Asset Management, Extreme Weather, and Proxy Indicators

Final Report
February 2021

BRIDGE ENGINEERING CENTER

IOWA STATE UNIVERSITY
Institute for Transportation

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This pilot project is one among many efforts by the Iowa Department of Transportation (DOT) and the Iowa Highway Research Board (IHRB) to develop and enhance a risk-based transportation asset management plan (TAMP). This project specifically focused on flooding and developed a suite of methodologies and proxy indicators to assess the risk of transportation assets to this hazard.

Multiple flood events were simulated on a segment of the transportation network to predict bridge closures based on overtopping in order to determine areas that may be especially vulnerable and the effects of this vulnerability on the transportation network.

Bridge sensitivity to flooding was analyzed using easily accessible data on bridge parameters and condition ratings to determine the structural condition of Iowa's bridges, the geomorphic sensitivity of the channels, and the importance of each bridge for the transportation network. Data were reviewed from historical flood events that have resulted in damage to bridges, and a statistical analysis was performed of the potential correlations between flood damage and bridge features.

An analysis of road sensitivity was conducted using different road segments with different elevations and pavement types. The potential for closures was determined for different flooding scenarios based on the likelihood of overtopping, and the potential for damage to different pavement types was analyzed based on historical data.

Lastly, a segment of the transportation network was overlaid with different flooding scenarios to show subnetwork vulnerabilities.

In addition to moving towards a risk-based TAMP, it is expected that these methodologies and the resulting vulnerability indices and proxy indicators will feed into other parallel efforts to assess and enhance the resiliency of Iowa's transportation infrastructure.</td></tr>
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EXECUTIVE SUMMARY

Transportation infrastructure is a complex system of different assets (such as bridges and pavements) that are required to function cohesively and deliver a host of different services and functions. The integration of risk-based approaches for responding to extreme weather events and adapting to climate change can complicate the life-cycle delivery of the services. This integration requires a holistic approach that can not only consider predictable asset deterioration but also incorporate new models for risk assessment and life-cycle planning to devise suitable planning approaches for adaptation and mitigation strategies.

Following the requirements of the Moving Ahead for Progress in the 21st Century Act (MAP-21), the Iowa Department of Transportation (DOT) is developing a risk-based asset management plan for the National Highway System (NHS) to improve and preserve the condition of the assets and the performance of the system. The continued development and use of asset management systems and performance-based decision making raises the question as to how the risks associated with climate change and extreme weather events can be linked to asset management tools and decision making processes.

The goal of this research was to incorporate climate change and extreme weather considerations into transportation asset management plans (TAMPs). In particular, this study aimed to do the following:

- Examine the linkage between the recently completed Federal Highway Administration (FHWA)-funded Climate Change Vulnerability Assessment Pilot by the Iowa DOT—and other ongoing efforts related to assessing vulnerability, enhancing resilience, and developing next-generation life-cycle cost analysis tools within the Iowa DOT—and risk-based TAMPs in response to the MAP-21 legislation.

- Develop proxy indicators specific to Iowa and applicable to the other Midwest states that could eventually be integrated into the updated Vulnerability Assessment Scoring Tool (VAST).

- Generate a network-level life-cycle planning framework that accounts for the impact of recurrent extreme events such as flooding and that can be integrated into TAMPs.

- Identify procedures, methods, and proxy indicators for assessing the vulnerability of assets, the potential data requirements, and a pathway for future implementation.

1. INTRODUCTION

1.1. Purpose of Study

Extreme weather events pose serious threats to transportation infrastructure assets and cause difficulties for the transportation agencies managing infrastructure systems. Climate models predict an increase in the frequency and intensity of precipitation in Iowa (Anderson et al. 2015). Over the past decade, the state of Iowa has experienced the impact of climate change and extreme weather events on its transportation infrastructure and services. The massive flooding events experienced in different parts of the state, such as the 2008 Cedar and Iowa River floods, the 2010 flood in the South Skunk River basin, and the more recent 2016 floods in the Shell Rock, Cedar, Wapsipinicon, and Winnebago River basins, all of which have resulted in closures on multiple Interstates and major highways, are examples of the potential threats from extreme weather conditions faced by the Iowa Department of Transportation (DOT).

Similar threats are expected to arise as the developing climate trends continue to place increasing amounts of stress on transportation assets. Considering the uncertainties associated with climate trends and the ever-increasing stresses on transportation infrastructure, the state of Iowa needs to assess the potential exposure to extreme weather events, define appropriate vulnerability measures or proxy indicators, and plan to reverse the adverse effects of such hazards by developing mitigation strategies and planning response and recovery efforts.

Following the requirements of Moving Ahead for Progress in the 21st Century (MAP-21), the Iowa DOT is developing a risk-based asset management plan for the state’s portion of the National Highway System (NHS) to improve and preserve the condition of the state’s assets and the performance of its infrastructure system. The continued development and use of asset management systems and performance-based decision making raises the question as to how the risks associated with climate change and extreme events can be linked to asset management tools and decision making processes.

This pilot project is one step among many other efforts by the Iowa DOT and the Iowa Highway Research Board (IHRB) to develop and enhance a risk-based transportation asset management plan (TAMP). This pilot project focused on flooding as the main extreme weather event and developed a suite of different methodologies to assess the risk of bridges and pavements to this hazard. In addition to moving towards a risk-based TAMP, it is expected that these methodologies and the resulting vulnerability indices and proxy indicators will feed into other parallel efforts to assess and enhance the resiliency of Iowa’s transportation infrastructure.

The first task for this project was to compile information regarding common types of transportation asset damage caused by flooding. Information about these damage modes was used to select the most appropriate methods for reviewing the sensitivity and vulnerability of assets and to choose the appropriate proxy indicators.

Bridge sensitivity was then reviewed using easily accessible data to determine the structural condition of Iowa's bridges, the geomorphic sensitivity of the channels, and the importance of each bridge for the transportation network. This process helped determine how sensitive Iowa's bridges are to flooding. Next, data were reviewed from historical events that have resulted in damage to bridges, and a statistical analysis was performed of the damage and its potential correlations to different features of the assets. The last method for the bridge vulnerability analysis involved simulating multiple flood events on a segment of the transportation network to predict bridge closures based on overtopping to determine areas that may be especially vulnerable and the effects of this vulnerability on the transportation network.

A similar method was used for an analysis of roads, where a sample segment was selected and the potential for closures was determined for different flooding scenarios based on the likelihood of overtopping. The type of pavement was an important aspect of this study, because vulnerable areas of the network can be identified based on the saturation of different pavement types.

Lastly, a segment of the transportation network was overlaid with different flooding scenarios to show subnetwork vulnerabilities.

1.2. Context and Scope

The Iowa DOT manages over 22,000 lane miles of road and over 4,000 bridges. Several of these assets experience flooding due to extreme rain events (e.g., the June 2008 flooding of the Cedar and Iowa Rivers) or the quick melting of snow (e.g., the March 2019 flooding of the Missouri River). As extreme events continue to increase in intensity and frequency, the Iowa DOT aims to ensure that the physical health of its infrastructure and the consequent economic prosperity of state of Iowa is maintained through a risk-based transportation asset management program that improves the cost-effectiveness and performance of the transportation system, delivers the Iowa DOT's customers the best value for the money spent, and enhances the Iowa DOT's credibility and accountability in its stewardship of its transportation assets (Iowa DOT 2018).

In 2015, the Iowa DOT led a study to assess the vulnerability of transportation infrastructure under extreme weather events and climate change (Anderson et al. 2015). The project was part of the Federal Highway Administration (FHWA) Climate Change Resilience Pilot program (FHWA 2020). Iowa's pilot project focused on the two river basins: the Cedar River basin and the South Skunk River basin. An innovative methodology was developed to generate streamflow scenarios given climate change protections. The Iowa DOT's project was the only one out of 20 FHWA pilot projects to link climate projections of precipitation with streamflow simulation to enable a vulnerability assessment under climate change projections. The methodology extracted daily precipitation data from 19 climate models at 22,781 grid points for the years 1960 through 2100. It generated a continuous 140-year streamflow simulation and used a U.S. Geological Survey (USGS) protocol for estimating streamflow quantiles.

The project developed a climate data model with high spatial and temporal accuracy for hydrologic simulation. Because of the innovative methodology used, a high accuracy in the predicted changes in rainfalls was achieved. Practical considerations were made to translate the simulated hydrology into engineering metrics. As an example application, the vulnerability of six bridge and highway locations within the two basins was evaluated, and solutions to increase the resilience of the existing hydraulic design for the bridges in these locations were provided.

The present project aimed to develop a process for integrating extreme weather and climate risk into asset management practices. Through this project, the Iowa DOT aimed to identify the hotspots from previous events and the potential risks from flooding and future weather events and to incorporate the relevant information on resilience into the Iowa DOT's transportation asset management program and life-cycle planning activities.

This goal was achieved by conducting a vulnerability assessment of the main assets of the Iowa DOT's transportation system: pavements and bridges. The project team had the opportunity to engage Iowa DOT staff across the agency and from different bureaus to identify opportunities to improve data collection. These future data collection efforts can help incorporate the extreme weather vulnerability analysis and proxy indicators developed in this study into the Iowa DOT's asset management programs and life-cycle planning systems, such as the Roadway Asset Management System (RAMS) and the Structure Inventory and Inspection Management System (SIIMS). There will also be opportunities to implement the results of this study into the Iowa DOT Prioritization and Scoping Tool.

1.3. Background

Floods are the most common natural disaster in the United States and can be detrimental to communities, causing negative economic impacts, impaired travel mobility, and the destruction of infrastructure. As the population grows, man-made structures are utilizing more land and altering natural water flows. This, coupled with climate change, has led to an increase in both the intensity and frequency of floods (Douben 2006, Douglas et al. 2017). These increasingly intense and frequent floods can cause severe damage and destruction to anything in their path, which can especially affect transportation assets.

Transportation assets are some of the most vulnerable infrastructure during floods because, by necessity, many of these assets are built near or over waterways. Proximity to the water may leave these assets closed for long durations, considering that the average flood duration in North America is approximately nine days (Douben 2006), which causes negative economic impacts within a community. Even after the flood waters recede, it is possible that these assets remain closed for a longer duration due to cleanup or repair efforts or because the asset suffered severe enough damage to render it unsafe for travel. The resilience and recovery of the transportation network are therefore important factors in flood-related emergency response planning (Zhang and Alipour 2020a, 2020b). Several recovery techniques for transportation assets are discussed in the relevant literature (Alipour et al. 2018, Zhang et al. 2018, Zhang and Alipour 2020c)

The leading cause of bridge damage is scouring of the streambed material from around the bridge foundation caused by floods (Ameson et al. 2012). Scour occurs when fast moving water erodes the soils from the streambed or when the water flow is disrupted by objects (such as bridge piers or abutments), the latter of which causes a more turbulent flow and leads to deeper erosion in a local area around those objects. With the soil around those objects washed away, the bridge foundation can become unstable and compromise the overall structural condition of the bridge. Several countermeasures to combat scour can be used and typically consist of revetment placed around the foundations of bridges (Freeseman et al. 2019).

Moreover, floods often carry more debris than the waterway typically carries due to the higher water elevations, and this debris can become lodged against bridge piers, as shown in Figure 1.1. This additional surface area results in greater hydrostatic force on the bridge, which can be especially problematic if scour is present because the debris can affect the turbulence of the water and thereby increase the scour around the bridge piers.

Bridge Engineering Center

Figure 1.1. Wood debris lodged around a bridge pier (bridge 3437.9S218)

Another possible damage mode to bridges during floods is when the flood waters reach the elevation of the superstructure. This can create an uplift force due to the superstructure's buoyancy, and if air pockets remain trapped between the girders, the result may be deck unseating or even complete superstructure liftoff. If the water level is higher still, overtopping may occur, where the water flows over the bridge deck. The debris carried by the flood waters, along with the water itself, can damage the bridge deck surface or parapets, which could result in a prolonged bridge closure. This damage to bridges during extreme floods can be very costly. An estimated $15 million worth of bridge damages occurred during the 1993 upper Mississippi River basin floods, which caused 23 bridge failures. The failure modes of these bridges included pier and/or abutment scour (19 bridges), lateral bank migration (2 bridges), debris accumulation (1 bridge), and an unknown cause (1 bridge) (Ameson et al. 2012). Figure 1.2 shows the 2008 flooding of the Cedar River in downtown Cedar Rapids, Iowa, where the 16th Avenue bridge (at the bottom of the figure) is overtopped and the 1st, 2nd, and 3rd Avenue bridges, which span across Mays Island, are also overtopped.

Iowa Civil Air Patrol

Figure 1.2. High water elevation in Cedar Rapids in 2008

By their nature, roads are typically at lower elevations than bridges along the same route. This means that higher water levels will inundate roads before bridges, which Figure 1.2 illustrates. This also means that longer stretches of roadway will be affected by flooding compared to bridges. Roads and pavements can suffer from several damage modes due to flooding. These include rutting, cracking, increased surface roughness, or subgrade degradation, each of which can shorten the life of the pavement, resulting in higher maintenance or repair costs.

The strength of a pavement is an important measure of pavement performance and durability. The strength of a pavement is often measured by falling weight deflectometer (FWD) testing. In a study by Gaspard et al. (2007), post-flooded pavements were found to be weaker than pavements that had not been affected by flooding; this was true for asphalt concrete (AC), portland cement concrete (PCC), and composite pavements. In these tests, the strengths of the AC and PCC pavements were not affected by the duration of the flood, but the strength of the composite pavements was affected for submersion durations of one week, two weeks, or three or more weeks. Sultana et al. (2016a) suggested that the best method for checking structural strength after a flood is to test the deflection of the pavement. Flooding results in higher deflection values and a decreased structural number (SNC) for pavements (Sultana et al. 2014).

Because floods can last for long durations, it is important to understand how the duration of submersion can affect pavements. Gaspard et al. (2007) showed that the strength of a pavement is reduced regardless of the amount of time that the pavement is submerged and that damage occurs even for short submersion durations. The strength of a hot mix asphalt (HMA) pavement will begin to become compromised if it is submerged by flood waters for longer than six hours, and the pavement can even begin to weaken within two hours of submersion (Mallick et al. 2017). Flexible pavements suffer a loss of structural strength more rapidly than other pavement types after being affected by a flood. It was found that the subgrade California bearing ratio (CBR) for flood-affected flexible pavements decreased by up to 67% and the structural number decreased by up to 50% (Sultana et al. 2015).

Any damage or deterioration to the pavement prior to flooding will influence how that pavement is affected by inundation. Helali et al. (2008) found that submerged HMA pavements that had experienced prior distortion and cracking, including alligator, map, transverse, and longitudinal cracking, deteriorated significantly more rapidly than non-flooded HMA pavements. In the same study, similar results were found for PCC pavements that had experienced prior distortion and transverse cracking. Flooding accelerates the deterioration of roads, especially those with higher pre-flood rutting (Sultana et al. 2016b).

MAP-21, signed into law in 2012, required each state DOT to develop a risk-based TAMP. Some of the objectives of this plan in Iowa have been to guide funding and help manage bridges and pavements across the state, define the relationship between proposed funding levels and expected results, develop a long-term outlook for asset performance, and unify existing data, business practices, and divisions to achieve the Iowa DOT’s asset management goals.

This study provides methods that complement the goals and objectives of the Iowa DOT’s TAMP. Existing data were used in new ways to provide better clarity on current and historic asset conditions and damage modes. Flooding data were analyzed to determine the probability of damage occurrence to determine especially vulnerable asset locations. Bridge parameters and condition ratings were used to determine the probability of risk in hopes of finding correlations between physical bridge characteristics and damage incurred. In this way, it is believed that future versions of Iowa’s asset management plan can utilize these data to allow for better funding allocation, more visibility for asset condition, and better preparedness in the face of flooding events. Road sections were analyzed by elevation and pavement type for different flooding periods to determine the potential for road closures due to overtopping and potential damage to different pavement types based on historical data.

