Closed roads and bridges after each flood event on the base network

Flood Scenario	2-Year	5-Year	10-Year	50-Year	200-Year
Closed Roads	35	49	58	81	95
Closed Bridges	4	8	10	14	16

The number of closed roads increased from 35 links after the 2-year flood to 95 links after the 200-year flood. The number of closed bridges increased from 4 to 16 as the flood scenarios worsened from the 2-year flood to the 200-year flood, respectively.

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After the number of closed roads and bridges were determined, the topological values of node degree, link density, and redundancy were calculated (see Table 4.6).

Table 4.6. Topological characteristics of the base network after each flooding event

Characteristic	2-Year	5-Year	10-Year	50-Year	200-Year
Node Degree	3.611	3.534	3.489	3.374	3.300
Link Density	0.003	0.003	0.002	0.002	0.002
Redundancy	0.170	0.170	0.165	0.164	0.162

The node degree values indicate between 3 and 4 links connected to every node in the network on average. As the flooding scenarios worsen, the average links per node decreases. The slight decrease in node degree indicates an increase in disconnected links. The link density value differences are minuscule, which suggests a limited number of nodes linked directly to other nodes. This could have been inferred given the network is made up of 700 nodes and 744 links. There would be many more links and fewer nodes if the network had a higher link density. The redundancy calculation also reinforces these calculations, because the redundancy values are also very small.

There are not many alternative routes to use as detours if roads are blocked in this network. Looking at these characteristics, one could infer that this network would have major problems with destructive flood events.

An important aspect of this study was to compare the cost of rebuilding and indirect economic impacts versus flood mitigation. The costs for rebuilding segments of roads and bridges were determined from Detailed Damage Inspection Reports (DDIRs) documented from previous flooding events in Iowa. The cost of repair used in this analysis was one common average value of $74,388.60 per mile, which was calculated from all the separate bridge and road repair costs, while the reports listed a description for the damages sustained on a specific asset, as shown in Figure 4.7.
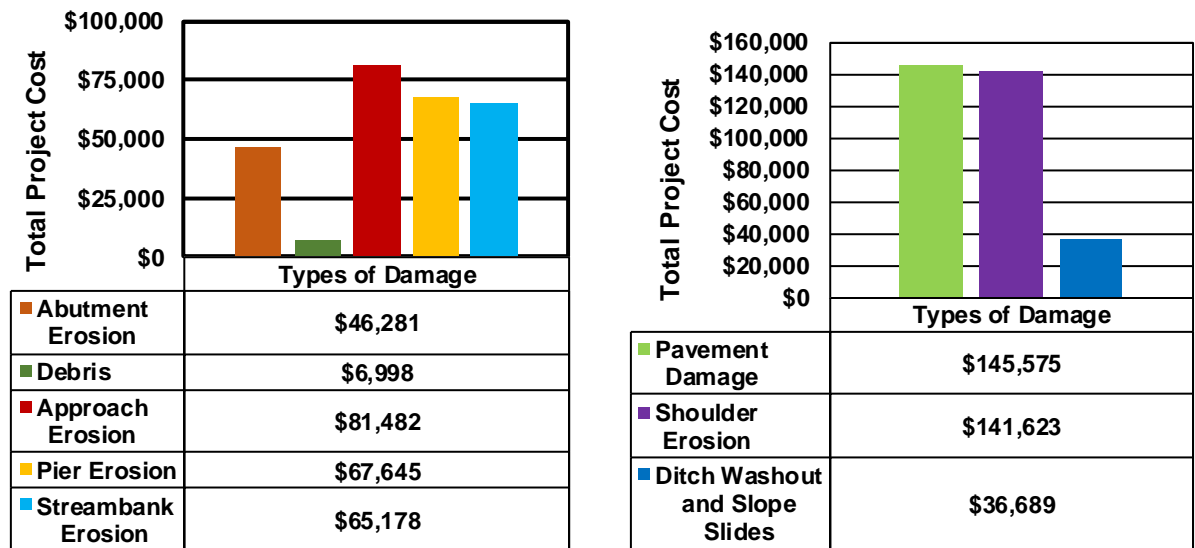
■ Abutment Erosion	$46,281
■ Debris	$6,998
■ Approach Erosion	$81,482
■ Pier Erosion	$67,645
■ Streambank Erosion	$65,178

■ Pavement Damage	$145,575
■ Shoulder Erosion	$141,623
■ Ditch Washout and Slope Slides	$36,689

Figure 4.7. The cost of each damage averaged to create a repair estimation cost

The tasks completed to repair the damages are shown below the bar charts with their corresponding costs. After collecting all the data, the most common tasks were documented and average costs were determined for each damage type. The average costs for the common tasks were added together to create the average cost for each bridge or road damage type.

To conduct a financial analysis, the total road miles closed was determined to find the cost of road repairs. This value was calculated by summing the length of all the closed road sections. The total post-flood road miles closed more than doubled from 17.00 to 36.24 miles in the 2-year and 200-year simulations, respectively. Using the average damage repair cost value and the assumed closure times in Table 4.4, the total repair costs were calculated.

The repair costs increased at the same rate as the closed road miles since an overall average value was used per mile for the repair cost. The repair costs increased from $1.265 million to $2.696 million. Since no roads were being raised for pre-flood mitigation in this scenario, the total direct cost is only the cost of repairs, as shown in Table 4.7.

Table 4.7. Direct costs of mitigation and repairs on the base network

	2-Year	5-Year	10-Year	50-Year	200-Year
Post-Flood Closed Miles	17.00	18.94	26.66	33.61	36.24
Pre-Flood Mitigation ($million)	0	0	0	0	0
Post-Flood Repair ($million)	1.265	1.409	1.983	2.500	2.696
Total Direct Cost ($million)	1.265	1.409	1.983	2.500	2.696

In addition to direct costs, indirect costs were calculated so the total cost can be used in a benefit/cost analysis for each scenario to determine if mitigation is financially beneficial. The

total indirect cost is the summation of the delay and opportunity costs. All calculated indirect costs are presented in Table 4.8.

Table 4.8. Indirect costs for the base network ($thousand, with duration)

Cost	2-Year	5-Year	10-Year	50-Year	200-Year
Opportunity	398.7	1,194.9	2,411.7	5,708.8	14,518.8
Delay	0.0	0.3	0.0	3.9	9.2
Total Indirect	398.7	1,195.1	2,411.7	5,712.8	14,528.0

The delay cost is very low for the first three flooding scenarios, as the closure time is obviously short, and it increases to $3,900 and $9,200 for the 50-year and 200-year floods due to the longer closures. One more reason for the delay costs being so small is they only sum the delay from trips that are taken. This network is closed enough from the floods that very few trips can be taken. More sections are closed in the 50-year and 200-year scenarios or when the water gets deeper in the same spots but there is still a relatively long alternative route available to reach the destination, so the delay cost increases.

Opportunity cost is considerably higher than the cost of delayed trips. The costs of opportunity lost from closed assets start at $398.7 thousand for the 2-year flood and increases to $1,194.9, $2,411.7, $5,708.8, and $14,518.8 thousand through the 200-year flood.

The total of the indirect costs for the base network increases from $398.7 thousand during the 2-year flood to $14,528.0 thousand during the 200-year flood. The opportunity costs are significant because most of the trips taken on an average day have to be canceled given there is no available route to take.

4.4.2. Improved Network

The second case analyzed the benefits of pre-flood mitigation across the entire network. This improved network raises every section of road in the network that has a flood water depth of less than 2.5 feet. Figures in Appendix A.2 and A.3 have the flooded road water depth information for all flood scenarios. According to the flooded road water depth charts, there are up to 60 closed road sections in the base network with a floodwater depth less than or equal to 2.5 feet. Improved network pre-flood mitigation would open many road sections compared to the base network condition and sustain network performance during the same flood events or scenarios. Figure 4.8 shows the flooding on the improved network after the 2-year flood simulation.
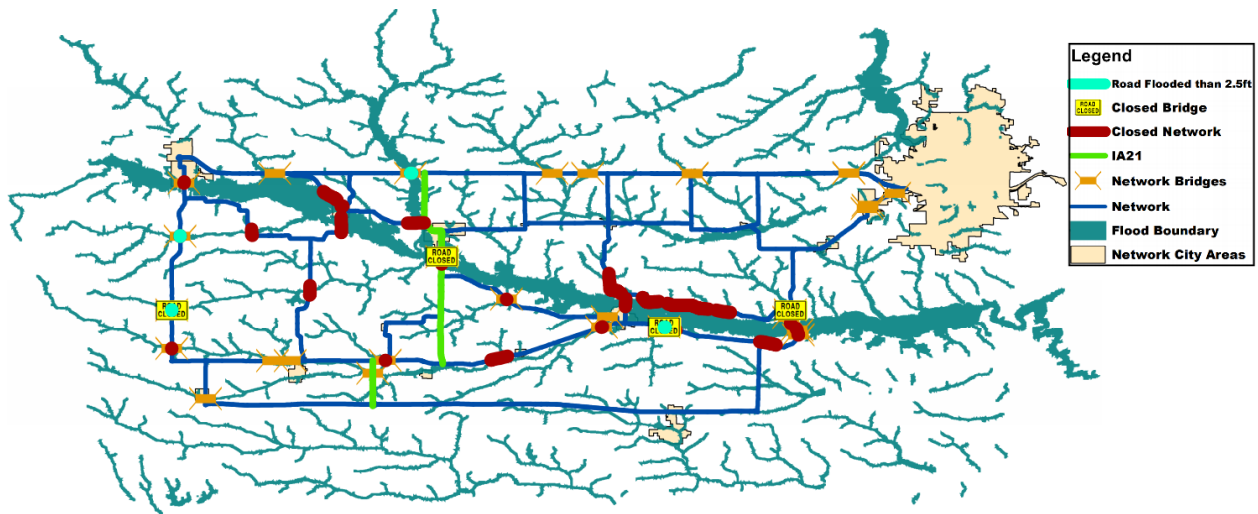
Figure 4.8. Improved network flooding after a 2-year event

The other flood simulations are included in Appendix A. Suffice it to say, this mitigation case made a drastic difference in closed road sections for every flood scenario. The number of closed roads for the 2-year flood scenario dropped from 35 to 8 when comparing the base network to the improved network. Similarly, significant decreases in road closures occurred for the other four scenarios as well, in order, as follows: 49 to 13, 58 to 15, 81 to 22, and 95 to 41. All scenarios experienced at least a 59% decrease in the number of closed roads. Since this improved network did not do any pre-flood mitigation on bridges, the number of closed bridges was the same for all base and improved network flood scenarios. The closed road and bridge information is shown in Table 4.9.

Table 4.9. Closed roads and bridges after each flood event on the improved network

	2-Year	5-Year	10-Year	50-Year	200-Year
Closed Roads	8	13	15	22	41
Closed Bridges	4	8	10	14	16

Topologically, the three characteristics discussed previously—node degree, link density, and redundancy—were also calculated for this improved case. The node degree of the network is very similar to the values of the base network, but it slightly improved for all flood event scenarios evaluated. This indicates that a few links that were cut off from nodes by being flooded by less than 2.5 feet were now connected again, which raised the node degree value slightly. The link density of the improved network remained unchanged except for the 10-, 50-, and 200-year calculations when compared to the base network. The newly connected links made little change to the overall link density values. Finally, the redundancy of the improved network also increased for all flooding simulations. The topological characteristics are shown in Table 4.10.