2. METHODS AND TECHNICAL APPROACH

Risk is typically defined as the product of the probability of occurrence of the event, the probability of damage, and the consequence of damage. This definition provides an understanding of the impact of hazards on communities. However, the state of Iowa defines risk as the probability of occurrence of the event multiplied by the probability of damage (Iowa DOT TAMP 2018). For this study, the probability of occurrence can be generalized by how often a flood will occur that may cause damage to transportation assets. The probability of damage is the likelihood that the flood event will actually cause damage to the affected assets.

It is important to understand the environmental stressors that may result in risk or damage to transportation assets. For risk of flooding in Iowa, these stressors consist of heavy precipitation, primarily occurring in late spring, and snow and ice melt in the early spring. Floods caused by these stressors can result in several negative impacts to transportation assets, including bridge scour due to fast moving water, large debris accumulation around piers due to higher water levels dragging in trees from the banks, and overtopping of bridges or roadways when the water level exceeds the road surface level, which leads to faster deterioration of the deck or undermining of the pavement. High water levels can overtop roadways, which, in turn, can suffer damage such as surface texture loss, rutting, and interlayer bonding loss and layer movement.

Some types of damage to these assets are not always preventable, or the cost of preventing damage may be too great. It is therefore advantageous to predict damage in order to better allocate resources and funding for maintenance, repairs, and future construction of transportation assets. Proxy indicators can be useful in making such predictions. The following are several factors that can be used as proxy indicators:

- Locations of frequent flooding – By monitoring locations that are known to flood, the affected assets can be closely monitored for damage, and, based on the needed repairs, a maintenance schedule can be fitted appropriately and could be interpolated for other assets in the area that may not see flooding as frequently.
- Structural ratings – National Bridge Inventory (NBI) ratings for bridges can be used to evaluate the overall structural health of target bridges in comparison to a given bridge population. Bridges rated as being in average condition can be used as baseline indicators, while the extreme outliers could be used as bounds.
- Criticality to the network – In addition to structural rating, NBI data can be used to determine traffic information, detour routes, and other information relevant to the criticality of both bridges and roads. The mean and extreme bounds could again be used as proxy indicators to ensure that highly critical transportation assets are more closely monitored.
- Historic damage – Based on previously recorded damage and repairs to affected assets, the physical attributes related to the assets' designs can be correlated with the potential for damage, which would thus allow those attributes to be used as proxy indicators.

Figure 2.1 summarizes the recommended steps in establishing a transportation asset management plan that considers environmental stressors.

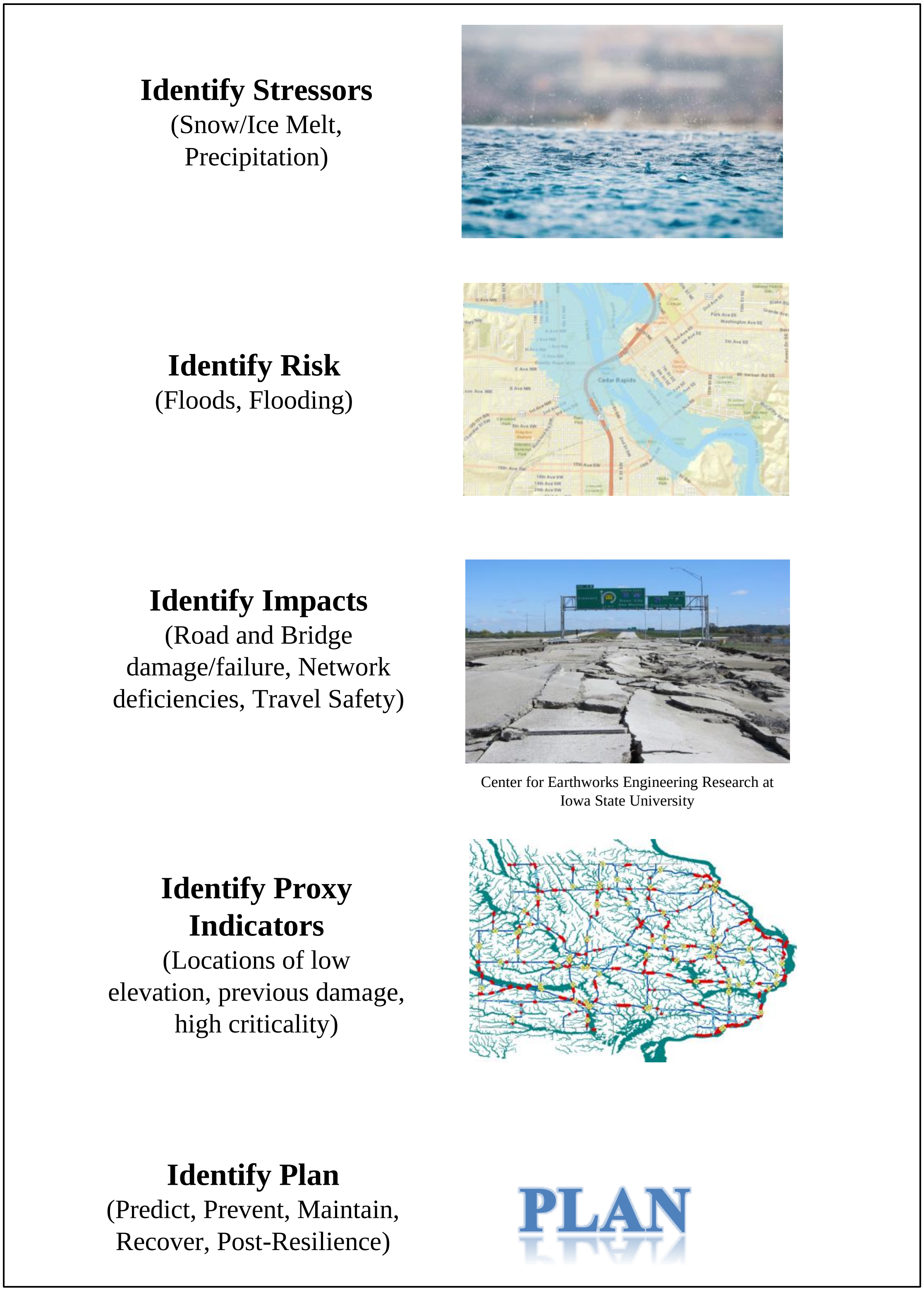


Figure 2.1. Establishing a transportation asset management plan that considers environmental stressors

3. DEVELOPING PROXY INDICATORS FOR BRIDGES

Bridges are the most important component of the transportation network. They connect various roads, or links, throughout the network. Any damage to a bridge could cause a partial or full closure of the bridge and drastically affect the flow of traffic. Complete closures can cause long detours by redirecting traffic on a longer route to the nearest crossing of the waterway. Partial closures could result in lane closures, which can cause slower moving traffic and longer travel times, or could result in weight limitations in which heavier vehicles are redirected to alternate routes.

3.1. Modes of Flood Damage to Bridges

Flooding can cause damage to bridges through several damage modes. Scour is the most frequent cause of bridge damage due to flooding. The depth of scour can vary greatly due to several parameters of the bridge itself and is based on water velocity and depth. When an object disrupts the natural flow of water, a turbulent flow is formed, which is the case with bridge piers and abutments. This turbulent flow tends to pick up streambed soils from around the piers and abutments and carry them farther downstream. A resulting hole in the streambed soil is then formed that exposes more of the bridge footing or piles. Bridges are designed for this scouring scenario and should be structurally stable if the flood falls within the limit of the design. Instability may occur, however, in multihazard scenarios, such as scour combined with dynamic loading from seismic activity (Alipour et al. 2013).

Overtopping occurs when the flood water level reaches the elevation of the bridge deck. Additional water pressure acts on the bridge because the water is now acting over the area of the bent and the bridge girders, parapets, and guard rails. This additional water pressure causes much larger lateral forces on the bridge and could be acting on a longer moment arm if scouring at the piers is also at play. The bridge would likely be closed well before any structural instability occurs due to the combination of these damage modes (scour and overtopping) because the water level would render the bridge impassible or unsafe to cross. After the high water level recedes, the surface texture on the pavement may also have eroded because water may have washed debris over the deck surface. With an overly smooth pavement surface texture, the bridge can be unsafe to cross during rain or wind scenarios.

Debris can also become lodged around the bridge in places such as the piers, guardrails, or abutments. This additional debris results in additional surface area and therefore increases the hydraulic force on the bridge. Scour depth has also been found to increase with the presence of debris at the piers due to the turbulent nature of the water around these obstacles. The combination of additional lateral force and a longer moment arm from increased scour depth creates a less stable bridge.

3.2. Overview of Methods

It is necessary to know the current condition of Iowa's bridges and better understand which parameters may make a bridge more sensitive to flooding. By using only NBI data, an index method was created to rate bridges by their vulnerability and sensitivity to flooding in terms of stream channel instability, structural condition, and the criticality of the bridge to the network. With these data, the hotspots in Iowa where bridges may be more susceptible to flood damage were located.

These hotspots and vulnerability index results show the current sensitivity of bridges in the state to flooding, but it is often useful to use historic data to determine the causes of bridge damage. For this reason, data were collected from bridges damaged in major floods to ascertain the type of damage, a cost estimate for repairs, and the physical attributes of the bridges. Using these data, this method examined trends and relationships between the bridge parameters as predictor variables and the repair cost as the response variable.

Even without physical damage done to the bridge, closures can still occur with high water levels. When water levels reach the height of the bridge seat or girders, they are often deemed unsafe for traffic. Using data for bridge elevations along with flood period elevations ranging from 2-year to 500-year flooding, bridge closures were predicted for Iowa DOT District 6. This information is important for identifying the bridges that may be vulnerable to flood waters and the routes that may need to be redirected, which may cause increased traffic elsewhere. The findings of this method can be directly applied to the entire state of Iowa to determine the overall impact of high flood waters on Iowa's bridge assets.

Many states have emergency response plans for extreme flooding, but not all of these plans specify the response to bridge damage (Alipour 2016). Therefore, these methods provide excellent opportunities for integrating risk into Iowa's TAMP. Bridge sensitivity analysis can help identify bridges that may need additional maintenance or those that require more funds for repairs. Relationships between bridge attributes and flood damage can be used to perform preventative maintenance as well as identify the bridges that may be a priority for repair after flooding. Predicting which bridges may be overtopped can provide insight as to which routes need detours and how those detours can impact the transportation network. These methods are described in detail in the next three sections.

3.3. Bridge Sensitivity Index Approach

The 2019 NBI database for Iowa was used for this study. The database included 24,044 bridges in the state. Those bridges were then filtered by the type of service under the bridge (#42B) to include only those that are over a waterway or a waterway combined with another service such as a railway or highway. Then, the structure type (#43B) was filtered to remove culverts from the data because those structures are outside the scope of this study. This filtering resulted in 17,858 total bridges over waterways in Iowa, of which only 1,869 are under the maintenance responsibility of the state, as filtered by NBI item #21. Table 3.1 shows a further breakdown of the number of bridges that are maintained by the Iowa DOT in each district.

Table 3.1. Iowa DOT bridges over waterways by district

District	Iowa DOT Waterway Bridges
1	256
2	310
3	297
4	320
5	258
6	304

The sum of the bridges in the six districts is less than the total number of Iowa DOT-maintained waterway bridges because some bridges appear in the NBI database but do not show an asset number in SIIMS when a report query is created. This could either be due to the maintenance responsibility being incorrectly listed in the NBI for some bridges, bridges no longer existing, or typos in either the NBI or SIIMS database. If the complete dataset of bridges needs to be analyzed in future work, a manual process for checking bridges without asset numbers in SIIMS would need to be performed. Figure 3.1 shows the distribution of bridges used in this study.

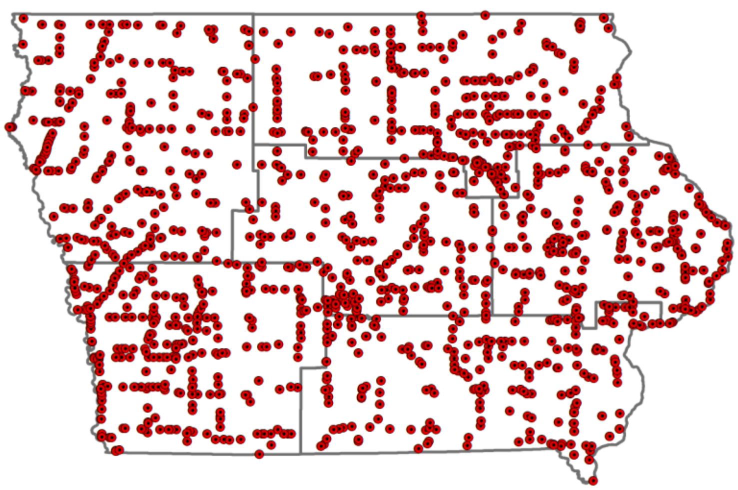


Figure 3.1. Iowa DOT bridge locations over waterways

3.3.1. Stream Channel Instability

Scour of the streambed is a common occurrence in which fast moving waters wash away the soil on the bottom of the channel, which can be disastrous around bridge foundations. Bank erosion is another common hazard associated with streams, which over time can slowly change the channel geometry, change the water attack angle to the bridge, or shift material from the bank to an area closer to the bridge, affecting the bridge approach or abutments. The Iowa DOT has installed many erosion control measures to slow or prevent scour and erosion, such as riprap, spur dikes, or bank vegetation. There are often instances of high water carrying debris such as trees, roots, or branches that constrict the flow of the stream, thereby creating faster moving water. This debris can become lodged beneath the bridge, and if the bridge opening is not sufficient for the volume of water being carried, then overtopping can occur. These many hazards can be grouped into the general category of stream channel instability.

Following the procedure of Johnson and Wittington (2011), a bridge's vulnerability to stream channel instability was assessed using a continuous four-point scale that rates the overall vulnerability as low, moderate, high, or very high. Stream channel instability is an important measure in evaluating the overall sensitivity of a bridge over a waterway because of the constantly changing nature of streams. The NBI was used to gather inspection data about the bridges and streams in this analysis to determine the bridges' vulnerability to stream channel instability. The following three data items from the NBI were used:

- Scour Criticality (#113) identifies the current risk of scour at each bridge based on assessment or calculation of the scour depth.
- Channel Protection (#61) describes the physical condition of the channel, riprap, slope protection, or stream control devices.
- Waterway Adequacy (#71) appraises the waterway opening under the bridge with respect to the flow of the waterway.

In the NBI, these three data items are evaluated on a 0 through 9 scale, with each item being rated slightly differently, but for all three items a 9 indicates the best possible rating and the lower the rating, the more vulnerable the bridge, with 0 indicating bridge closure. In order to provide better clarity of the sensitivity, a scale of 1 through 4 was used for this study, with 1 through 4 corresponding to excellent, good, fair, and poor, respectively, for each individual parameter. Table 3.2 summarizes this rating scale and how it relates to the scale provided in the NBI.

Table 3.2. Rescaled NBI ratings

Condition	NBI Rating	Rescaled Rating
Excellent	8-9	1
Good	6-7	2
Fair	3-5	3
Poor	0-2	4

The rescaled rating was chosen to be a 1 through 4 scale similar to that used by Johnson and Wittington (2011) due to the descriptions of the NBI ratings. For the three data items used in the stream channel instability index, a rating of an 8 or 9 is described as the equivalent of a stable condition or having no deficiencies. A rating of a 6 or 7 is a condition where minor damage may have occurred or where there is a slight chance of minor damage occurring. The exception to this is with scour criticality (#113), where a 6 refers to a situation where the bridge has not yet been evaluated for scour. Only one bridge, located on Iowa Highway 175 over the Missouri River at the border of Nebraska, had a rating of a 6 at the time of this study. This specific bridge had a rating of 6 for scour criticality for the two prior years as well, so the rating does not seem to be the result of a recording error, but the risk appears to be minimal if it is assumed that this bridge that has not been evaluated for scour is considered to be in good condition. Fair condition, which corresponds to an NBI rating of 3, 4, or 5, refers to damage or potential damage that is relatively major but has not yet affected the stability of the bridge. Lastly, an NBI rating of 0, 1, or 2 reflects damage that is severe enough to affect the structural integrity of the bridge or indicates that the bridge has already been closed due to the damage incurred.

With the rescaled rating system, stream channel instability was calculated for each bridge based on a weighted average of the three parameters. The weights associated with each parameter indicate the level of importance each plays in the overall stream channel instability but can easily be altered if other parameters are added or if individual judgement warrants a change. Channel Protection was deemed to be the highest weighted parameter, with a weight of 0.40, due to the generalized nature of the parameter and the checks that are required for the inspection. This parameter includes evaluation and inspection of the stream stability, excessive water velocity, and the condition of any riprap, slope protection, and stream control devices. Both Waterway Adequacy and Scour Criticality have a weight of 0.30. These parameters do not necessarily affect every bridge and therefore have slightly less weight than Channel Protection, which can describe any bridge location. When calculating this weighted average to create the stream channel instability index, the range was considered continuous between 1 and 4.

These three data items are not necessarily the only parameters that determine the overall stream channel instability. Others who have applied this method have used a scour risk calculation along with observed scour (Blandford et al. 2019) or a combination of other parameters, including bank cutting, bank slope angle, flow habit, channel pattern, and others (Johnson 2005, Johnson and Wittington 2011). Because none of these parameters are listed in the NBI, they require the individual agency in charge of bridge maintenance and inspection to gather these data. The Iowa DOT does include a qualitative description of each waterway in SIIMS, which was not used for this study. This could be used to provide additional data about streams and therefore increase the reliability of stream channel instability ratings; however, the data in this field are very limited.

To provide information specific to the Iowa DOT, the data presented in the following sections include only bridges maintained by the state unless otherwise specified. The distribution of stream channel instability ratings is shown in Figure 3.2 for these state-owned bridges over waterways. These data do not follow a normal distribution and are heavily weighted toward a rating of 1 in the rescaled rating system. Several reasons for this include the fact that over 48% of the ratings for Waterway Adequacy in the NBI database were 8 or 9, which indicates excellent condition. A large percentage of the Scour Criticality and Channel Protection ratings also indicated excellent condition, which helped contribute to the high number of bridges with a rating of 1 for stream channel instability. No ratings were worse than 3 (fair condition) in the rescaled system, but this does not necessarily mean that none of these bridge locations are vulnerable to stream channel instability.

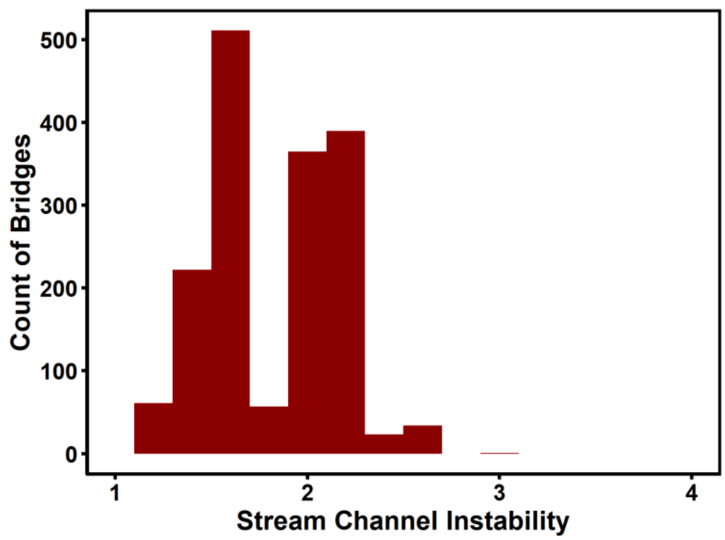


Figure 3.2. Histogram of stream channel instability index

3.3.2. Structural Condition

The structural condition of the bridge may be the most obvious contributor to the bridge sensitivity index value. Several parameters can factor into the overall structural condition, but using the evaluation ratings from the NBI is the simplest method because the data should be reported on an annual basis and hence are collected using a similar standard. The NBI has a parameter called Structural Evaluation (#67), which provides a concise overview of the condition of the bridge based on the observed parameters of superstructure condition and substructure condition. For this parameter, whichever rating is lower between superstructure condition and substructure condition is used for the overall structural evaluation. This rating was used to indicate structural condition unless the inventory rating and average daily traffic count warranted a lower rating. The structural evaluation can therefore be considered a conservative estimation of the structural condition of the bridge because it uses the feature in the worst condition to determine the rating, but a more meaningful rating would include multiple parameters, as the following method lays out.

A bridge can suffer damage due to flooding in several different areas. The substructure is the most obvious, since the water is constantly applying a force on the piers. In addition, scour of the streambed material and local scour around the piers can increase this force and increase the moment arm on which the force is applied. Impacts from debris or even barges or other vessels can damage the piers as well, and the accumulation of this debris can increase scour depths around the piers. The superstructure can also be impacted if water levels are high enough, which can cause structural issues with the girders or safety concerns with the guardrails. Debris can also lodge in bearings or degrade the bearings to prevent them from functioning properly for thermal expansion and contraction. When water levels reach the height of the superstructure, the buoyancy force has the potential to uplift the entire superstructure. If water levels overtop the bridge, the deck surface is vulnerable to damage due to the water deteriorating the surface more quickly than it would otherwise deteriorate or smoothing the texture necessary for traction and carrying debris that can scar the roadway. A rating system for structural condition is dependent on all three of these areas of the bridge, which is why the following NBI parameters are used to calculate this rating:

- Deck Condition (#58) describes any cracking, scaling, delamination, corrosion, splitting, or other damage in the deck, depending on the deck material.
- Superstructure Condition (#59) describes any cracking, deterioration, misalignment, bearing issues, or other damage in the superstructure.
- Substructure Condition (#60) describes any cracking, settlement, scour, corrosion, or other damage in the piers, footings, piles, and other substructure components.

These NBI data are each rated on a scale from 0 through 9, with 9 indicating excellent condition and 0 indicating failed condition. Each of these parameters is based on a multiple point inspection and changes based on the material or the type of bridge being inspected. For these reasons, it may be difficult to directly compare the rating of a steel girder bridge with footings to that of a concrete girder bridge with a pile foundation; however, in this study it is assumed that the condition rating is consistent across all bridges.

A four-point scale was adopted once again to rate the structural condition as either excellent, good, fair, or poor. Because the NBI scale used for these parameters is similar to the scale used for the parameters for stream channel instability, the rescaling shown in Table 3.2 was also used for the structural condition rating. An NBI rating of 8 or 9 indicates that no problems were observed, so these NBI ratings indicate an excellent condition rating in the rescaled rating system. An NBI rating of 6 or 7 indicates minor problems, so these NBI ratings indicate a good condition rating. An NBI rating of a 4 or 5 indicates either advanced or minor section loss, and a rating of 3 indicates that local failures are possible. Even with these losses, these NBI ratings correspond to a fair condition rating in the rescale system, which may not be an appropriate name for this condition, but the numerical scale should still be appropriate. NBI ratings of 0, 1, or 2 indicate either advanced deterioration where closing may be required or indicate that the bridge has already closed due to its condition.

The distribution of results is shown in Figure 3.3, where the majority of bridges have a condition rating of 2, or good condition. Similar to the stream channel instability index, this is due to a high number of similar NBI ratings for the given parameters. Almost 90% of the Deck Condition ratings indicated good condition, which includes NBI ratings of 5, 6, or 7. Over 68% of the Superstructure Condition and almost 75% of the Substructure Condition ratings also indicated good condition. More important than analyzing the percentage of bridges in good condition is to analyze the how many bridges were rated as being in fair or poor condition in terms of structural conditions. The percentages of Deck Condition, Superstructure Condition, and Substructure Condition ratings that indicated fair condition were 0.86%, 0.53%, and 0.21%, respectively. Only one bridge in the population had a poor condition rating for any of the parameters. This bridge happened to have an NBI rating of 0 for all three parameters because the bridge was closed due to the structural issues. This resulted in a single bridge having a structural condition index value of 4, with the next highest being 2.75.

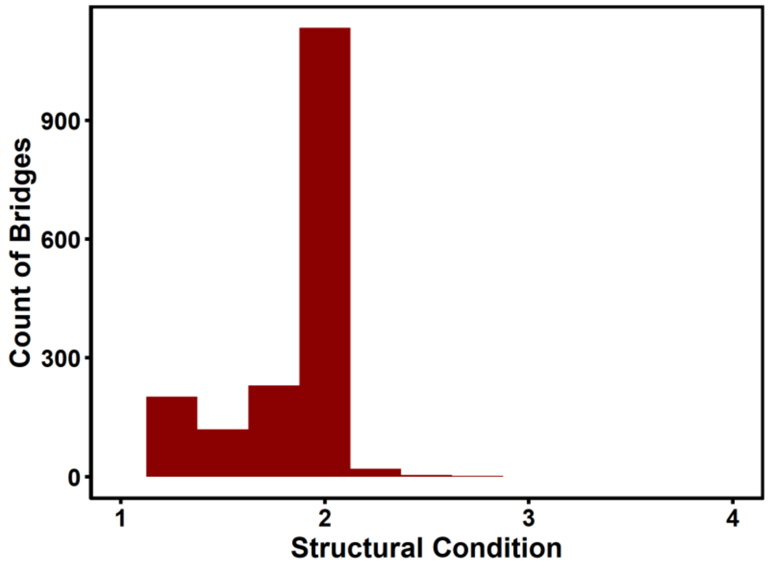


Figure 3.3. Histogram of structural condition rating

3.3.3. Bridge Criticality

The bridge sensitivity index is not only reliant on stream channel instability and structural condition; it is also important to know the criticality of the bridge for day-to-day traffic and the overall transportation network. A bridge that carries heavy traffic and suffers minor damage that causes a short-term closure could be considered more vulnerable than a minimally travelled bridge that experiences a long-term closure. Similar to the system used to assess stream channel instability and structural condition, a four-point scale based on NBI data was used to assess bridge criticality.

Criticality was determined using data associated with bridge usage (i.e., average daily traffic, functional class, etc.) in addition to the potential cost of replacement if that bridge suffered severe damage, which was estimated using bridge parameters (i.e., length, width, etc.). The cost of replacement may be better included in an estimate of the probability of a consequence rather than an assessment of the criticality of a bridge, which indicates the probability of risk, but replacement cost can still be a valuable addition to the data defining bridge criticality. Overall, this is a clean and simple method for comparing the bridges in a network to each other to easily identify bridges that may be more vulnerable during a flood.

The NBI data used for determining bridge criticality are as follows:

- Average Daily Traffic (#29) is a simple count of the vehicles traveling over a given bridge.
- Average Daily Truck Traffic (#109) is the percentage of heavy trucks in the average daily traffic.
- Functional Class (#26) categorizes the use of the bridge in terms of urban or rural and the type of road or highway it serves.

- Bypass Detour Length (#19) indicates the length of the detour route if the bridge were to be closed.
- Structure Length (#49) is the length of the bridge measured in meters.
- Roadway Width (#51) is the width of the roadway over the bridge measured in meters.
- Number of Spans (#45) is the number of spans that the bridge contains.

With the exception of Functional Class, these NBI data are all continuous parameters, unlike the categorical ratings used for stream channel instability and structural condition. This makes rescaling the parameters slightly more arbitrary, since the values of each parameter do not correspond to the scale used by Johnson and Whittington (2011), so a different rescaling system was used. Table 3.3 summarizes the rescaling of each parameter for bridge criticality. The different possible values for Functional Class were grouped, with local routes and rural minor collector routes having the lowest vulnerability, with a rating of 1, and principle arterial routes having the highest vulnerability, with a rating of 4. The other rescaled ratings were estimated and based on ratings found in Johnson and Wittington (2011) and KTC (2019).

Table 3.3. Rescaled bridge criticality ratings

Functional Class	Average Daily Traffic	Average Daily Truck Traffic	Bypass Detour Length	Structure Length	Number of Spans	Roadway Width	Rescaled Rating
8, 9, 19	<500	<200	<5	<15	1	<7.4	1
7, 16, 17	500–1,999	200–999	5–15	15–25	2	7.4–9.4	2
6, 14	2,000–7,500	1,000–5,000	15–25	25–32	3	9.4–11.7	3
1, 2, 11, 12	>7,500	>5,000	>25	>32	>3	>11.7	4

The bridge criticality index is more consistently distributed than the other two indexes discussed. However, it is still skewed toward having a large number of critical bridges in the population. This distribution histogram is shown in Figure 3.4.

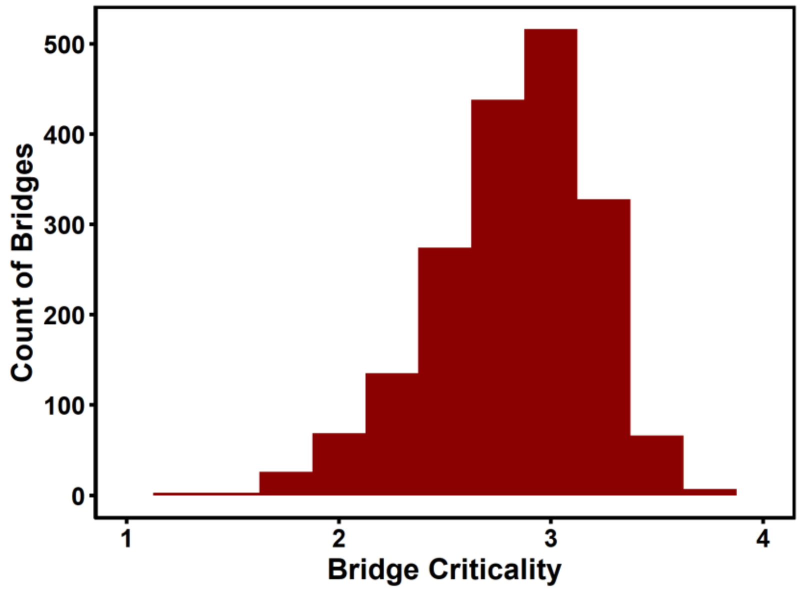


Figure 3.4. Histogram of bridge criticality index

3.3.4. Bridge Sensitivity Index

With indexes having been built for stream channel instability, structural condition, and bridge criticality, a total index was derived to determine the total bridge sensitivity index. These three indexes are each important in determining bridge sensitivity, but a weighted average approach was used to designate which indexes should have the highest priority. Safety was the highest priority when determining the weight of these indexes. Structural condition is the most obvious index associated with safety, since poor structural health could lead to collapse and cause serious injuries and fatalities. For this reason, the structural condition index constitutes 50% of the bridge sensitivity index. In addition to safety, economic and travel impacts were assessed because these are the main functions of bridges. The bridge criticality index is the main driver of these impacts and therefore contributed significantly to the bridge sensitivity index.