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Table 4.10. Topological characteristics of the improved network after each flooding event

Characteristic	2-Year	5-Year	10-Year	50-Year	200-Year
Node Degree	3.734	3.706	3.694	3.657	3.557
Link Density	0.003	0.003	0.003	0.003	0.003
Redundancy	0.171	0.171	0.171	0.170	0.169

The number of closed roads was discussed previously, but the more important factor is the change in the number of closed roadway miles. This statistic also dramatically decreased for every flood scenario. All flood event simulations have fewer than 9 closed road miles compared to the lowest previous number, which was 17 miles, in the base network analysis. The indirect costs might decrease given fewer closed road miles, but the direct cost of pre-flood mitigation increases. The cost to raise each road that has flood water depth over the pavement less than 2.5 feet was $38.72 million for the 2-year flood and increased to $69.28 million for the 200-year flood. This is a large cost, but repair costs significantly decreased with fewer closed roads to repair after a flood event. Costs dropped at least 75% for all five flooding scenarios.

The mitigation cost to raise the roads and the repair cost summed together are the total direct cost on the network. The direct cost is much greater than that for the base network because the mitigation costs on the improved network are demanding. The base network only had the direct cost of repairs (as shown previously in Table 4.7). The direct costs of the improved network are shown in Table 4.11.

Table 4.11. The direct costs of mitigation and repairs on the improved network

	2-Year	5-Year	10-Year	50-Year	200-Year
Post-Flood Closed Miles	1.51	2.19	3.72	6.95	8.53
Pre-Flood Raised Miles (Flooded Roads < 2.5 ft)	15.49	16.75	22.94	26.66	27.71
Pre-Flood Mitigation ($million)	38.72	41.88	57.35	66.65	69.28
Post-Flood Repair ($million)	0.112	0.163	0.277	0.517	0.635
Total Direct Cost ($million)	38.83	42.04	57.63	67.17	69.91

As previously described, the indirect cost is the summation of the cost of delays plus opportunity cost. One might infer that the delay cost for the improved network should be less than that of the base network with fewer closed roads. However, the delay cost is greater due to more trips being taken on the improved network. There are fewer canceled trips and more delays because detours still exist and more travelers are using the network. As previously discussed, the base network had small delay costs because motorists could not travel on the network with destination routes closed or limited to the degree that they were in the base case. With more open roads for the first three flood scenarios, they still may not be the most direct route, so the delay cost is higher. Once the flood scenario hits the 50- and 200-year event levels, the delay cost drops because there are

enough roads closed that more trips are canceled. The delay that was present for those trips is now zero.

The opportunity cost is much lower for the first three flood scenarios when compared to the base network because there are not many canceled trips; instead, they are delayed as previously discussed. Again, the opportunity cost increases dramatically for the last two flood scenarios because more trips are cancelled and more opportunities are lost.

The total indirect costs for this network are considerably less for the 2-, 5-, and 10-year floods than they were for the base network. The last two flood scenarios also have lower indirect costs, but they are closer to the previous network simulations (see Table 4.12). All scenarios have a large decrease in opportunity costs and an increase in delay costs.

Table 4.12. The indirect costs of the improved network ($thousand, with duration)

Cost	2-Year	5-Year	10-Year	50-Year	200-Year
Opportunity	0.0	30.2	60.4	3,144.2	12,424.0
Delay	9.8	72.6	181.4	47.5	13.6
Total Indirect	9.8	102.8	241.8	3,191.7	12,437.6

In this case, the opportunity and delay costs are inversely proportional. If the delay costs are large, the opportunity costs are small. The delay cost increases when there are many trips with a small number of available routes. Opportunity cost increases when many trips are canceled because there are no available routes. In the improved network, very few segments flood during the 2-year flood event, so the delay cost is low with zero lost opportunities. Moving to the 5-year flood scenario, there is an increased delay cost but a small opportunity cost. This means there are road segments closed but enough roads open that few trips are cancelled. Since there are fewer routes, the delay cost increases. The same thing is occurring for the 10-year flood scenario. More roads are closed, but there could be one route open for all the remaining trips, drastically increasing the delay cost. Once the 50-year event occurs, more trips are cancelled due to closed roads. There are still some trips being completed but with a delay due to congestion.

Figure 4.9 depicts total closed miles on the base nework along with the ratio of mitigated miles and closed miles on the improved network.
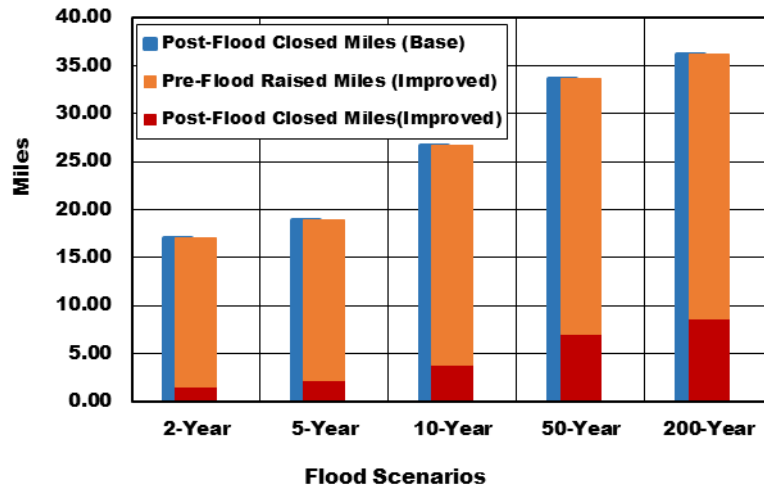
Figure 4.9. Comparison of post-flood closed road miles between the base and improved

The figure shows the number of roadway miles that are actually helped by raising them 2.5 feet. The large difference between the blue and red columns indicates there are many miles of mitigated roads.

4.4.3 IA 21 Improved

The third and final case for the network analyzes how the network would perform if only sections of IA 21 (and not the entire network) that had a flood water depth of less than 2.5 feet were raised. There are two or three sections of roadway on IA 21 that have a flood water depth less than 2.5 feet, depending on the flood scenario. No other roads in the network were altered from the base case for this comparison. The bridge with ID 0654.2S021 is flooded less than 2.5 feet from a 2-year flood and the bridge with ID 7940.3S021 is flooded less than 2.5 feet from a 10-year flood (as shown in the previous Table 4.1). With the road pavement raised, both bridges are considered mitigated and will not flood in these flood event analyses. For all flood scenarios, two fewer bridges are flooded and either two or three fewer roads are closed from the mitigation on IA 21 (see Table 4.13).

Table 4.13. Closed roads and bridges after each flood event on the IA 21 improved network

	2-Year	5-Year	10-Year	50-Year	200-Year
Closed Roads	33	47	55	78	92
Closed Bridges	3	7	8	12	14

The topological characteristics help to show the impact on the network and are presented in Table 4.14.

Table 4.14. Topological characteristics of the IA 21 improved network after each flooding

Characteristic	2-Year	5-Year	10-Year	50-Year	200-Year
Node Degree	3.614	3.543	3.503	3.386	3.311
Link Density	0.003	0.003	0.003	0.002	0.002
Redundancy	0.171	0.171	0.168	0.166	0.164

The node degree of the system is slightly larger than that of the base network with a few extra links going in and out of their connected nodes. The link density is not visibly affected in the calculations but is slightly improved. Finally, the redundancy of the network has also slightly improved across all flood scenarios. The availability and accessibility of IA 21 has increased the redundancy of the network because this road can be used for detours more often.

From Table 4.15, there are only 0.13 raised roadway miles for the 2-year flood scenario, and that increases to 2.33 miles for the 200-year event. These values are much lower than those for the base network values of 17.00 miles and 36.24 miles, respectively.

Table 4.15. Direct costs of mitigation and repairs on the IA 21 improved network

	2-Year	5-Year	10-Year	50-Year	200-Year
Post-Flood Closed Miles	16.87	17.61	25.31	31.28	33.91
Pre-Flood Raised Miles (Flooded Roads < 2.5 ft)	0.13	1.33	1.35	2.33	2.33
Pre-Flood Mitigation ($million)	1.43	4.43	5.79	8.23	8.23
Post-Flood Repairs ($million)	1.222	1.277	1.811	2.255	2.451
Total Direct Cost ($million)	2.65	5.71	7.60	10.49	10.68

The costs to raise these road sections are $1.43 million and $8.23 million for the 2-year and 200-year events, respectively. The repair costs are less than that of the original base network with slightly fewer road miles closed from flooding.

Overall, the direct cost for the IA 21 improved network scenario is more than that of the base network. It costs more to raise the road sections than to repair them once after a flood event according to the calculations. The 200-year direct costs of $10.68 million were more than three times as much as the base network direct costs of $2.696 million. All direct cost information is listed in the bottom row of Table 4.15.

The indirect costs are important in evaluating whether mitigating IA 21 will be worth the initial direct financial investment. The indirect costs are presented in Table 4.16.

Table 4.16. Indirect costs of IA 21 improved network after every flood scenario ($thousand, with duration)

Cost	2-Year	5-Year	10-Year	50-Year	200-Year
Opportunity	393.1	1,165.5	2,268.7	5361.6	13,708.5
Delay	0.0	0.3	0.5	1.3	2.9
Total Indirect	393.1	1,165.7	2,269.2	5,362.9	13,711.5

When compared to the base network, the delay costs are approximately the same for the 2-, 5-, and 10-year floods and are less for the 50- and 200-year floods. By having IA 21 open more, there is another north/south road for users to travel on. If motorists can travel through the middle of this transportation network instead of driving around the outside due to floods, it decreases delay time.