The total bridge sensitivity index was calculated through a weighted average of stream channel instability (0.25), structural condition (0.5), and bridge criticality (0.25). Based on this calculation, the bridge sensitivity index histogram of all state-maintained bridges over water is shown in Figure 3.5. This chart shows a slightly skewed distribution similar to that of the criticality index but has a lower mode due to the contributing indexes of structural condition and stream channel instability. For the sample population of 1,869 bridges, the average sensitivity index was 2.04 with a standard deviation of 0.24.

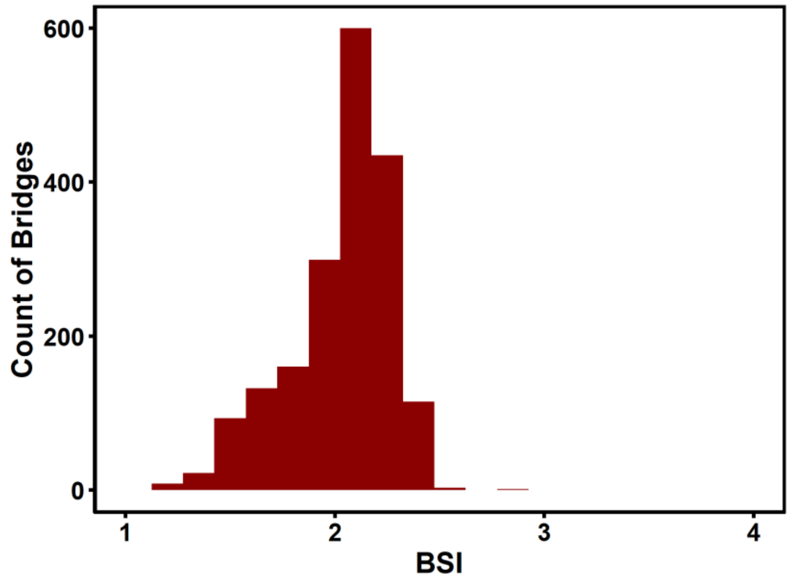


Figure 3.5. Bridge sensitivity index for all Iowa DOT bridges over waterways

The individual parameters that make up each index were scaled from 1 to 4, indicating excellent, good, fair, or poor condition, respectively. When these parameters are combined in a weighted average, the scale compresses significantly because no single bridge has all minimum or all maximum index values. A baseline index score was needed to determine what a typical bridge would score for the bridge sensitivity index. For this, all three index parameters were included, and any condition rating was assumed to be a 7, indicating good condition. All other parameters were taken as the average value of the population, with the exception of Functional Class, for which the mode was used. These values along with the bridge sensitivity index rating are shown in Table 3.4.

Table 3.4. Baseline bridge sensitivity index

Parameter	Value
Scour Criticality	7
Waterway Adequacy	7
Channel Protection	7
Deck Condition	7
Superstructure Condition	7
Substructure Condition	7
Functional Class	2
Average Daily Traffic	5,571
Average Daily Truck Traffic	857
Bypass Detour Length	12.7
Structure Length	869
Number of Spans	3
Roadway Width	121
Baseline Bridge Sensitivity Index	2.25

For this baseline bridge, the stream channel instability index is 2.00, the structural condition is 2.00, and the criticality is 3.00, which results in an overall bridge sensitivity index rating of a 2.25. Even with a criticality of 3.00, this bridge was assumed to be the baseline of a moderately vulnerable bridge. To determine the vulnerability ranges of low, moderate, high, and very high, this baseline sensitivity index was used along with the standard deviation of the index. Table 3.5 summarizes the ranges of vulnerability for the bridge sensitivity index.

Table 3.5. Ranges of vulnerability for the bridge sensitivity index

Vulnerability	Bridge Sensitivity Index Range
Low	<2.01
Moderate	2.01–2.25
High	2.26–2.50
Very High	>2.50

This method can be used to evaluate all state-owned bridges over water in Iowa. Other methods in this report use only a sample population often dictated by a single district. For this reason, it is necessary to determine any differences in a bridge's sensitivity based on geographical location. This can also be useful in searching for areas that may see more flooding or areas that have a larger number of structurally deficient bridges. Iowa's six transportation districts were used as geographical boundaries, and analysis of variance (ANOVA) was performed on the bridge sensitivity index scores based on the districts in which the bridges are located. The overall p-value was less than 0.001, which indicates that there is a statistically significant difference between the mean bridge sensitivity index among districts. All pair-wise comparisons were considered using Tukey's honestly significant difference (HSD) method with $\alpha = 0.05$ and are summarized in Table 3.6. Each group membership indicates similar means within that group. District 3 is included in all group memberships, which shows that the mean bridge sensitivity index value of District 3 is not significantly different from that of any other district.

Table 3.6. Tukey HSD results for bridge sensitivity index

District	Group Membership			Mean Bridge Sensitivity Index
2	A			2.073
6	A			2.064
5	A	B		2.052
3	A	B	C	2.024
4		B	C	2.006
1			C	1.988

Table 3.6 shows that there are differences in bridge sensitivity based on location. To try and visualize these differences better, Figure 3.6 through Figure 3.9 show heat maps for each index used. In these maps, each point represents a single bridge. The darker red points represent the most vulnerable bridges, and the darker blue points represent the least vulnerable bridges.

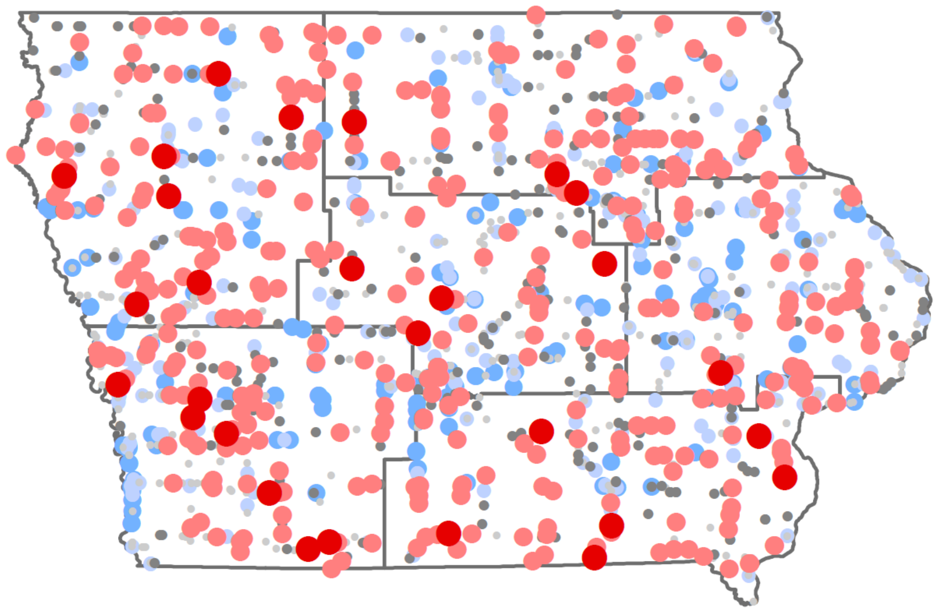


Figure 3.6. Stream channel instability index heat map

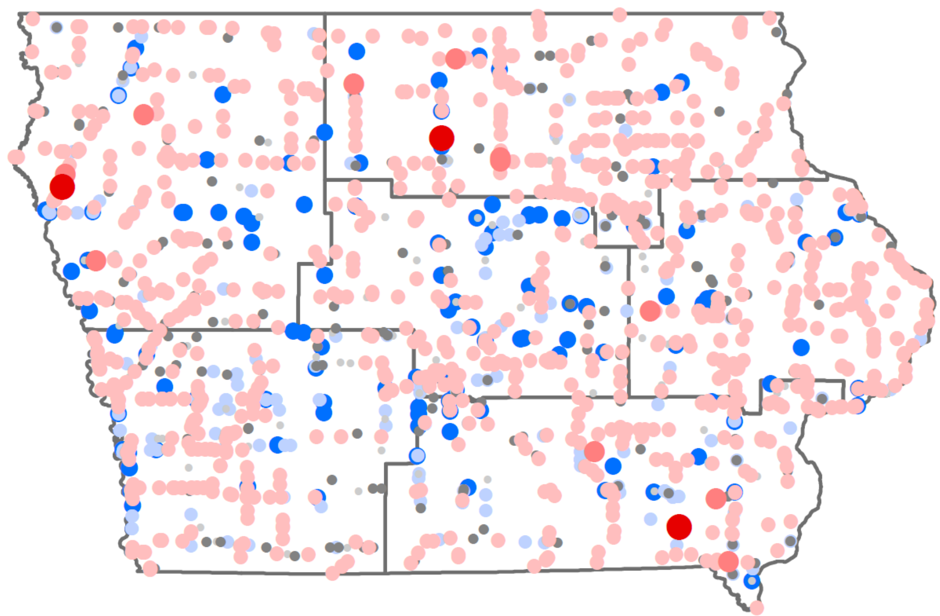


Figure 3.7. Structural condition index heat map

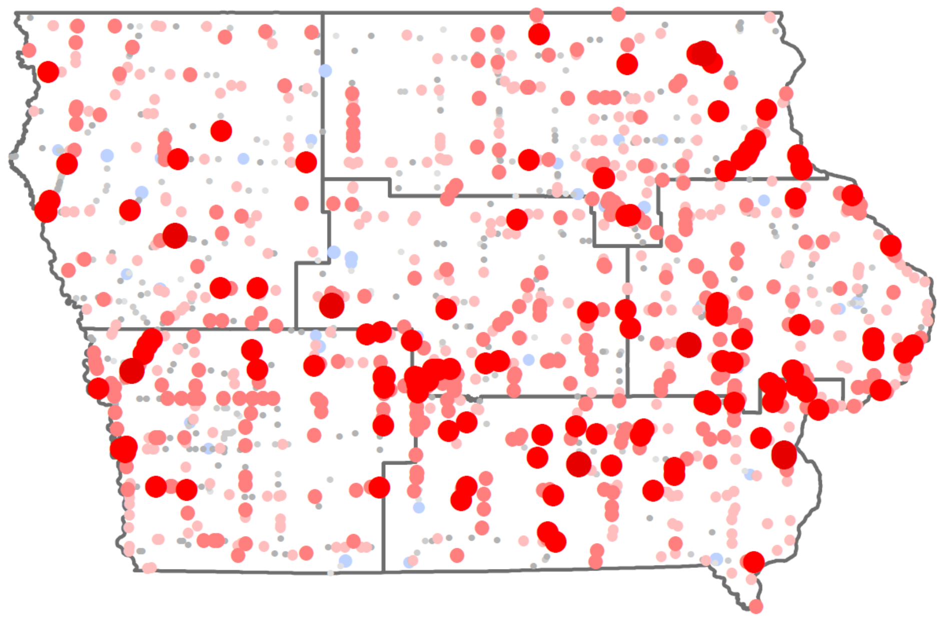


Figure 3.8. Criticality index heat map

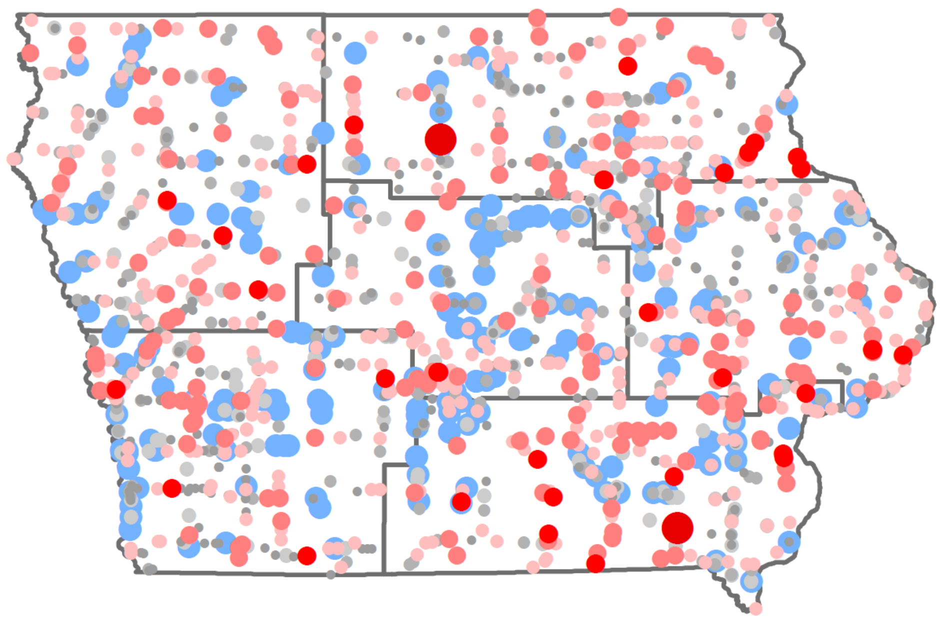


Figure 3.9. Bridge sensitivity index heat map

Bridge sensitivity index scores can be used to find specific bridges at the maximum or minimum sensitivity range and can be used as proxy indicators to monitor and evaluate these bridges for future use. The other index values could be used in a similar manner for monitoring only structural condition, stream channel instability, or criticality. The scales and cutoff points presented in this section are arbitrary and could be modified if desired. This does not mean that the data presented here are irrelevant, but rather that the data can be adapted to fit a wider scope or can change with added parameters. Understanding the bridge population's sensitivity to flooding before a flood happens can be a powerful tool to better prepare, predict, and react to future events where damage may occur.

The bridge sensitivity index does not take into consideration the risk of or vulnerability to certain flooding events. The purpose of this index is to evaluate certain parameters and inspection criteria to identify bridges that might be sensitive to flooding due to stream channel conditions, condition rating, or daily usage and potential repair costs. Even though a bridge registers a low or moderate vulnerability on the bridge sensitivity index, a major flood may nevertheless cause damage that would affect the bridge's integrity. An analysis of the actual damage associated with flooding was needed to better understand how the physical characteristics of a bridge are related to the repair costs caused by flood damage. A method for determining these relationships is explored in the following section.

3.4. Statistical Methods Based on Historical Damage

Studying historical events and responses to them provides an excellent opportunity to learn from them and fill in missing data. As part of the FHWA's Emergency Relief (ER) program, state DOTs are required to document instances in which ER funding was assigned to different cases of failure. Detailed damage inspection reports (DDIR) are prepared to document damage and the scope and estimated costs of repair work, prove eligibility for repairs and improvements, and classify the work performed as either emergency or permanent repair.

The research team reviewed DDIR documents generated in the aftermath of flooding events in Iowa from 1998 to 2014 and extracted data describing the type of damage suffered by Iowa DOT transportation assets, the required repairs and associated requirements for the repairs, and the costs associated with different levels of failure.

Within this timeframe, damage was recorded for 361 bridges. About half of these bridges had usable asset numbers that could be accessed via SIIMS. Several of these bridges did not have valid asset numbers and could not be found in SIIMS. Many records had the bridge's structural number, which was then cross-referenced with the asset number. The majority of these bridges could not be accurately identified for various reasons, including possible incorrect data input, unknown structural number format, or asset numbers that did not match between databases. In total, 170 bridges were found for which damage was recorded and data were available in SIIMS; these bridges were used in this study. Several damage modes had recorded repair costs associated with one of the following:

- Abutment or Berm Erosion – These two types of bridge damage were often grouped together in the DDIRs, and because of their close proximity they were treated as one damage type. This type of damage involves washing away either the soil from the berm slope near the abutments or the soil around or under the abutments.
- Pier Scour – This type of damage refers to the erosion of streambed material at or around the piers.