The opportunity cost also decreases for every flood scenario because fewer trips are canceled with IA 21 open more. The opportunity cost is still very large because many other roads in the IA 21 improved network are still flooding. Figure 4.10 provides a visual comparison between the total closed miles in the base network and the ratio of closed and raised miles in the IA 21 improved network. Many miles of roads are still closed from flooding but raising IA 21 is an improvement.
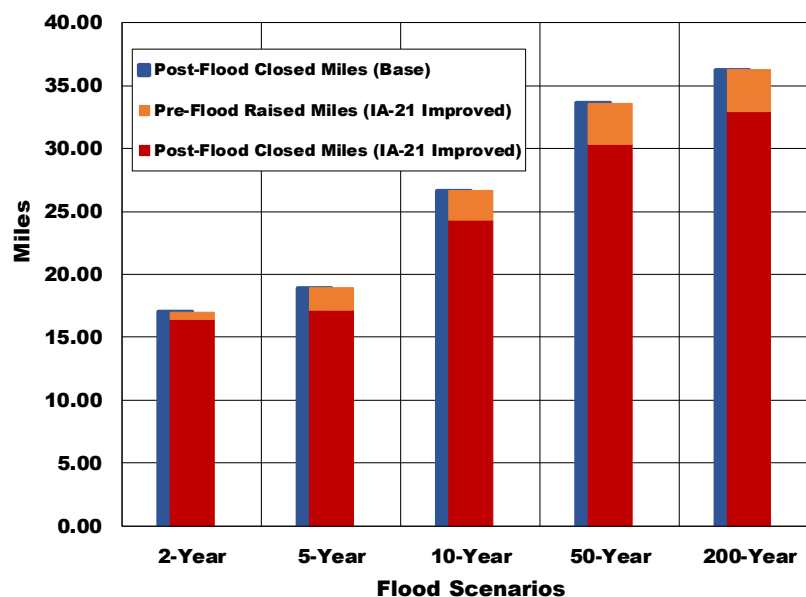
Figure 4.10. Comparison of post-flood closed road miles between the base and IA 21 improved networks

Figure 4.11 provides a visual comparison between indirect costs of the three analyzed network cases.
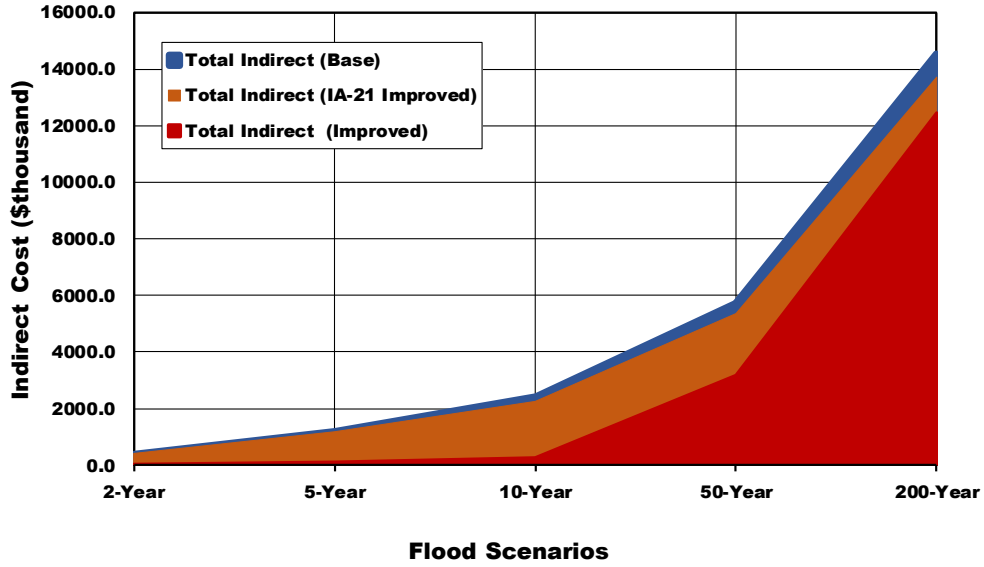
Figure 4.11. Comparison between the indirect costs for all networks and flooding scenarios

Both improved networks decreased indirect losses from mitigating roads. However, the improved network makes the largest difference for the 2-, 5-, and 10-year floods, which are also the common floods that the network will experience. Once the flood events worsen, the 2.5-foot raised road sections do not make a large enough difference, because the flooded road water depths are increasing. More roads are being flooded and are flooded by deeper water.

4.4.4 Benefit/Cost Analysis

To decide whether and when these two actions are financially beneficial in the long term, this part introduces a benefit/cost ratio approach that is done by summing the difference of repair costs under the Base case and any of the two flood-mitigation cases, with the difference of indirect delay and opportunity costs under the Base case and any of the two flood-mitigation cases, and then timing the occurrence probability of a flood to calculate the annual losses, then multiplying that by the years for the cumulative effect, and finally dividing that effect by the difference of mitigation construction cost between any of the two flood-mitigation cases and the Base case (see previous equation (4.1)).

$$\frac{Benefit}{Cost} Ratio = \frac{[(C_{rep,b}-C_{rep,f}+C_{D,b}+C_{O,b}-(C_{D,f}+C_{O,f})]\times P_{occur,f}\times years}{C_{mit,f}-C_{mit,b}} \tag{4.1}$$

If the value of the benefit/cost ratio is greater than 1 after a few years, which implies the monetary loss-saving in the long run is larger than the additional flood-mitigation investment, the mitigation strategy applied in the analysis is financially beneficial. For a visual illustration, see Figure 4.12.
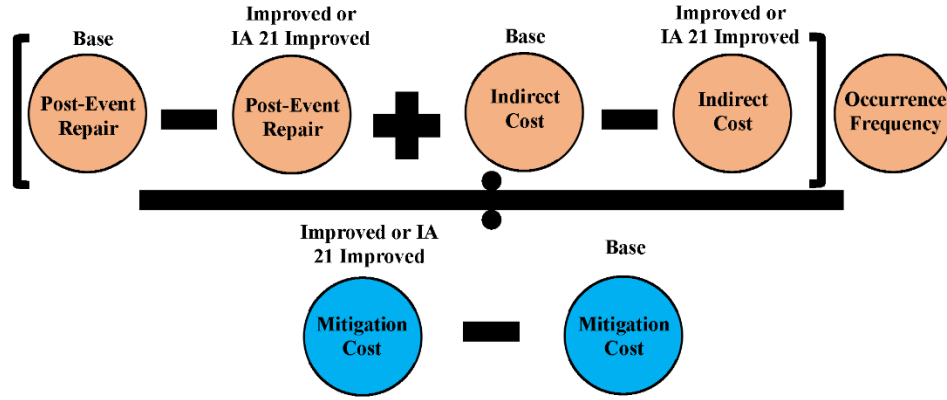
Figure 4.12. Visual representation of the benefit/cost ratio calculation

In equation (4.1), $C_{rep,b}$ and $C_{rep,f}$ are the repair costs for the Base case network and one of the mitigated networks under any flood, f, respectively. The indirect costs under any flood, f, of the Base case network and one of the mitigated networks are $C_{D,b} + C_{O,b}$ and $C_{D,f} + C_{O,f}$, respectively. $C_{D,b}, C_{D,f}$ are the indirect losses attributed to traffic delay under the Base case network and one of the mitigated networks; similarly, $C_{O,b}, C_{O,f}$ are the total opportunity costs for various flood scenarios. The costs at the denominator are the mitigation costs of one of the mitigated networks ($C_{mit,f}$) and of the Base case network ($C_{mit,b} = \$0$). $P_{occur,f}$ is the annual occurrence probability of a flood f.

It can be seen that conflicts exist when implementing flood mitigation measures. The most desirable flood-mitigation strategy should be the one that provides the most effective mitigation performance. However, it brings an unaffordable investment for planners who always face the limitation of funding. So, these two factors generate conflicts. To weaken the conflicts and reach a balanced solution, the long-term benefit/cost ratio was analyzed here, and the results are listed in Table 4.17.

Table 4.17. Benefit/cost ratio results for all cased under five flood event scenarios

Flood intensity	2-Year	5-Year	10-Year	50-Year	200-Year
Cumulative flood mitigation effect after 3 years (×$1,000 for loss savings)					
Loss savings (IA 21-Improved)	1,814	786	502	110	27
Benefit/Cost Ratio (IA 21- Improved)	1.27	0.177	0.087	0.013	0.003
Loss savings (Improved)	2,472	1,491	1,225	287	65
Benefit/Cost Ratio (Improved)	0.064	0.036	0.021	0.004	0.001
Cumulative flood mitigation effect after 35 years (×$1,000 for loss savings)					
Loss savings (IA 21- Improved)	21,158	9,174	5,856	1,285	314
Benefit/Cost Ratio (IA 21- Improved)	14.848	2.071	1.012	0.156	0.038
Loss savings (Improved)	28,836	17,395	14,294	3,352	760
Benefit/Cost Ratio (Improved)	0.745	0.415	0.249	0.050	0.011
Cumulative flood mitigation effect after 70 years (×$1,000 for loss savings)					
Loss savings (IA 21- Improved)	42,316	18,348	11,712	2,569	629
Benefit/Cost Ratio (IA 21- Improved)	29.696	4.141	2.023	0.312	0.076
Loss savings (Improved)	57,672	34,789	28,589	6,704	1,520
Benefit/Cost Ratio (Improved)	1.489	0.831	0.498	0.101	0.022

When the benefit/cost ratio is more than 1, it means the cost on the mitigation realizes a higher savings on infrastructure repair and user loss than the value of the mitigation cost, which leads to a long-term financial benefit. Due to the uncertainty of flood events, it is difficult to say exactly which flood will occur at which year. Thus, this study adopted the flood probability to the calculation of annual flood impacts, so that the annual impact of a flood is the product of the losses if the flood happens along with its occurrence probability.

Finally, the cumulative flood-caused loss is easily estimated by the annual flood impact timing years. After that, the long-term benefit/cost ratio is the division of the cumulative flood-caused loss by the one-time flood mitigation investment.

When it comes to the details of Table 4.17, first, when the number of years goes to 3 after the use of flood mitigation, the IA 21 Improved mitigation action starts to create a positive benefit/cost ratio (1.27) result to mitigate the 2-return-year flood. The Improved mitigation stays in a very low benefit/cost ratio due to the huge investment, but less than 0.064. When it reaches 35 years,

which is nearly half of the life cycle for most infrastructures, for the IA 21 Improved mitigation, there is even a possibility for the 10-return-year flood to occur, so the cumulative loss-savings can still cover the mitigation cost.

For the Improved mitigation, the ratios remain less than 1 but are obviously improved with 35-year flood scenario. On the other hand, at the end of the network assets' lifetimes, the IA 21 Improved mitigation shows much more benefit on the loss-savings under the possible floods with 2-, 5-, and 10-return-years. Because the 50- and 200-return-year floods have very low annual occurrence probabilities of 0.02 and 0.005, respectively, that may not even occur in the entire life cycle, the low benefit/cost ratios highlight the inefficiency to spend millions of dollars to mitigate a very small-probability event, which is also reasonable in practice.

One additional positive sign is that the Improved mitigation activity realizes a loss-savings benefit against a 2-return-year flood, although it is at the end of the assets' lifetimes.

In summary, with the analysis of the benefit/cost ratio, the most balanced and cost-effective flood mitigation decision for planners is the implementation of the IA 21 Improved action because it requires a smaller financial investment while achieving greater benefits, particularly for more frequent floods.

4.4.5 Analyses of Multi-Scale Resilience Index

The final measurement of network performance is the MRI. This index was calculated given all five flooding scenarios (2-, 5-, 10-, 50-, and 200-year) for all three network cases. (Figures presenting the MRI radar charts are included in Appendix B.) The robustness index after the 2-year flood for the base network was 83.05%. This percentage decreased for the more hazardous flooding scenarios all the way down to 74.35% for the 200-year flood (see Table 4.18).