- Pier Debris – The repair costs often included costs for debris removal around piers. There were instances where the DDIR did not specifically say the debris was around the pier, but because the piers are the most common point of collection, it was assumed that pier debris was where the damage occurred.
- Bank Erosion – Either upstream or potentially downstream of the bridge, the bank has begun to erode in close enough proximity to the bridge to justify classifying it as damage to the specific asset.
- Streambed Scour – This is similar to pier scour, but instead of being specifically around the piers, it could occur anywhere in the channel around the bridge area.

In this study, the relationships between the damage occurrence/cost and the physical bridge attributes were analyzed via logistic and simple linear regressions in order to better understand which attributes may or may not play a role in the severity of damage during floods. Because mostly bridge attributes were used in the analyses and a minimal amount of data on the stream channels was available, bank erosion and streambed scour were excluded from this study. By using quantitative formulas for each of the damage modes, physical bridge attributes could be obtained that have a known relationship to that damage.

The Iowa DOT does not rely on estimations of abutment scour from the FHWA's Hydraulic Engineering Circular No. 18 (HEC-18) and recommends using them with caution (Iowa DOT 2019). Because the Iowa DOT does not include a method for estimating abutment scour, Froehlich's equation from HEC-18 was used for this estimate. Froehlich's equation for calculating abutment scour, which was developed using a regression analysis of 170 live-bed scour measurements (Froehlich 1989), is shown in equation (3.1) and was used as the basis for this study.

$$\frac{y_s}{y_a} = 2.27 K_1 K_2 \left(\frac{L'}{y_a}\right)^{0.43} Fr^{0.61} + 1 \tag{3.1}$$

where:
y_s = Scour depth, ft
y_a = Average depth of flow on the floodplain
K_1 = Coefficient for abutment shape
K_2 = Coefficient for angle of embankment to flow
L' = Length of active flow obstructed by the embankment, ft
Fr = Froude number, ft/s

The average depth of flow can be estimated using the elevation of the streambed and the elevation stage of the floodwater. The abutment shape refers to three possible configurations: a spill-through abutment, which is the most common construction in this study; a vertical wall abutment; or a vertical wall with angled wingwalls. The coefficient for the angle of embankment to the flow is assumed to be the same as the skew angle of the bridge relative to the stream. The length of active flow obstructed by the embankment is very difficult to calculate based on information available. This variable depends on the floodwater elevation stage, the channel geometry, and the length of the embankment into the channel. Because the channel geometry is difficult to obtain and the corresponding calculation would be a function of channel geometry, this variable was not included in this study. Water velocity is used in the calculation of the Froude number. Water velocity also depends on the water elevation, discharge rate, and channel geometry, so the Froude number was also not used in this study.

Scour is the erosion of riverbed material due to flowing water and is the most common cause of bridge failure during flooding events. It can create particularly dangerous conditions around piers and abutments by obstructing the flow of water, resulting in a more turbulent condition. Several factors can affect scour magnitude at the piers and abutments, including velocity of the approach flow, depth of flow, width of the pier, length of the pier, bent configuration, size and gradation of bed material, angle of flow attack, pier or abutment shape, bed configuration, and ice formation or jams and debris. Unlike for abutment scour, the Iowa DOT uses HEC-18 for estimating pier scour depth, which can be estimated using equation (3.2) (Ameson et al. 2012).

$$y_s = 2.0 y_1 K_1 K_2 K_3 \left(\frac{a}{y_1}\right)^{0.65} \left(\frac{V_1}{(g y_1)^{0.5}}\right)^{0.43} \tag{3.2}$$

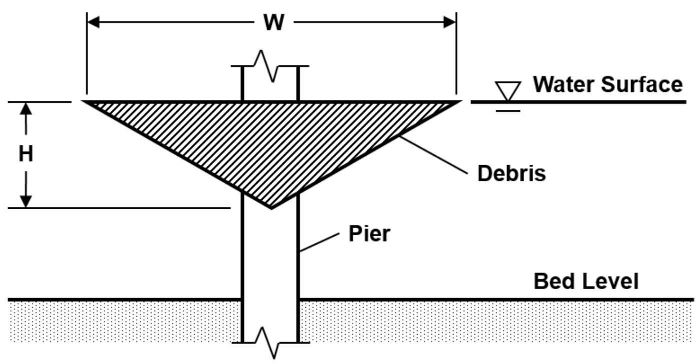
where:
y_s = Scour depth, ft
y_1 = Flow depth directly upstream of the pier, ft
K_1 = Correction factor for pier nose shape
K_2 = Correction factor for angle of attack of flow
K_3 = Correction factor for bed condition
a = Pier width, ft
V_1 = Mean velocity of flow directly upstream of the pier, ft/s
g = Acceleration of gravity, ft/s^2

The actual depth of scour was not necessarily important in this study because the object was to simply predict whether scour damage will result in repair costs regardless of the depth. It is logical to assume that there would be a correlation between the depth of scour and the cost of repair; however, the exact scour depth at the piers was not recorded at the time when the damage occurred. The scour rating condition of the bridge as recorded in the NBI database can give a good indication of the severity of scour during the year in which the flood damage occurred.

Most bridges that cross a waterway at an angle other than 90 degrees are skewed to match the angle of flow, and therefore the angle of attack should be close to zero. This is not an exact value because the attack angle may change based on different flooding events with different water elevations or velocities. An example of this happening could be when a bridge is located after a bend in a waterway; when the water crests the banks of the waterway, the angle of water approaching the bridge could change. The pier nose shape coefficient corresponds to either a semicircular nose shape or a square nose shape, which can be found almost exclusively on pile bents. Other pier nose shapes are possible, but only these two were found on the bridges included in this study. The width of the pier is determined by the width normal to the direction of flow. Since the attack angle is assumed to be close to zero, this value is simply the width of the pier.

The unscoured depth of flow can be determined by noting the water elevation at the time when the damage occurred.

Pier debris is much less defined than both pier and abutment scour. There are estimations of how large the debris raft can become when calculating pier scour depths, as shown in Figure 3.10, but there are no equations that include bridge attributes. Instead of using empirical formulas for this damage state, a strictly intuitive approach was used to determine the parameters that may affect debris accumulation. The number of spans of the bridge is very important for identifying the number of piers and therefore the number of chances for pier debris to accumulate. The geometry of the pier may also be a good indication of how easily debris can become lodged against a pier, so pier width, pier nose shape, and bent type are important variables to include. The flood stage of the stream is also very important because a higher water elevation results in more debris being washed downstream, and high water can also lodge debris higher up on the pier.



AASHTO, (adapted and modified from AASHTO Load and Resistance Factor Design)

Figure 3.10. Debris accumulation at a bridge pier

The formulas for abutment scour and pier scour have been tested and/or observed, and the parameters of these equations are known to contribute to scour depth. These formulas have errors associated with them due to the relatively unpredictable nature of scour (Alipour et al. 2013, Kingla and Alipour 2015, and Fioklou and Alipour 2019), but they are generally accepted as accurate estimates. Logistic and linear regressions using actual data can be expected to align closely with the results of these formulas.

The study described in this section—to develop proxy indicators of the vulnerability of bridges to flooding based on historical damage—has the following three goals:

- Visualize the relationship between bridge parameters and the cost of damage repairs, with the expectation that relationships are present based on the parameters in equations (3.1) and (3.2).
- Include additional variables that are not present in equations (3.1) and (3.2) in hopes of determining new relationships between different types of damage and easily accessible parameters from the NBI.

- Correlate NBI parameters to the costs associated with pier debris to better understand the physical bridge attributes or stream characteristics that lead to this damage.

Out of the 170 bridges for which damage was recorded between 1998 and 2014, a small percentage was affected by one of the three specific damage modes examined in this study. For example, pier scour only affected 39 bridges out of the 170 total bridges recorded. This resulted in the majority of bridges having zero cost associated with each type of damage, so it was important to distinguish which bridges had been damaged and which ones had not been damaged. In this way, a logistic regression could be performed for each of the parameters in question to determine any statistical significance between the parameter and the response.

The next step was to perform a linear regression on the data points that experienced damage. Zero-value points were removed from the data set for this method because they would create a large bias in fitting a model. The goal with this method was to identify any linear trends between the bridge parameters and the response to better predict the repair costs once damage has occurred. There are other methods to use besides linear regressions, and some may be better suited in that they do not assume the data are linear, but this method is a good starting point and can identify basic trends. Important information can be obtained from simple linear regressions, including R^2 values, p-values, and t-values, which are summarized as follows:

- R^2 Value – The percentage of the variation in the data that can be explained by the linear relationship between the response and the variable
- P-Value – The significance of the relationship; typically, $p < 0.05$ is considered significant
- T-Value/Z-Value – The ratio of the difference between the hypothesized value and the estimated value to the standard error

3.4.1. Abutment and Berm Erosion

Equation (3.1) summarizes a method to calculate abutment scour depth. The Iowa DOT recommends only using this method with caution because predicting abutment scour is difficult and this method may not lead to accurate estimations. This equation includes two continuous variables that could be analyzed via linear regression: flow depth and length of active flow obstructed by embankment. Flow depth data are very limited at the time of flood damage, so analyses with these data are part of future work. Data on the length of active flow obstructed by embankment are therefore also limited. The flow depth is needed to determine the obstructed length because the latter is a function of the abutment shape, bank slope, and water elevation. Many complications are involved in using this parameter, and these are planned to be addressed in future work.

For statistical analysis, it is important that variables are split into continuous or categorical variables. These variable types are analyzed differently when fitting a linear model: categorical variables only allow the fitted regression to fall into one of the predefined categories, whereas continuous variables allow the regression to be any positive value.

The following continuous parameters were included for correlations with abutment and berm erosion repair costs:

- Length – The length of a bridge is of interest because longer bridges are typically over wider streams or rivers, which may have faster moving currents that cause more abutment erosion.
- Age – The age of a bridge is of interest because as a bridge ages, the abutment scour or berm erosion could continue to develop and go unnoticed or be ignored and therefore contribute to significant repair costs during a major flood.
- Skew Angle – The skew angle can be equated to the angle of the embankment to the flow in equation (3.1) and is therefore expected to have a correlation with repair costs.
- Bridge Seat Elevation – This parameter is the minimum value of each of the two bridge seat elevations. The elevation by itself is not expected to be related to repair costs because it is not in reference to the flood water, but it was included in the analysis and can be compared to the streambed elevation.
- Streambed Elevation – This parameter is the minimum depth of the streambed below the bridge and was included in the analysis for the same reason as the bridge seat elevation.

The following categorical variables were analyzed:

- Abutment Type – This parameter directly relates to the coefficient value for abutment shape in equation (3.1).
- Abutment Foundation – This parameter was included to determine whether a piled abutment or an abutment solely on a strip footing impacts the amount of damage from abutment scour.
- Channel Rating – This parameter is a rating given to the stream channel based on criteria such as excessive water velocity, amount of slope protection, presence of riprap, condition of the channel, and the presence of debris affecting the flow.
- Substructure Rating – This parameter is a rating to assess the condition of the superstructure components, including those of the abutment foundations. The condition is evaluated based on cracking, settlement, and scour at the footing or piles of the foundation.
- Scour Rating – This parameter rates how vulnerable the bridge is to scour.

The logistic regression plots for the continuous variables are shown in Figure 3.11. The plots show the probability of damage occurring based on the defined continuous variables. All 170 bridges are represented by a point on each of the plots. Bridges that were damaged due to abutment/berm erosion were plotted as 1, indicating a 100% probability of damage, and the remaining bridges that were not damaged were plotted as 0, indicating a 0% probability of damage. For the case of abutment/berm erosion, 92 bridges suffered damage out of 170 bridges in the data set. The blue line on each of the plots represents the estimated probability of damage, with the gray shaded area as the confidence interval.

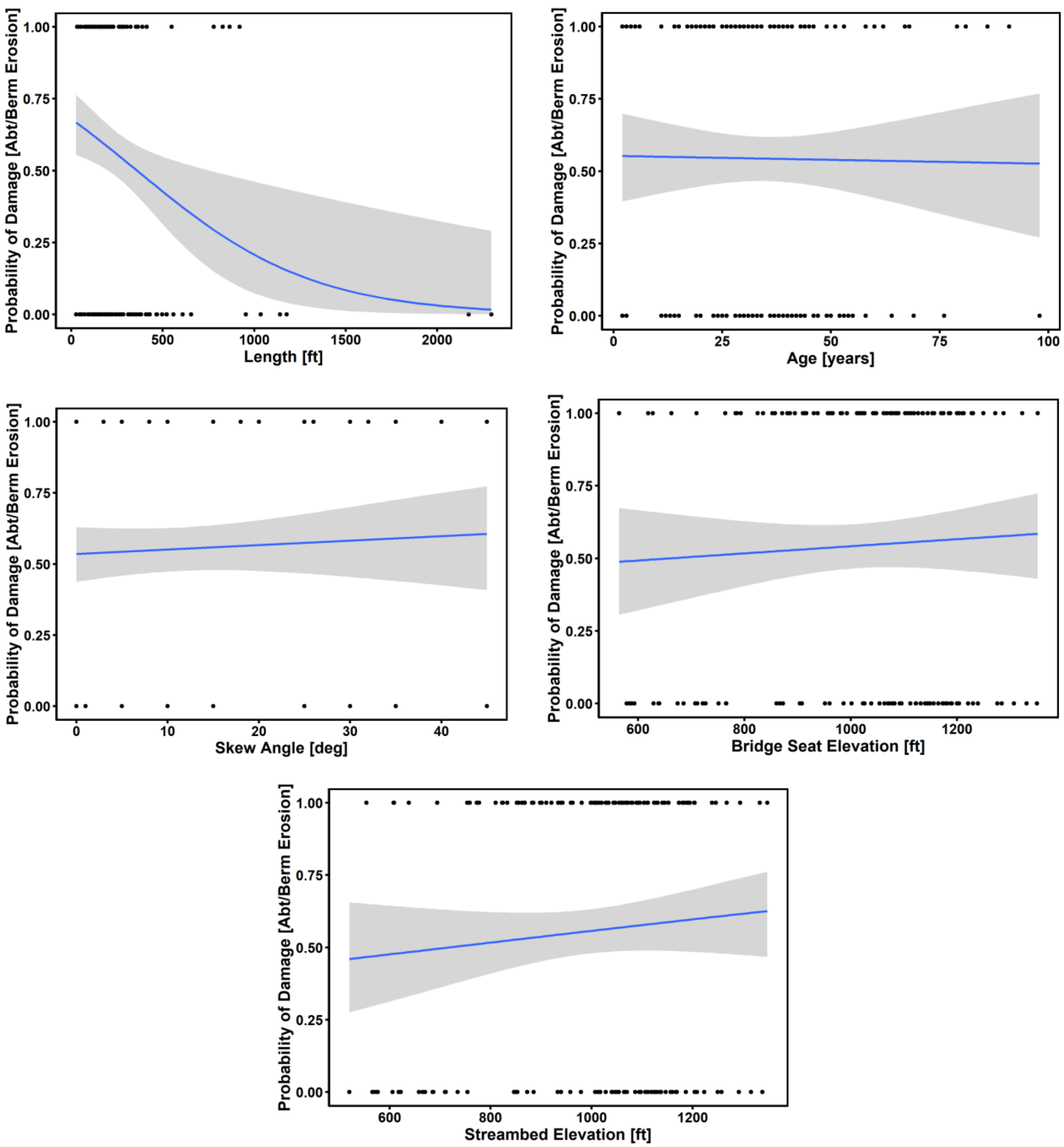


Figure 3.11. Abutment/Berm erosion logistic regressions

Table 3.7 summarizes the results of the logistic regressions for the continuous variables and presents the results for the categorical variables. The categorical variables cannot be plotted in the same manner as the continuous variables, so the results for the categorical variables are only summarized by a single p-value to show statistical significance in Table 3.7. For the continuous variables, both the intercept and the coefficient have values for the z-value and p-value, with the coefficient being of more importance in this study for showing a relationship with the given parameters.