Table 4.18. MRI results for each network case and flood scenario

Case for Each Scenario	2-Year	5-Year	10-Year	50-Year	200-Year
MRI (Base)	83.05%	81.40%	79.66%	77.18%	74.35%
MRI (Improved)	91.13%	79.06%	58.72%	87.27%	82.42%
MRI (IA 21 Improved)	**83.36%**	**82.24%**	**81.10%**	**78.64%**	**75.77%**

For the two mitigated networks to improve network robustness from the base network, their MRI result percentages need to be greater than that of the base network. This indicates that the network is more robust for each flooding scenario than for the base network. The improved network appears promising for three of the five flood scenarios, and particularly for the more hazardous flood events. The robustness index is approximately 10% higher for the 50- and 200-year flood events and 8% higher for the 2-year flood. However, the robustness index decreases for the 5- and 10-year floods. This could be attributed to the drastically high delay costs for these two flood events that were previously discussed.

The IA 21 improved scenario shows consistent and promising results. The MRI increases for all five flood events, which illustrates that the raised highway does improve the robustness of the network. Combine this robustness improvement with the lifetime financial savings previously discussed in the benefit/cost ratio analysis and it could be beneficial to take action.

5. CONCLUSIONS

Flooding is one of the most destructive hazards and can cause enormous direct and indirect losses to the transportation network, including closure of transportation assets, reduction of system connectivity and accessibility, extended traffic delays, and long out-of-distance miles that can result in the cancelation of trips. Inland areas, and particularly those in the vicinity of river basins, experience adverse impacts from intense flooding on an annual basis. Decision makers, designers, and planners who desire to provide a proper flooding prevention strategy need a way to interpret the extent of network-level closures due to flooding.

In this study, a robust pathway to achieving resilience was associated with three major components:

- Capacity of the system to absorb the shocks induced by flooding events either by having characteristics make the transportation network less vulnerable to flood events (such as higher elevations of roads and bridges and scour mitigation strategies for bridges, to name a few) or by providing alternative routes to potentially vulnerable roads and bridges

- Organizational capacity of the transportation agencies to restore the functionality of the network in the shortest possible time after flooding events, to reduce the recovery time with pre-defined plans, emergency contracts, and budgetary and human resources ready to be deployed (and potentially using strategies such as accelerated bridge construction for faster recovery) (Alipour et al. 2018)

- Capacity to plan for failures with the goal of benefitting from the window of opportunity provided to build to a better standard in such a way that the vulnerability of the transportation asset to future events of similar or even higher scales is reduced in the long term

This project developed a holistic framework to measure the robustness of the transportation network in an area prone to inland flooding as a first component of the three listed above. The framework is unique as the different measures considered in its development account for different characteristics of a network and are not considered in silos. For instance, the framework is capable of considering loss of connectivity but at the same time accounts for the fact that some segments of the system may become isolated and, as such, cancels out traffic accordingly.

The framework integrates the direct damage analysis on the closure of roads and bridges based on flood water depth, a connectivity functionality analysis by using indices of graph theory, and a flow-based network performance analysis with the classic four-step traffic model to capture the indicators associated with socio-economic losses. The composite action of these measures provides a holistic view of the transportation system, and one that was not developed before.

By application of the developed methodology on a large segment of the Iowa DOT primary system (in District 6), it was shown that the framework is capable of highlighting the hotspots in a system and provides a robust means to select locations of interest for pre- or post-event

planning purposes. The framework consists of a composite of different measures that capture not only aspects such as connectivity and level of system redundancy, but also represent the level of loss to the traveling public. The framework was developed such that the weights for each of the measures can be adjusted to represent the specific transportation agency's needs, missions, and goals.

The applicability of the framework in a project basis context was tried out on a smaller road segment (IA 21) that was shown to be flooded on a regular basis in recent years. For this purpose, a proposed mitigation approach by Iowa DOT engineers was considered and the benefit/cost analysis of the mitigation strategy was assessed using the developed MRI.

The project was able to use the historical repair costs from past events—from a parallel project currently ongoing—to realistically approximate the cost to repair closed roads and bridges if they were to be damaged. Many parts to this study originated from actual events and data that the Iowa DOT and the research team have accumulated over the years. This strengthens the validity of the findings of the research.

This study was complex and thorough compared to other studies in the past. The holistic view of direct and indirect costs in addition to the performance and robustness of the network is a new methodology. The scale at which this was done is also innovative.

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APPENDIX A: STUDY MAPS AND BAR CHARTS

A.1 Legend for Maps

Figure A.1 provides the legend for the maps in this appendix.
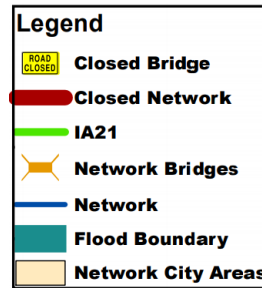
Figure A.1. Legend for all maps