Table 3.7. Abutment/Berm erosion logistic summary

Parameter	Intercept	S.E.	Z-Value	P-Value	Coefficient	S.E.	Z-Value	P-Value
Length	0.751036	0.259279	2.897	0.00377	-0.00209	0.000785	-2.66	0.00781
Age	0.211859	0.338161	0.627	0.531	-0.0011	0.008516	-0.129	0.897
Skew Angle	0.140692	0.199873	0.704	0.481	0.006429	0.01105	0.582	0.561
Bridge Seat El	-0.32477	0.831212	-0.391	0.696	0.000493	0.000808	0.61	0.542
Streambed El	-0.58487	0.813058	-0.719	0.472	0.000815	0.000805	1.012	0.312
Abutment Type	-	-	-	-	-	-	-	0.5015
Abutment Foundation	-	-	-	-	-	-	-	0.8023
Channel Rating	-	-	-	-	-	-	-	0.6795
Substructure Rating	-	-	-	-	-	-	-	0.6545
Scour Rating	-	-	-	-	-	-	-	0.824

Only one parameter shows a statistically significant probability of damage occurring due to abutment and berm erosion. Length ($p < .01$) is negatively correlated to the probability of damage, which indicates that longer bridges are less likely to experience abutment and berm erosion damage. This number may be biased because no bridges greater than 1,000 feet in length were affected by abutment and berm erosion in this sample population. All other parameters that were analyzed for this type of damage did not show any trends, as indicated by the relatively flat curves in Figure 3.11 and the lack of statistical significance based on the coefficient p-value in Table 3.7.

With logistic regression analysis having determined the relationships between certain parameters and the probability of damage, it is useful to determine a relationship between those parameters and the cost associated with the bridges that incurred damage. For this method, each of the bridges that had a cost (92 bridges for the case of abutment and berm erosion) was fitted to a linear model, with the linear regression plots shown in Figure 3.12. From visual observation, relationships are apparent with length, age, bridge seat elevation, and streambed elevation.

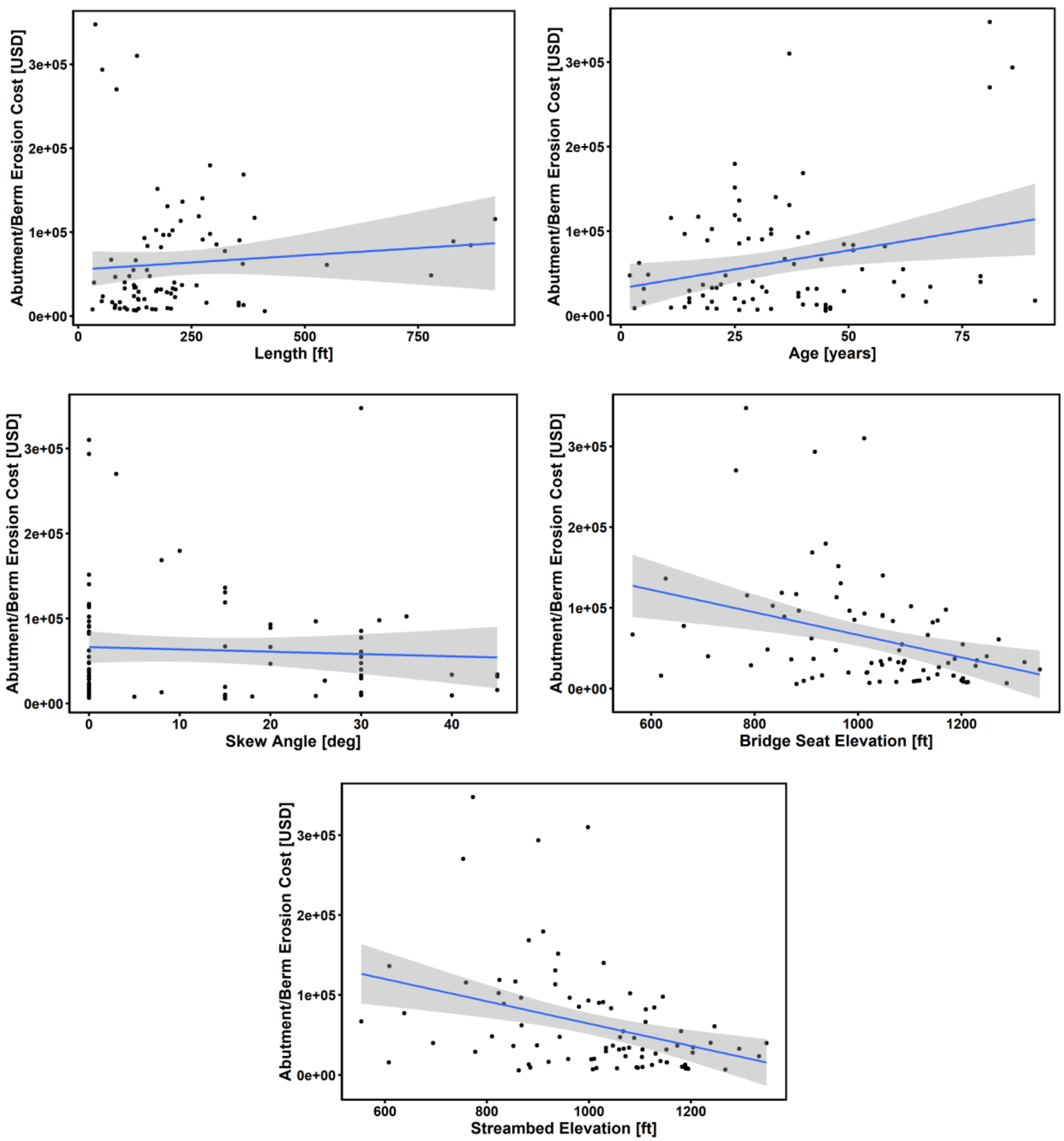


Figure 3.12. Abutment/Berm erosion linear regressions

These relationships can be checked using the regression summary presented in Table 3.8, where a higher R^2 value indicates that the model explains more of the variation and the coefficient p-value gives the statistical significance.

Table 3.8. Abutment/Berm erosion linear regression summary

Parameter	Intercept	S.E.	T-Stat	P-Value	Coefficient	S.E.	T-Stat	P-Value	R^2
Length	55360.63	11494.03	4.816	6.12E-06	34.25	39.4	0.869	0.387	0.008609
Age	32379.4	14372.9	2.253	0.0268	897.3	358.1	2.506	0.0141	0.06805
Skew Angle	66320.3	9381.6	7.069	3.69E-10	-272.7	504	-0.541	0.59	0.003353
Bridge Seat El	206104.1	41231.59	4.999	3.01E-06	-139.44	39.84	-3.5	0.000739	0.1247
Streambed El	203882.9	39382.66	5.177	1.41E-06	-139.57	38.54	-3.622	0.000489	0.1297

A lot of variation with the model is unexplained, as indicated by the low R^2 values, but there is still statistical significance. Both the bridge seat elevation ($p < 0.001$) and the streambed elevation ($p < 0.001$) are significant and have a negative relationship with the cost, in that higher elevations are related to lower damage costs. Because these elevations are not related to the elevation of the water that caused the flood, it is difficult to understand why this relationship is present. The age of the bridge is also statistically significant ($p < 0.05$), which was hypothesized previously. Unlike the logistic regression analysis, where the length of the bridge showed significance in terms of the probability of damage occurring, the linear regression data do not show significance. This means that length may be used to determine whether damage will occur but cannot determine the cost of that damage.

Linear models were also developed for the categorical parameters and are presented in the box plots in Figure 3.13 and in Table 3.9. Three of these categorical variables are condition ratings from the NBI database that follow the same rating scale described in Section 3.1.2, and the other two variables are the type of abutment foundation and the type of bridge abutment shape. The boxes in the plots represent bridges that fall within the 25th through 75th percentiles. The median is represented by the horizontal line inside of each box, and any outliers are points either above or below each box. It is difficult to determine relationships from the box plots themselves; however, the results are summarized in Table 3.9. Statistical significance is indicated by the overall p-values of three parameters: abutment type ($p < 0.001$), channel rating ($p < 0.01$), and scour rating ($p < 0.01$). For example, the results show that cost is dependent on abutment type, with an overall p-value of 0.0005, and specifically the cost for wingwalls is significantly higher than the cost for spill-through abutments ($p = 0.0001$).

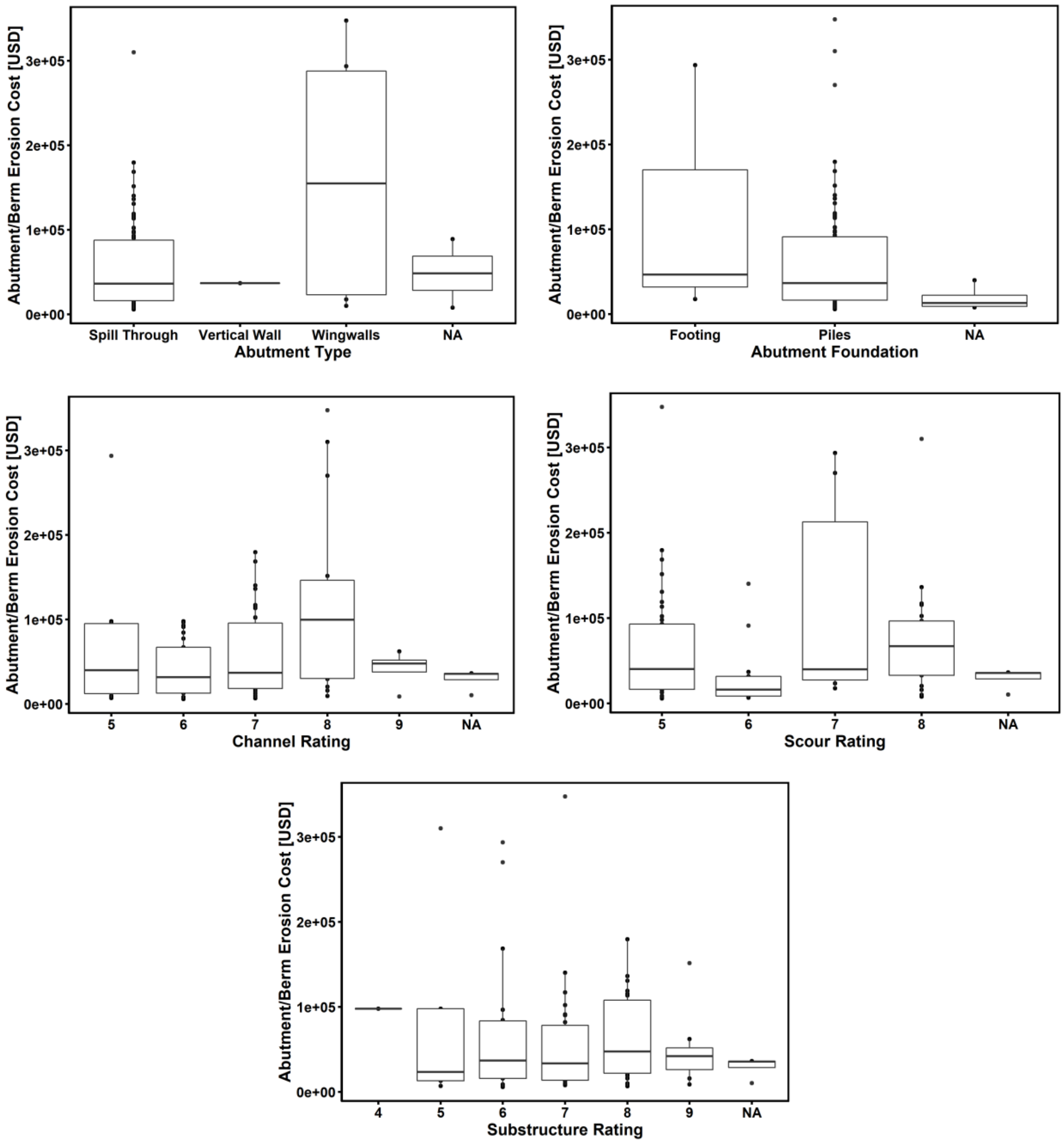


Figure 3.13. Abutment/Berm erosion categorical variable box plots

Table 3.9. Abutment/Berm erosion categorical variable summary

Parameter	Value	Coefficient	S.E.	T-Stat	P-Value	Overall P-Value	R^2
Abutment Type	Spill-Through	55566	6900	8.053	3.87E-12	5.17E-04	0.1597
	Vertical Wall	-18684	63243	-0.295	0.768374		
	Wingwalls	107502	26576	4.045	0.000113		
Abutment Foundation	Footing	119156	39117	3.046	0.00308	0.1566	0.0232
	Piles	-56886	39802	-1.429	0.15656		
Channel Rating	5	70269	20437	3.438	0.000918	0.008512	0.15
	6	-29500	24181	-1.22	0.225937		
	7	-12086	23173	-0.522	0.603363		
	8	49863	26758	1.864	0.065927		
	9	-28592	38233	-0.748	0.456685		
Scour Rating	5	63170	10383	6.084	3.36E-08	4.76E-02	0.08952
	6	-33456	19598	-1.707	0.0915		
	7	50884	29061	1.751	0.0836		
	8	11116	16871	0.659	0.5118		
Substructure Rating	4	97868	69817	1.402	0.165	0.8915	0.01992
	5	-7624	76480	-0.1	0.921		
	6	-29904	71460	-0.418	0.677		
	7	-41672	71147	-0.586	0.56		
	8	-32343	71098	-0.455	0.65		
	9	-47844	74052	-0.646	0.52		

To decipher the differences in mean cost further, ANOVA was performed for each categorical parameter that was statistically significant. The abutment type was statistically significant overall, with $p < 0.001$, so it was relevant to determine which type of abutment had the highest cost of repair due to abutment/berm erosion. The Tukey HSD method was performed with $\alpha = 0.05$ to determine similar groupings of means among the abutment types. Table 3.10 shows that a vertical wall abutment with wingwalls has a significantly higher repair cost than the other two abutment types.

Table 3.10. Tukey HSD abutment type comparison

Abutment Type	Group Membership		Mean Abutment/Berm Erosion Cost
Vertical Wall with Wingwalls	A		$163,067
Spill-Through		B	$55,566
Vertical Wall		B	$36,882

Similarly, the Tukey HSD method was performed for channel rating, and the results are summarized in Table 3.11. These results show that a channel rating of 8 (indicating a channel that is protected and in stable condition) is actually associated with a significantly higher mean repair cost than a channel rating of 6 or 7, which indicates minor damage, debris restriction, or a minor stream shift. This is the opposite of what would logically be assumed, which is that worse channel conditions would result in higher mean repair costs.

Table 3.11. Tukey HSD channel rating comparison

Channel Rating	Group Membership		Mean Abutment/ Berm Erosion Cost
8	A		$120,132
5	A	B	$70,269
7		B	$58,182
9		B	$41,677
6		B	$40,769

Lastly, the same analysis was performed for scour rating, and the findings are presented in Table 3.12. These results show that the only difference among the groups is that a scour rating of 7 (indicating that countermeasures for scour are in place and the bridge is no longer scour critical) is associated with a significantly higher repair cost than a scour rating of 6 (indicating that a scour calculation/evaluation has not been made). This is, again, an interesting finding that may not be logical.

Table 3.12. Tukey HSD scour rating comparison

Scour Rating	Group Membership		Mean Abutment/ Berm Erosion Cost
7	A		$114,054
8	A	B	$74,286
5	A	B	$63,170
6		B	$29,714

3.4.2. Pier Scour

As shown in equation (3.2), several parameters affect the depth of pier scour. This equation was used as a starting point to determine whether these parameters also relate to whether pier scour is present and whether there is a correlation between any given parameter and the cost associated with repairs. A limited amount of data was available for the variables of flow depth and velocity, and therefore these variables are not presented in this report but rather are suggested as an area of future work. Data were available for the parameters of pier width and skew angle, both of which were treated as continuous variables. The remaining variables in equation (3.2) were treated as categorical variables. Similar to Section 3.2.1 on abutment/berm erosion, additional parameters beyond those used in the equation were considered for determining relationships.

The following continuous variables were selected to examine statistical relationships for pier scour cost:

- Length – The length of a bridge has a direct correlation to the number of spans in that bridge. The more piers per bridge, the higher the probability that pier scour will occur or the greater the cost associated with pier scour.
- Age – The age of a bridge is of interest because as a bridge ages, pier scour could continue to develop and go unnoticed or be ignored and therefore contribute to significant repair costs during a major flood. Additionally, older bridges could have more deterioration (Alipour and Shafei 2016a, 2016b).
- Skew Angle – Equation (3.2) is dependent on skew angle, which contributes to the depth of scour.
- Pier Width – Equation (3.2) is dependent on pier width, which contributes to the depth of scour.
- Bridge Seat Elevation – There could potentially be a relationship between the elevation of a bridge and the amount of scour present.
- Streambed Elevation – This parameter is included for similar reasons to bridge seat elevation.

The following categorical variables were analyzed for pier scour:

- Bent Type – Different structures for the bent will cause water to flow differently, thus causing different amounts of scour to occur.

- Pier Foundation – If scour has reached the level of the footing or below, the cost associated with pier scour could change depending on the type of foundation in place to continue to support the pier.
- Pier Nose Shape – Equation (3.2) is dependent on pier nose shape, which contributes to the depth of scour.
- Streambed Material – Different soil types can erode more easily than others, which could affect the amount of scour around the piers.
- Channel Rating – This parameter is a rating given to the stream channel based on criteria such as excessive water velocity, amount of slope protection, presence of riprap, condition of the channel, and the presence of debris affecting the flow.
- Substructure Rating – This parameter is a rating to assess the condition of the superstructure components. The condition is evaluated based on cracking, settlement, and scour at the footing or piles of the foundation.
- Scour Rating – This parameter rates how vulnerable the bridge is to scour.

The logistic regressions plotted in Figure 3.14 show the relationship of each continuous variable to the probability of damage.

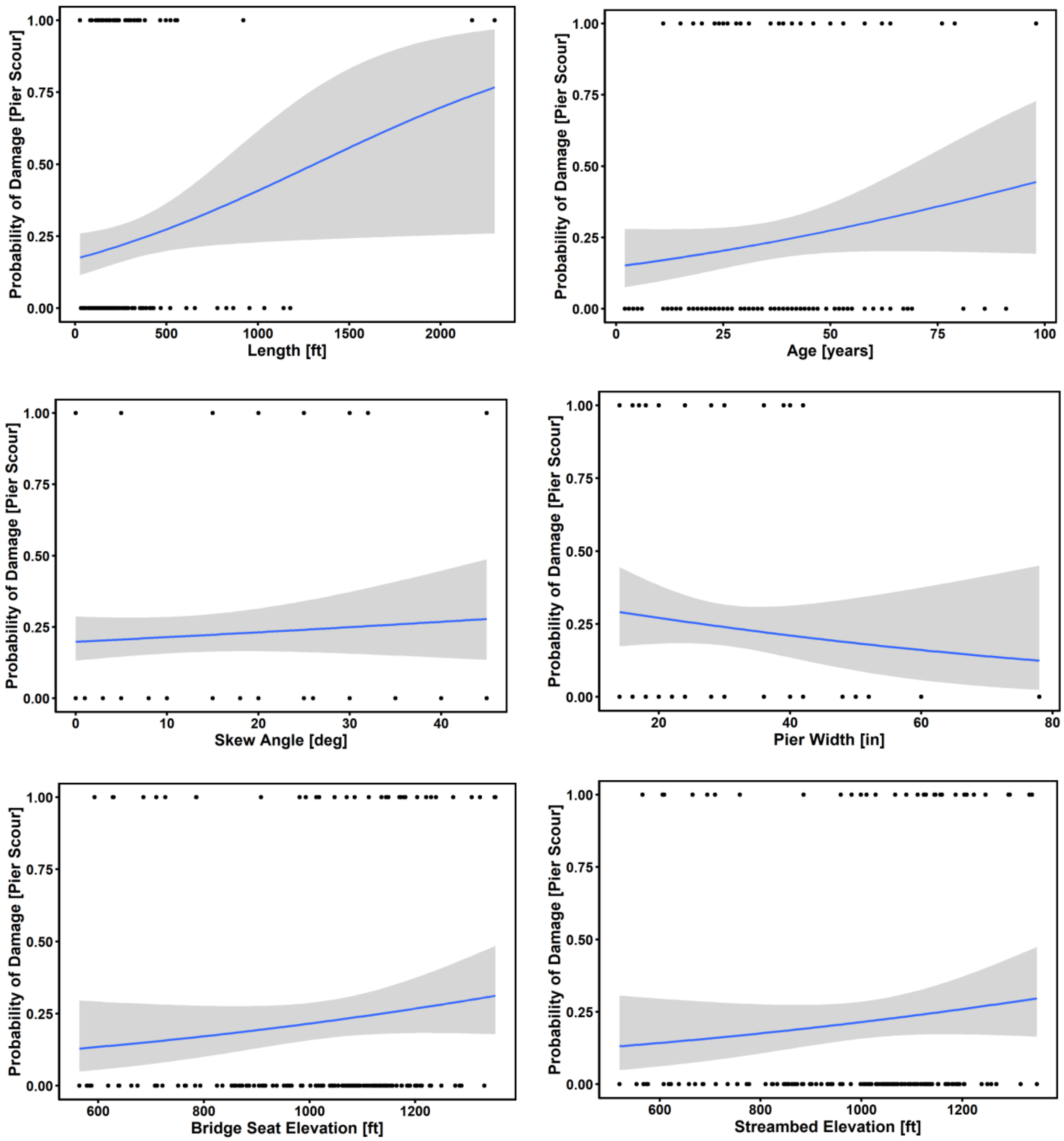


Figure 3.14. Pier scour logistic regressions

The only parameter that shows a probability of damage over 50% is length because of two longer bridges that have a cost associated with pier scour. The confidence interval is very wide for these longer bridges, which may be because the two longer bridges are outliers or because there are not enough bridges in the population to accurately model the probability of damage due to pier scour. Thirty-nine bridges out of the sample population of 170 had damage due to pier scour. Even with this small number of bridges and the outliers, Table 3.13 shows that length was statistically significant ($p < 0.05$). The type of pier foundation was also statistically significant in determining the probability of pier scour damage ($p < 0.05$).

Table 3.13. Pier scour logistic summary

Parameter	Intercept	S.E.	Z-Value	P-Value	Coefficient	S.E.	Z-Value	P-Value
Length	-1.57628	0.263023	-5.993	2.06E-09	0.001205	0.00057	2.113	0.0346
Age	-1.75166	0.41314	-4.24	2.24E-05	0.015603	0.009756	1.599	0.11
Skew Angle	-1.39651	0.24825	-5.625	1.85E-08	0.00984	0.01283	0.767	0.443
Pier Width	-0.65664	0.56579	-1.161	0.246	-0.01661	0.01798	-0.924	0.356
Bridge Seat El	-2.7109	1.096783	-2.472	0.0134	0.00142	0.001037	1.369	0.1709
Streambed El	-2.53937	1.066014	-2.382	0.0172	0.001242	0.001028	1.208	0.2269
Bent Type	-	-	-	-	-	-	-	0.2216
Pier Foundation	-	-	-	-	-	-	-	0.02445
Pier Nose Shape	-	-	-	-	-	-	-	0.4453
Streambed Material	-	-	-	-	-	-	-	0.3798
Channel Rating	-	-	-	-	-	-	-	0.1229
Substructure Rating	-	-	-	-	-	-	-	0.08172
Scour Rating	-	-	-	-	-	-	-	0.1105

The 39 bridges that had incurred damage-related costs were then plotted against each continuous parameter to determine a linear trend. A lot of unexplained variation was expected due to the small sample size, but finding statistically significant parameters was nevertheless possible. Figure 3.15 and Table 3.14 show the plotted and summarized linear regressions for the continuous variables.

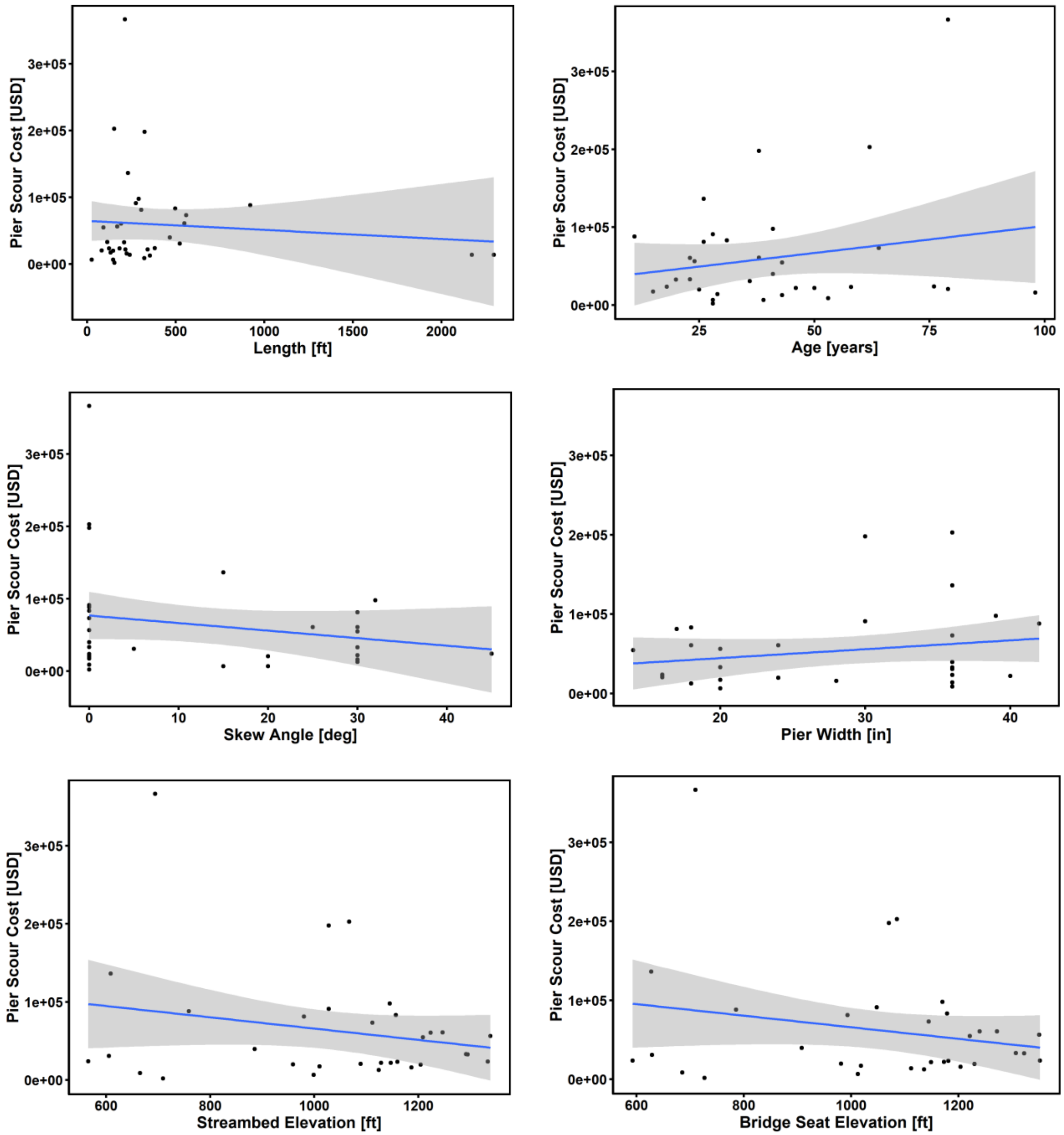


Figure 3.15. Pier scour linear regressions

Table 3.14. Pier scour regression summary

Parameter	Intercept	S.E.	T-Stat	P-Value	Coefficient	S.E.	T-Stat	P-Value	R^2
Length	64863.64	15024.62	4.317	0.000118	-13.59	24.28	-0.56	0.578974	0.008635
Age	32105.6	25244.3	1.272	0.212	695.9	572.9	1.215	0.232	0.03938
Skew Angle	76759	16142	4.755	3.79E-05	-1042	832	-1.253	0.219	0.04539
Pier Width	22304.8	27785.1	0.803	0.428	1118	911.6	1.226	0.229	0.04489
Bridge Seat El	139267.3	58089.22	2.397	0.0221	-73.29	54.09	-1.355	0.1844	0.05123
Streambed El	138219.6	57236.16	2.415	0.0214	-72.38	54.39	-1.331	0.1924	0.05092

As expected, the R^2 values are very low, which indicates that the model leaves much of the variation unexplained. There is also no statistical significance in any of these parameters, as indicated by the coefficient p-value. A larger sample size could give more insight into the relationship between these parameters and the cost associated with pier scour, but no relationships were observed in the current data.

The categorical variables are presented in Figure 3.16 and Table 3.15, which show that the bent type was statistically significant, with an overall p-value < 0.05. When the Tukey HSD method was performed for the bent type, however, there were no grouping differences, indicating that no conclusions can be made regarding the relationship between the type of bent and the cost associated with pier scour.