A.2 Network Scenario and Flood Event Maps
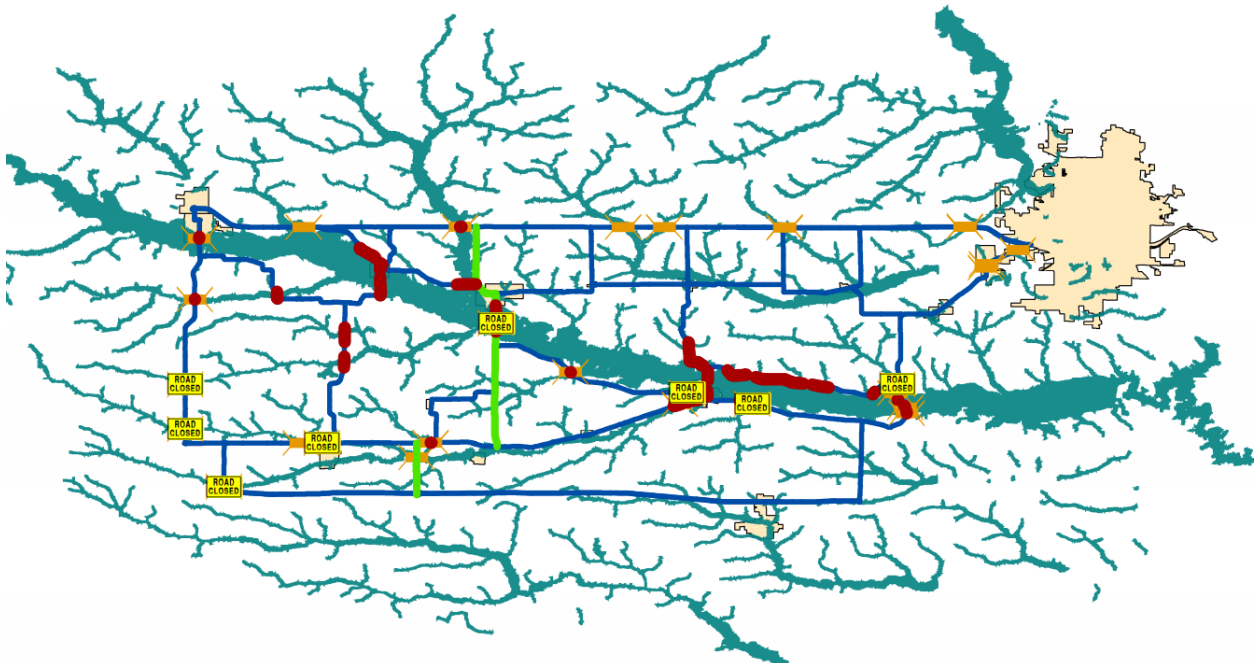
Figure A.2. Base network flooding after a 5-year event
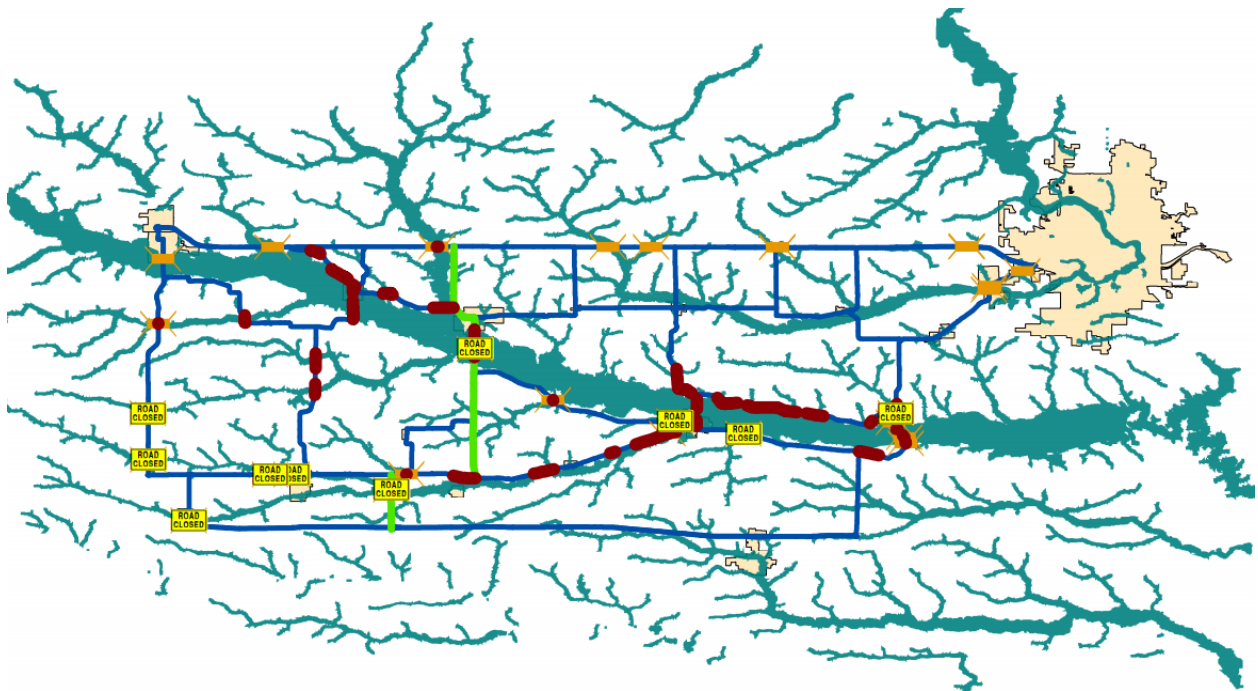
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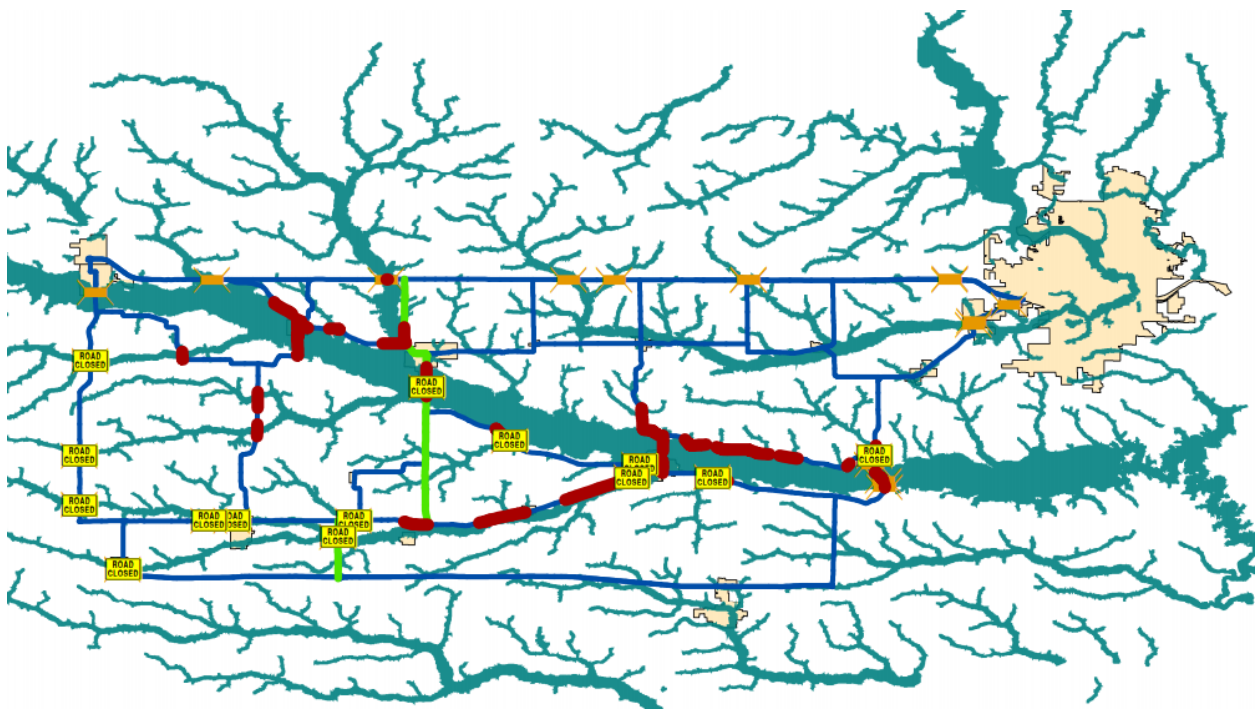
Figure A.4. Base network flooding after 50-year event
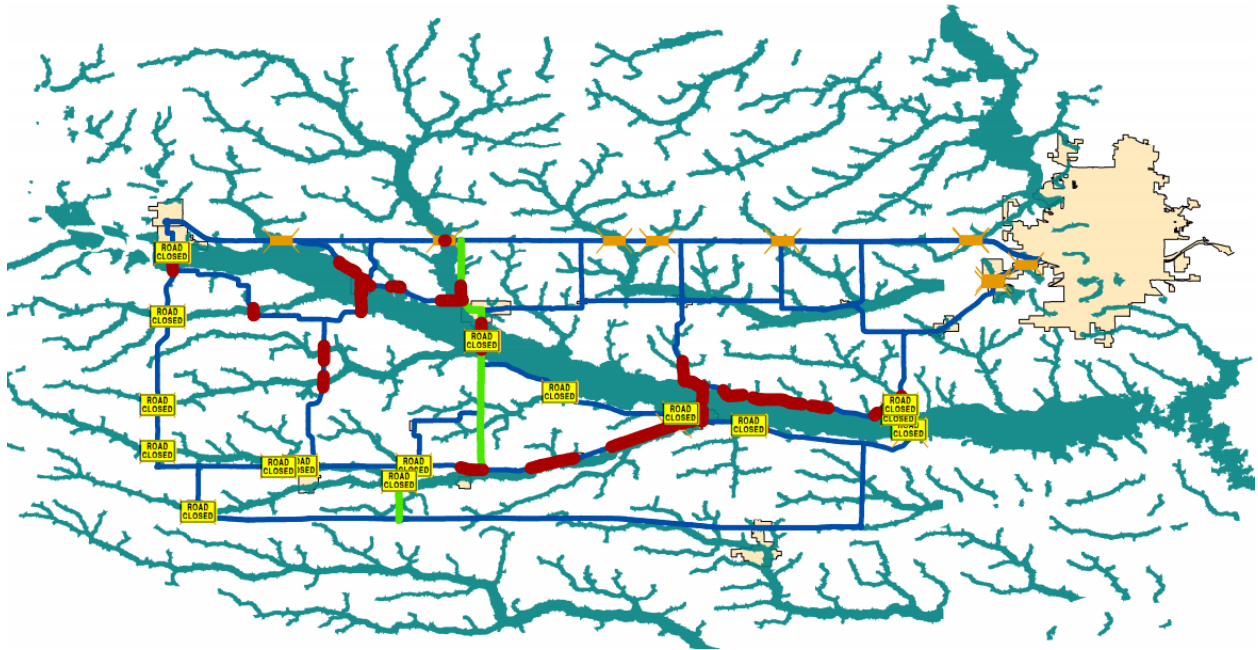
Figure A.5. Base network flooding after 200-year event
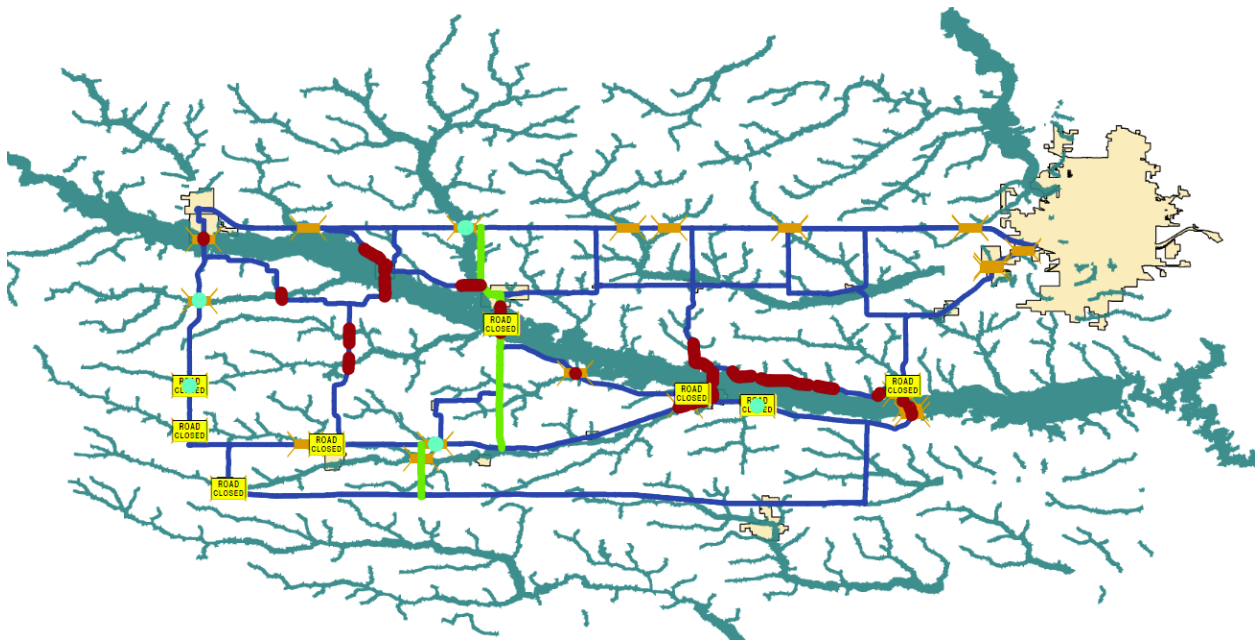
Figure A.6. Improved network flooding after 5-year event
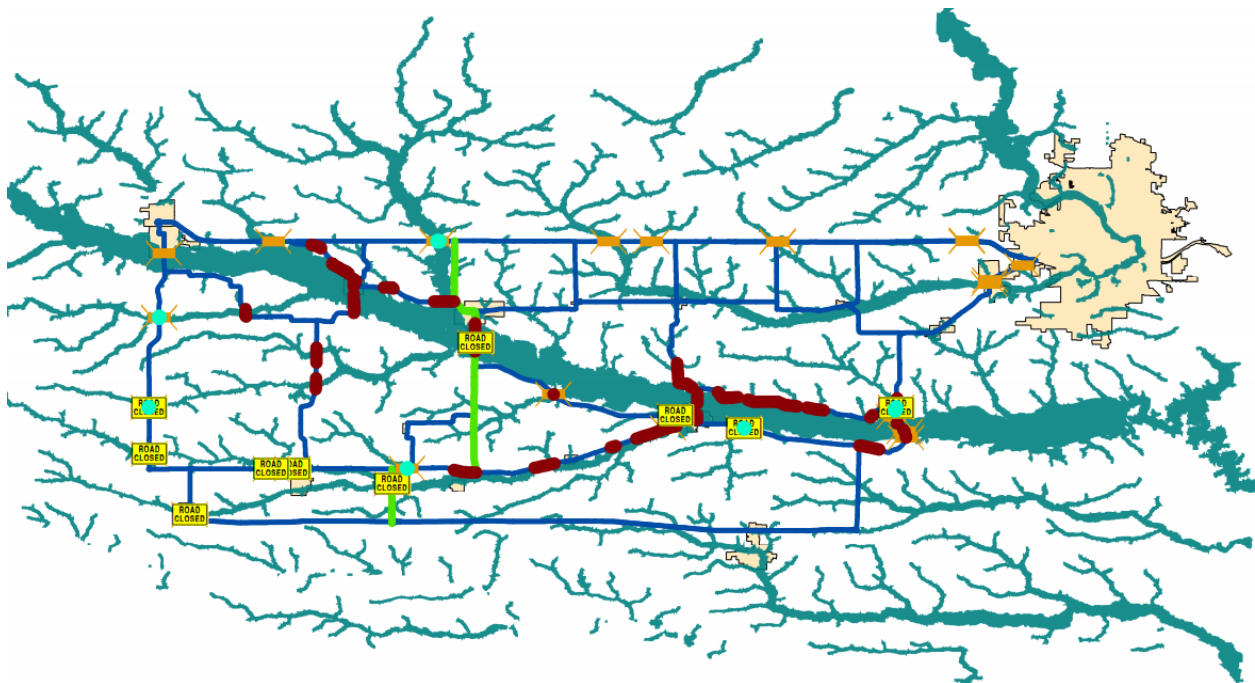
Figure A.7. Improved network flooding after 10-year event
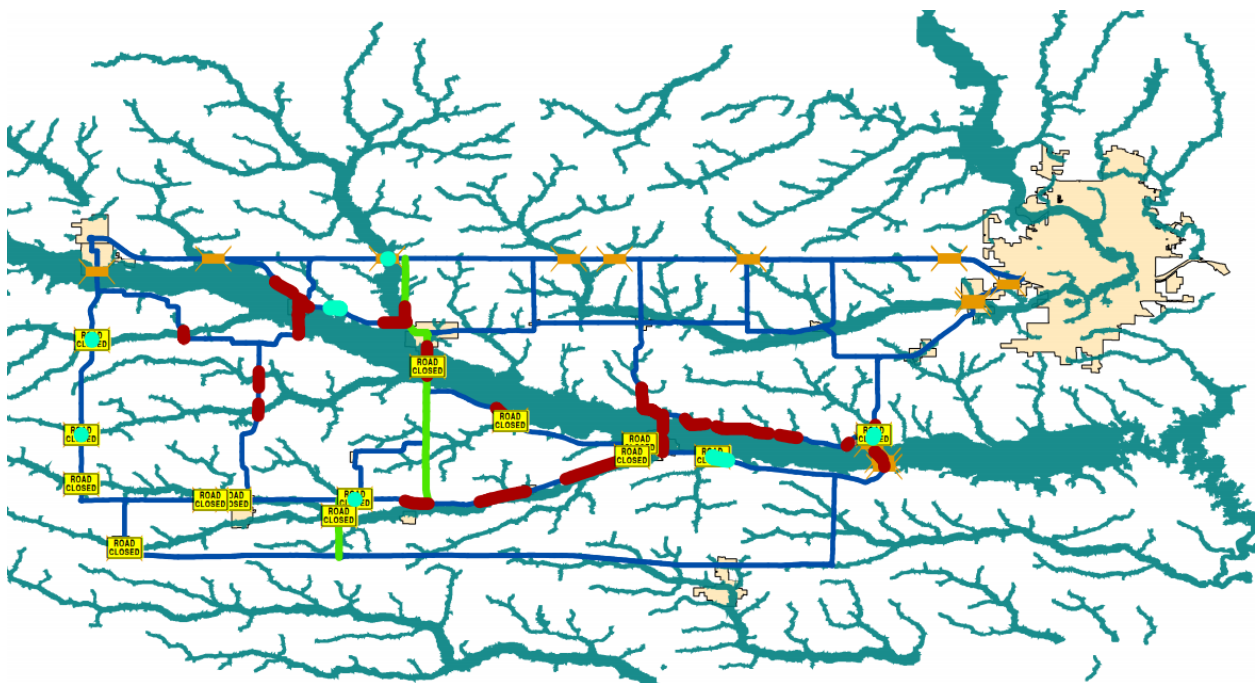
Figure A.8. Improved network flooding after 50-year event
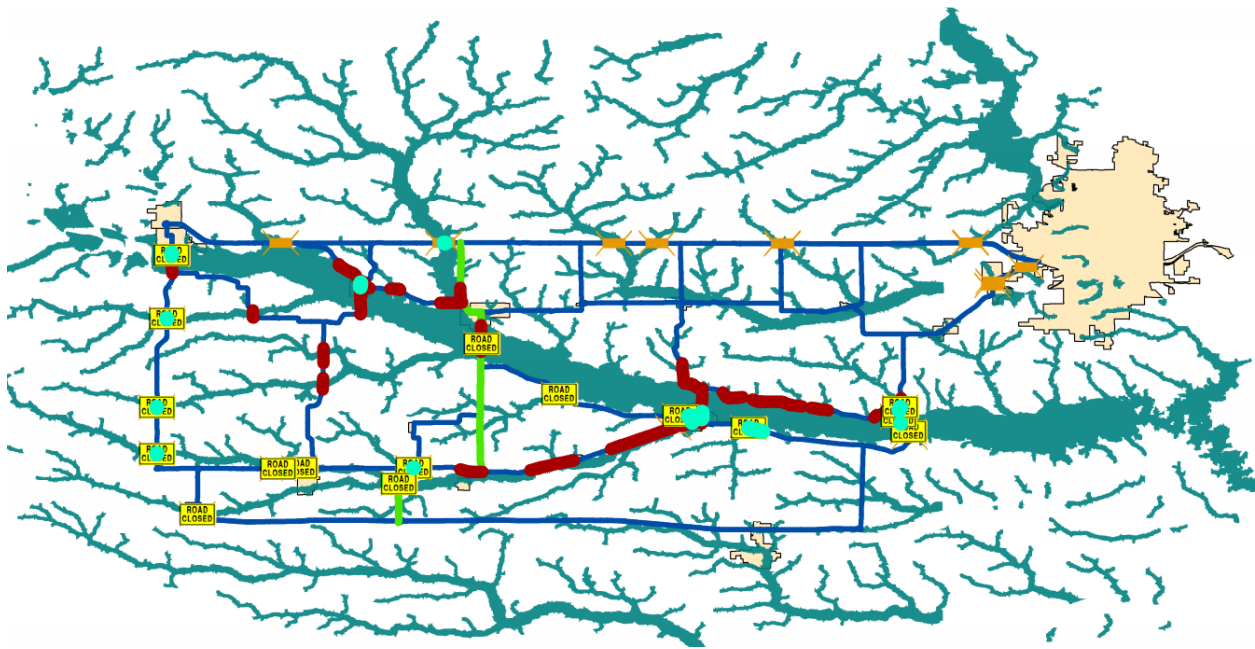
Figure A.9. Improved network flooding after 200-year event

A.3 Network Scenario and Flood Event Bar Charts
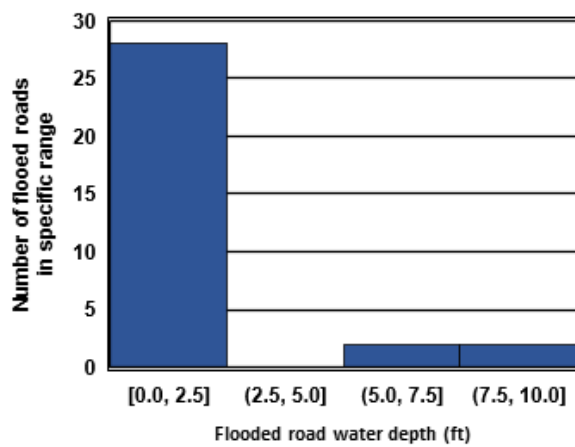
Figure A.10. Flooded road water depth of 2-year event on base network
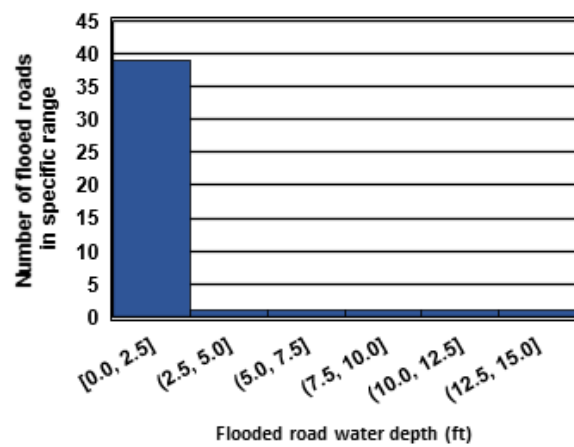
Figure A.11. Flooded road water depth of 5-year event on base network
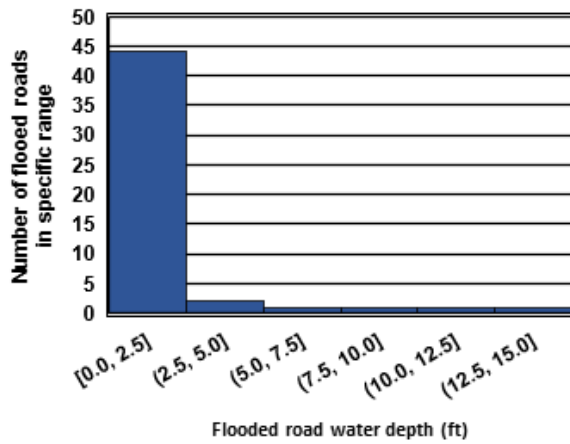
Figure A.12. Flooded road water depth of 10-year event on base network
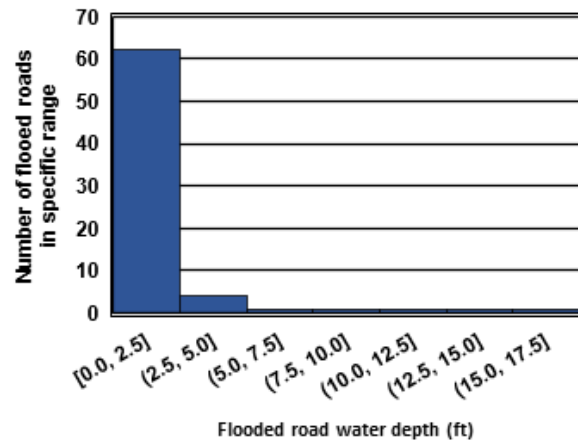
Figure A.13. Flooded road water depth of 50-year event on base network
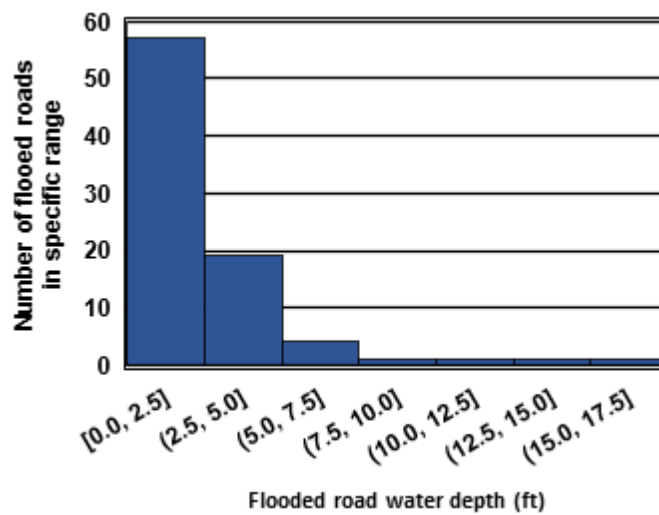
Figure A.14. Flooded road water depth of 200-year event on base network
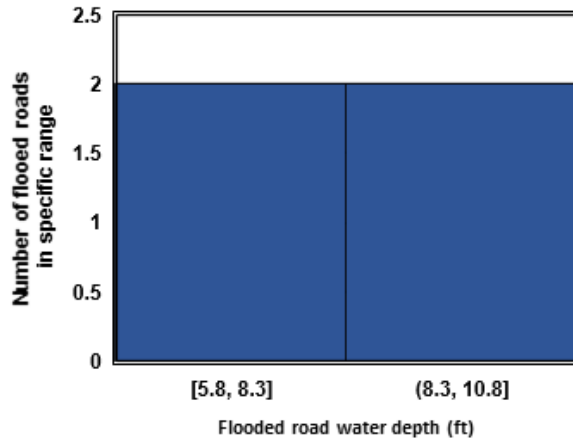
Figure A.15. Flooded water depth of 2-year event on improved network
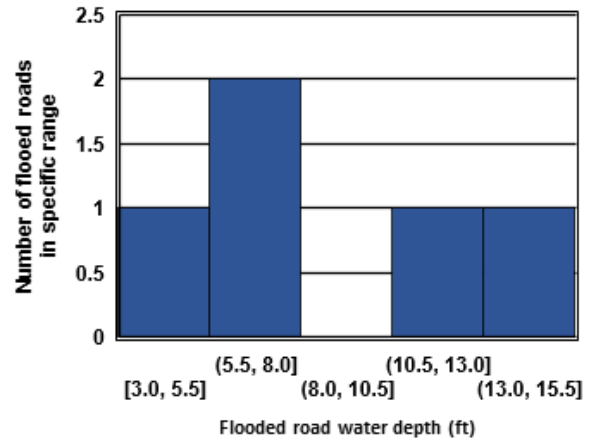
Figure A.16. Flooded water depth of 5-year event on improved network
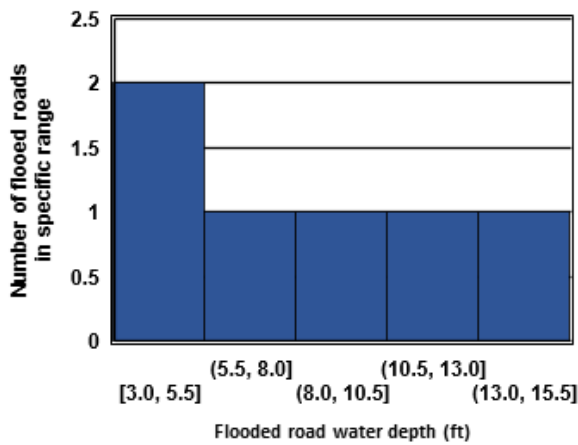
Figure A.17. Flooded water depth of 10-year event on improved network
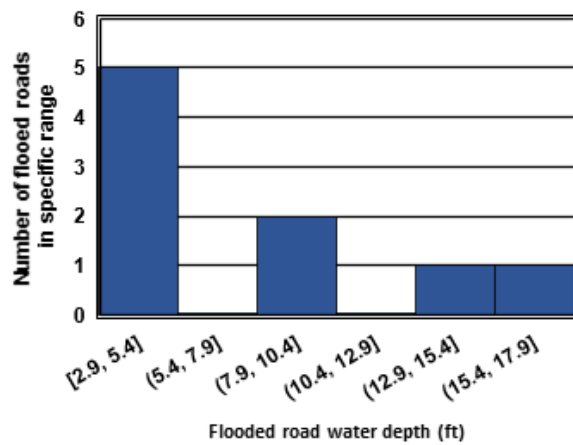
Figure A.18. Flooded water depth of 50-year event on improved network
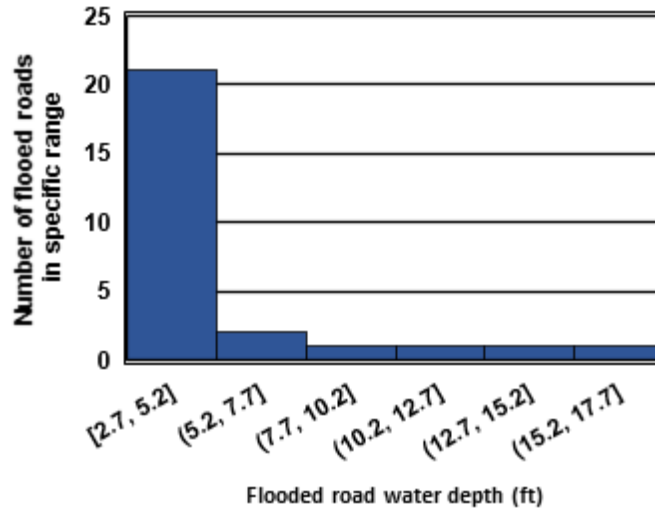
Figure A.19. Flooded water depth of 200-year event on improved network
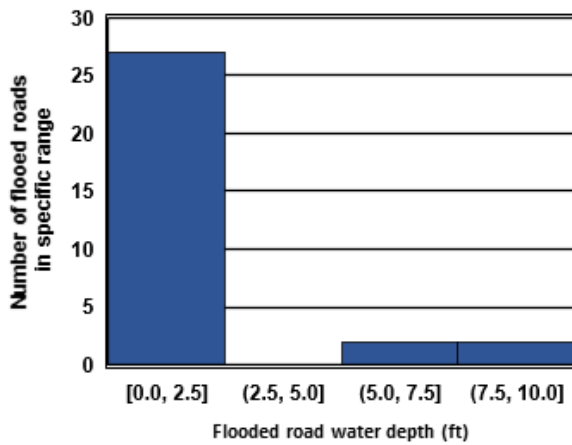
Figure A.20. Flooded road water depth of 2-year event on IA 21 improved
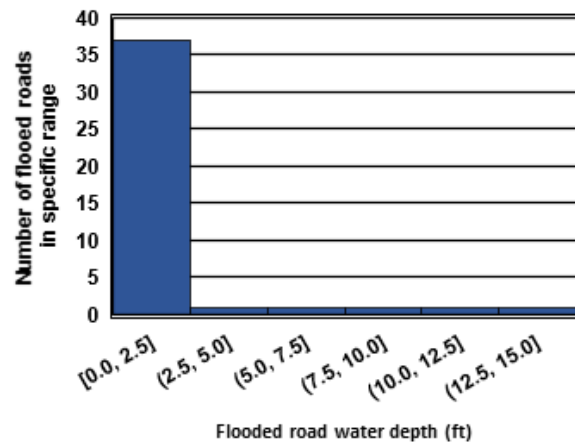
Figure A.21. Flooded road water depth of 5-year event on IA 21 improved
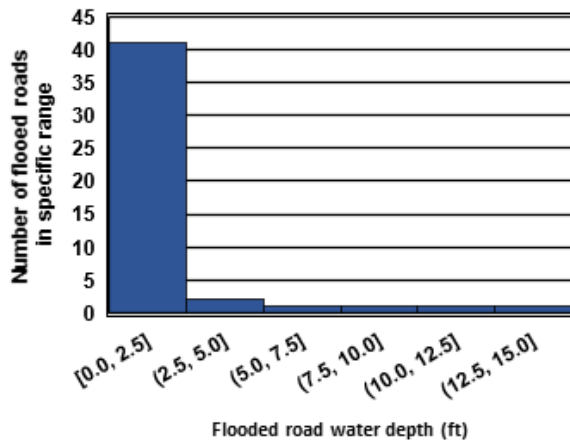
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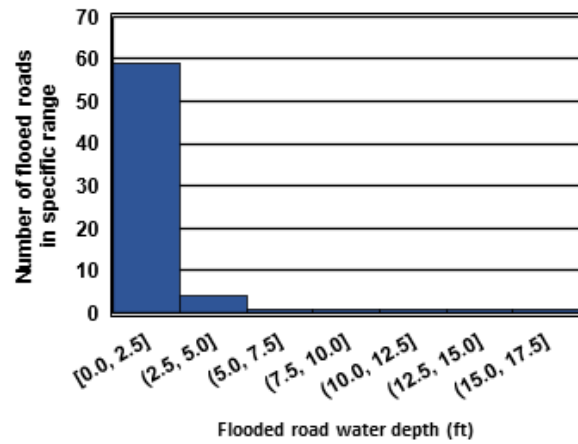
Figure A.23. Flooded road water depth of 50-year event on IA 21 improved
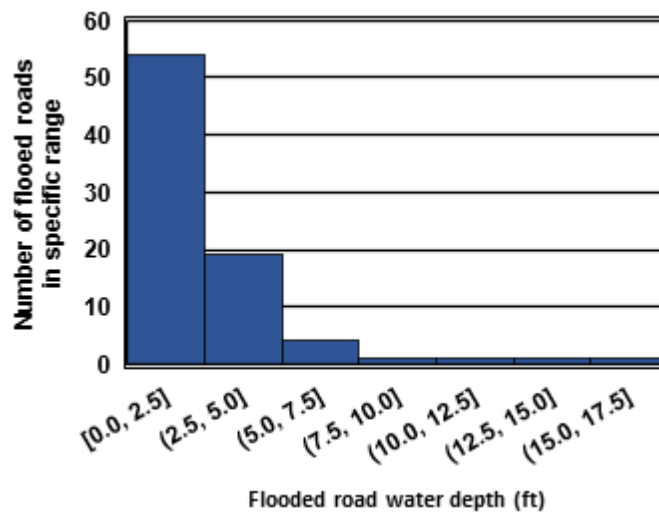
Figure A.24. Flooded road water depth of 200-year event on IA 21 improved

APPENDIX B: STUDY RADAR CHARTS

B.1 Base Network Multi-Scale Resilience Index (MRI) for All Flood Scenarios
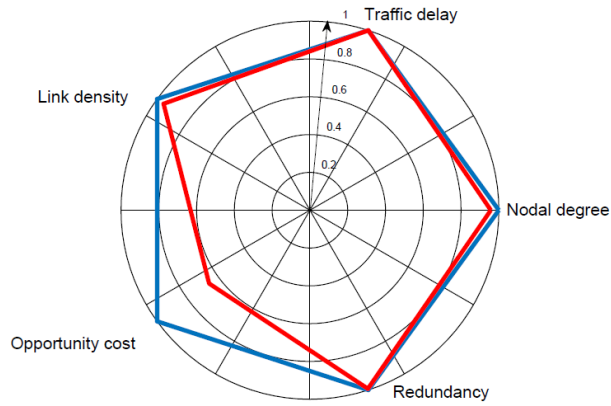
Figure B.1. Base MRI of 2-Year Event = 83.05%
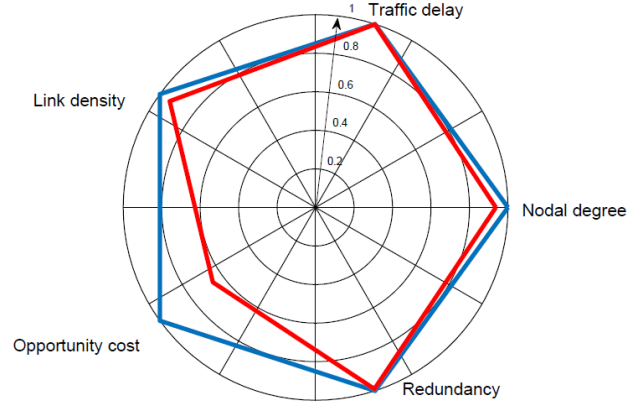
Figure B.2. Base MRI of 2-Year Event = 81.40%
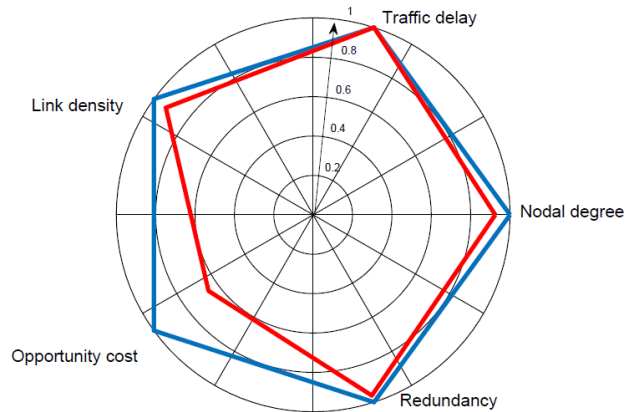
Figure B.3. Base MRI of 10-Year Event = 79.66%
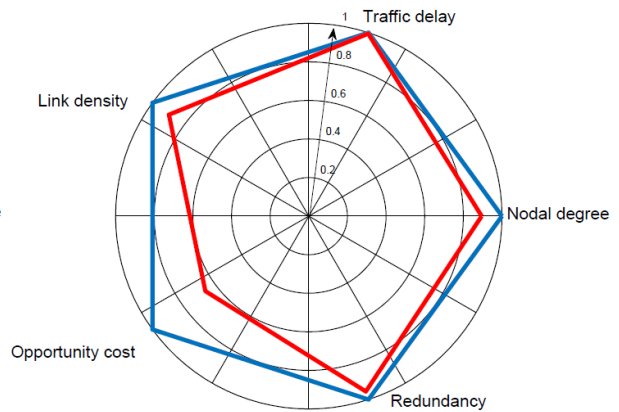
Figure B.4. Base MRI of 50-Year Event = 77.18%
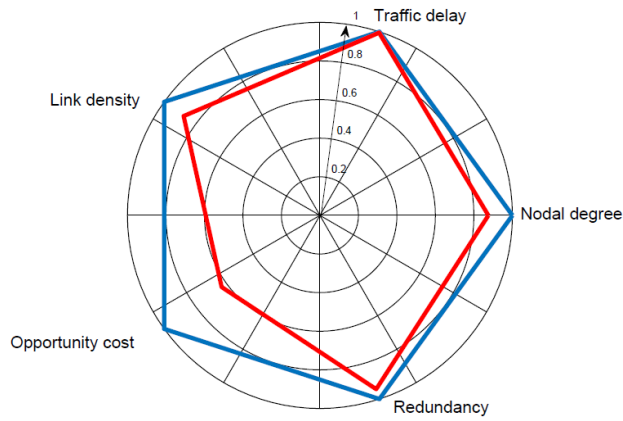
Figure B.5. Base MRI of 200-Year Event = 74.35%

**B.2 Improved Network Multi-Scale Resilience Index (MRI) for All Flood Scenarios**
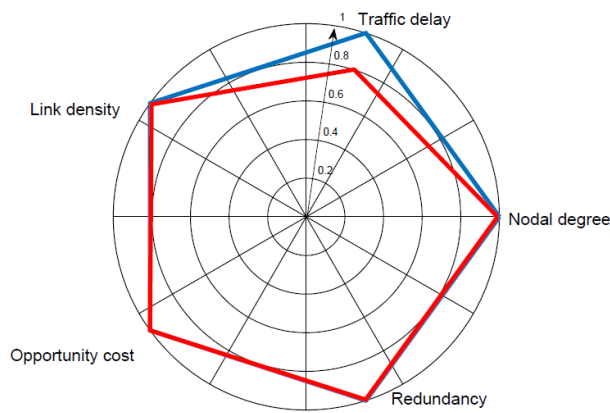
Figure B.6. Improved MRI of 2-Year Event = 91.13%
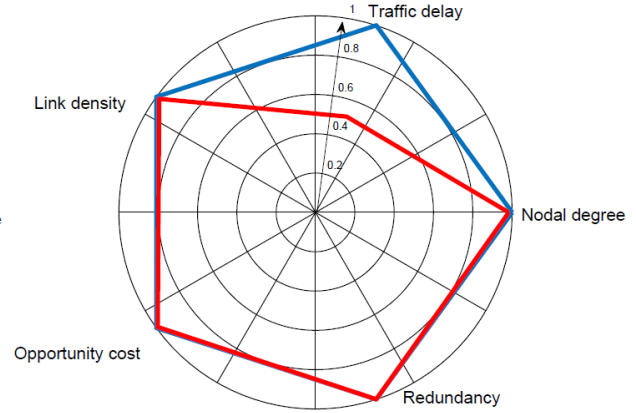
Figure B.7. Improved MRI of 5-Year Event = 79.06%
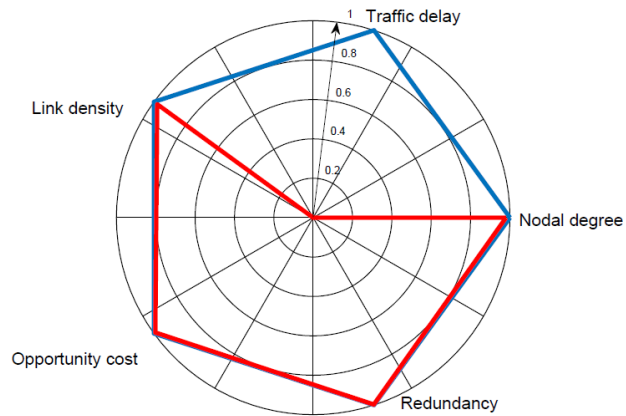
Figure B.8. Improved MRI of 10-Year Event = 58.72%
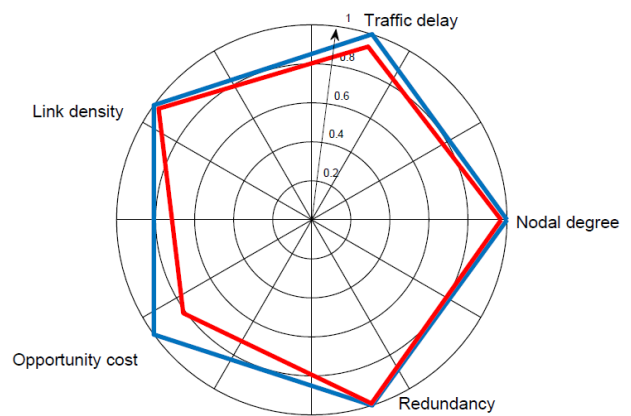
Figure B.9. Improved MRI of 50-Year Event =87.27%
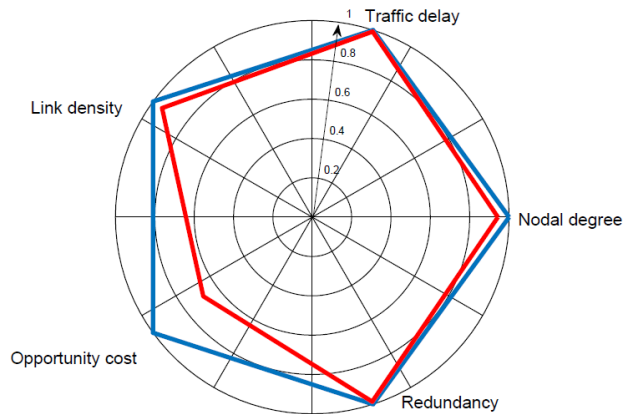
Figure B.10. Improved MRI of 200-Year Event = 82.42%

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B.3 IA 21 Improved Network Multi-Scale Resilience Index (MRI) for All Flood Scenarios
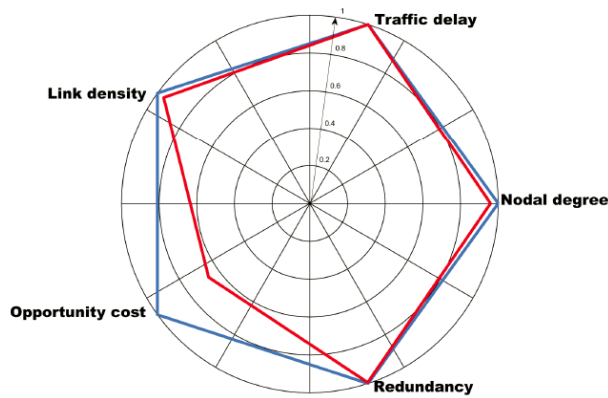
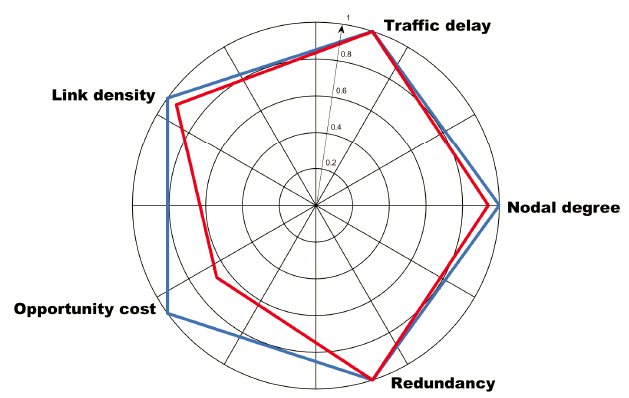
Figure B.11. IA 21 Improved MRI of 2-Year Event = 83.36%

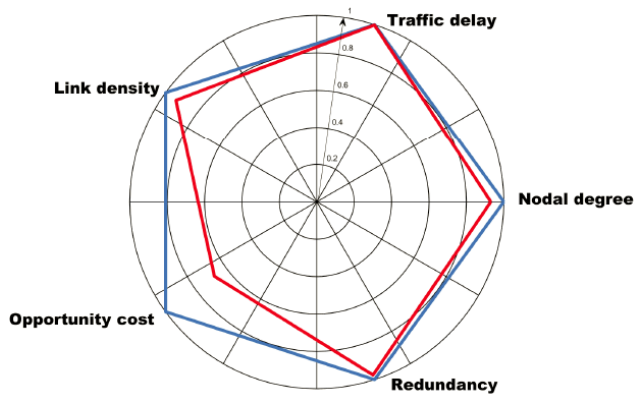**Figure B.12. IA 21 Improved MRI of 5-Year Event = 82.24%**

Figure B.13. IA 21 Improved MRI of 10-Year Event = 81.10%
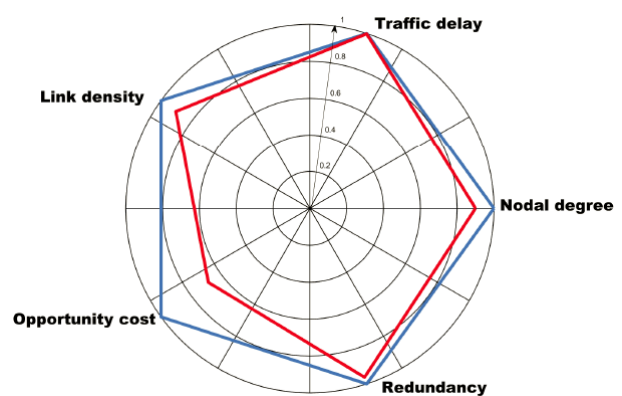

Figure B.14. IA 21 Improved MRI of 50-Year Event = 78.64%
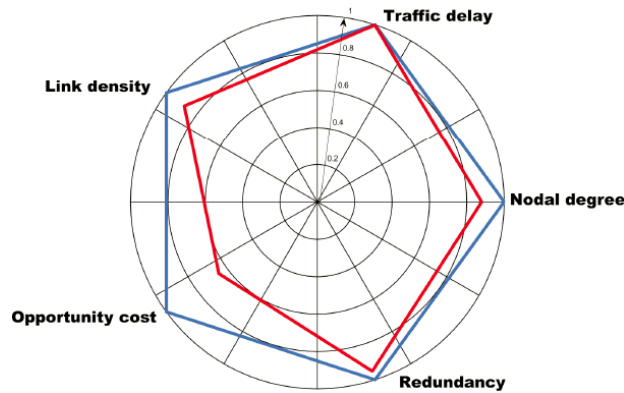

Figure B.15. IA 21 Improved MRI of 200-Year Event = 75.77%

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