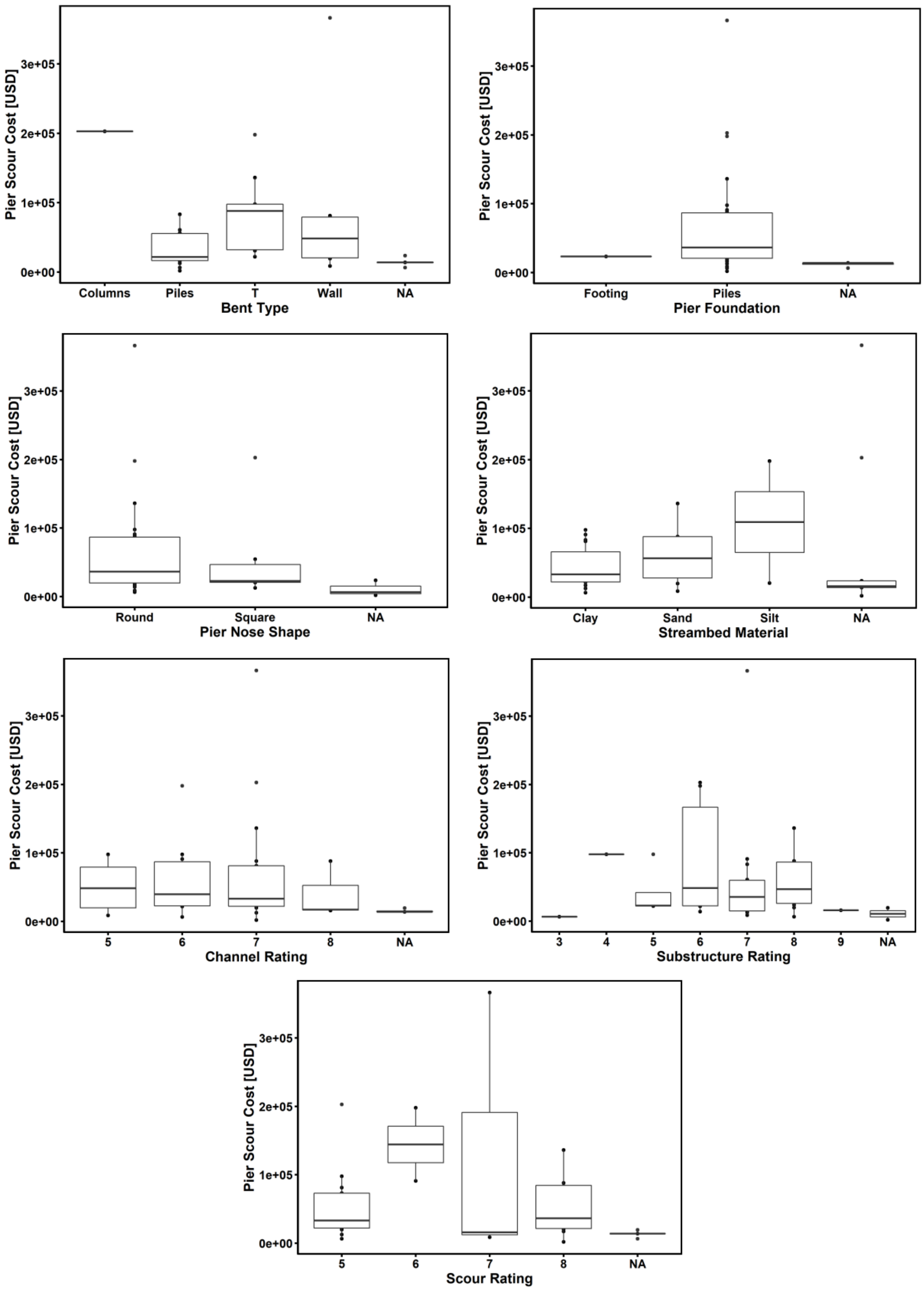


Figure 3.16. Pier scour categorical variable box plots

Table 3.15. Pier scour categorical variable summary

Parameter	Value	Coefficient	S.E.	T-Stat	P-Value	Overall P-Value	R^2
Bent Type	Columns	202747	66301	3.058	0.00466	0.03627	0.2441
	Piles	-170198	68475	-2.486	0.01873		
	T	-124060	69008	-1.798	0.08229		
	Wall	-107313	71613	-1.499	0.14445		
Pier Foundation	Footing	23273	72700	0.32	0.751	0.5759	0.009582
	Piles	41677	73761	0.565	0.576		
Pier Nose Shape	Round	63737	13200	4.828	2.86E-05	8.11E-01	0.001698
	Square	-7775	32334	-0.24	0.811		
Streambed Material	Clay	45239	9390	4.818	4.97E-05	0.1239	0.1433
	Sand	15363	17568	0.874	0.3896		
	Silt	63927	31145	2.053	0.0499		
Channel Rating	5	50776	37418	1.357	0.185	0.8774	0.02142
	6	9201	43694	0.211	0.835		
	7	21846	41587	0.525	0.603		
	8	-10389	57156	-0.182	0.857		
Substructure Rating	3	6567	74832	0.088	0.931	0.8862	0.07057
	4	91301	105828	0.863	0.395		
	5	34689	83664	0.415	0.681		
	6	82293	80828	1.018	0.317		
	7	55573	77458	0.717	0.479		
	8	50452	78484	0.643	0.525		
	9	9273	105828	0.088	0.931		
Scour Rating	5	54266	16818	3.227	0.00302	0.1254	0.1714
	6	90195	51836	1.74	0.09211		
	7	76122	43424	1.753	0.08981		
	8	-3482	26144	-0.133	0.89495		

3.4.3. Pier Debris

Unlike pier scour and abutment/berm erosion, pier debris is not estimated using an empirical formula. Debris accumulation can occur at various areas of the bridge, such as the abutment or even the superstructure if the water level is high enough, but debris most frequently accumulates at the piers, as indicated by data extracted from the DDIRs. Several factors related to flooding could cause the buildup of debris around piers, such as faster moving water in the middle of the stream, as opposed to near the abutments, and deeper water near the middle of the stream, where debris may be more likely to flow. As previously mentioned, the flood data (such as peak elevation, velocity, and discharge) available at each bridge location are limited. Future work is planned in this area to relate pier debris and other damage modes to these flood data.

The following bridge-specific continuous parameters were included in the analysis for logistic and linear regression:

- Length – The length of a bridge has a direct correlation to the number of spans in that bridge. The more piers per bridge, the higher the probability that debris will accumulate at a pier.
- Age – The age of a bridge may not have an obvious relationship to the potential for debris accumulation. This parameter is included to examine the possibility that older bridges may have a buildup of debris that goes unnoticed and could continue to catch additional debris over the years, although this hypothesis cannot be confirmed in this study.
- Skew Angle – A bridge that is skewed could expose more of the surface area of the pier to the flow and therefore collect additional debris.
- Pier Width – A wider pier has a larger surface area for debris accumulation
- Bridge Seat Elevation – Without a relationship to the flood water, the bridge seat elevation is not in reference to anything. However, a bridge with a lower elevation is farther downstream relative to other bridges in the sample population, and therefore more debris could flow through.
- Streambed Elevation – For similar reasons to the bridge seat elevation, more debris may flow through a streambed with a lower elevation relative to other streambeds in the sample population.

And the categorical parameters are listed as follows:

- Bent Type – It is hypothesized that bents that are comprised of multiple columns or piles catch more debris than a solid wall-type bent.
- Pier Nose Shape – Certain pier nose shapes may allow debris to slide past rather than catch and accumulate.
- Channel Rating - This parameter is a rating given to the stream channel based on criteria such as excessive water velocity, amount of slope protection, presence of riprap, condition of the channel, and the presence of debris affecting the flow.

The logistic regression results for the continuous variables are plotted in Figure 3.17, and the results for both the continuous and categorical variables are summarized in Table 3.16. Both pier width ($p < 0.01$) and bent type ($p < 0.05$) are shown to be statistically significant parameters for predicting the probability of pier debris. Longer bridge lengths, again, are related to a higher probability of damage, but this relationship is not statistically significant, which may be due to outlier bridges with lengths of over 2,000 feet.

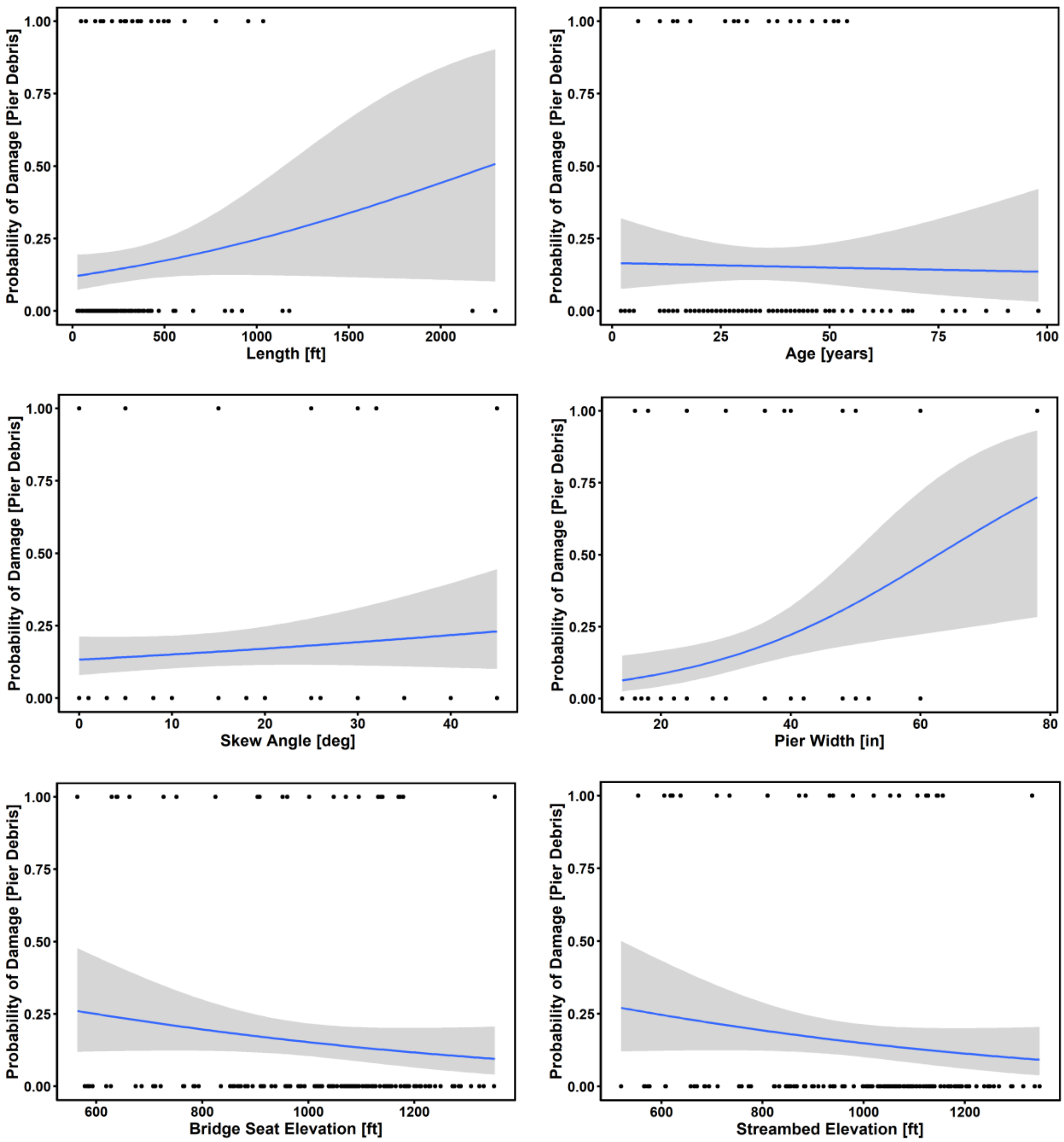


Figure 3.17. Pier debris logistic regressions

Table 3.16. Pier debris logistic summary

Parameter	Intercept	S.E.	Z-Value	P-Value	Coefficient	S.E.	Z-Value	P-Value
Length	-1.99942	0.293917	-6.803	1.03E-11	0.000884	0.000566	1.562	0.118
Age	-1.61692	0.464592	-3.48	0.000501	-0.00242	0.011891	-0.203	0.838832
Skew Angle	-1.8769	0.29006	-6.471	9.76E-11	0.01494	0.01429	1.045	0.296
Pier Width	-3.46331	0.746	-4.642	3.44E-06	0.05527	0.02027	2.726	0.00641
Bridge Seat El	-0.17969	1.061378	-0.169	0.866	-0.00153	0.001069	-1.435	0.151
Streambed El	-0.1762	1.034251	-0.17	0.865	-0.00157	0.001063	-1.476	0.14
Bent Type	-	-	-	-	-	-	-	0.01531
Pier Nose Shape	-	-	-	-	-	-	-	0.2807
Channel Rating	-	-	-	-	-	-	-	0.3463

With the zero points removed, the linear regressions for the continuous variables, shown in Figure 3.18 and Table 3.17, indicate that none of these variables has a statistically significant relationship to cost.

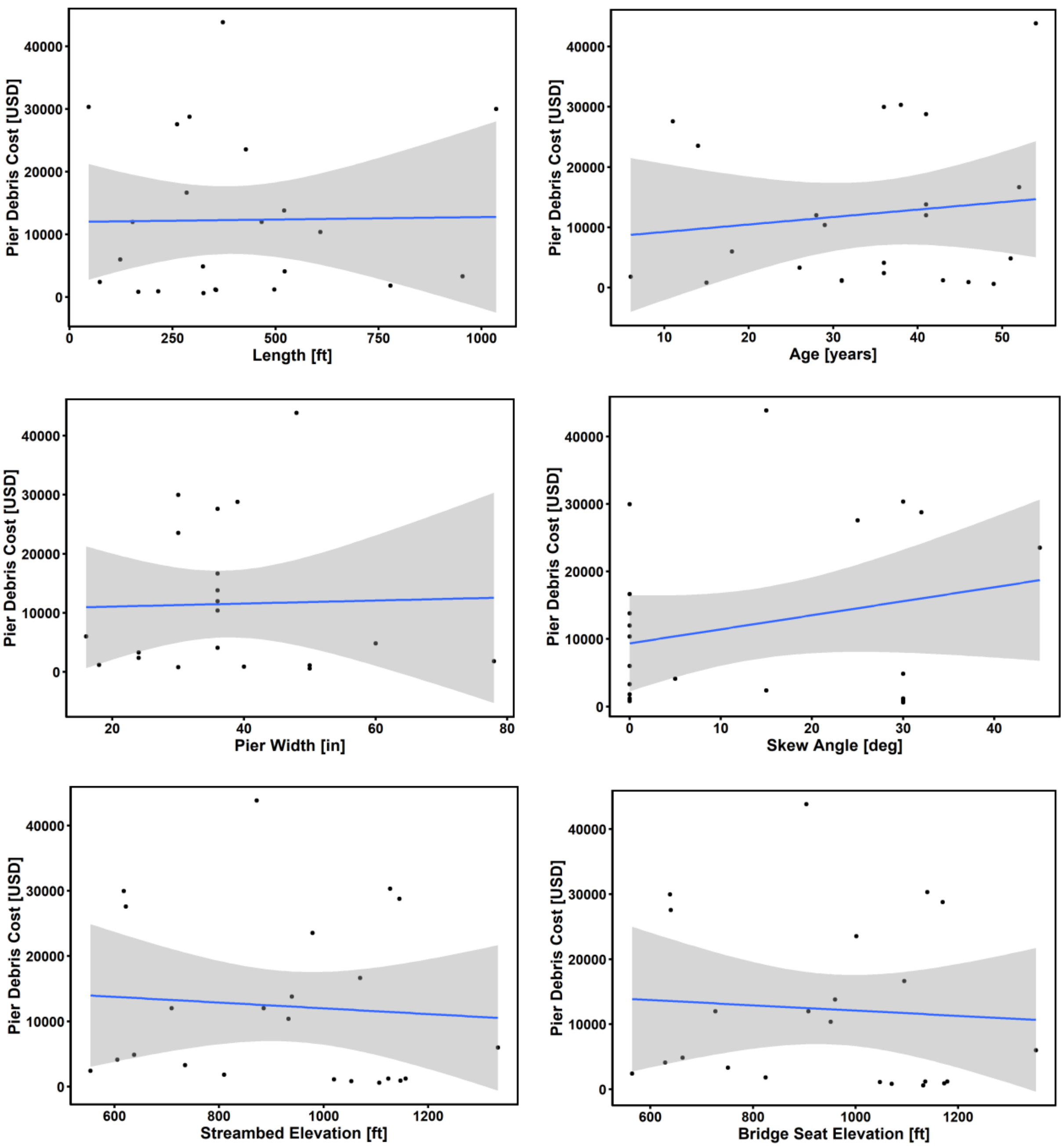


Figure 3.18. Pier debris linear regressions

Table 3.17. Pier debris regression summary

Parameter	Intercept	S.E.	T-Stat	P-Value	Coefficient	S.E.	T-Stat	P-Value	R^2
Length	1.20E+04	4.87E+03	2.459	0.0219	7.80E-01	1.06E+01	0.073	0.9421	0.0002341
Age	8.02E+03	7.26E+03	1.104	0.281	123.6	197.2	0.627	0.537	0.01679
Skew Angle	9367.3	3438.7	2.724	0.0121	207.9	167.2	1.243	0.2262	0.06299
Pier Width	10547.95	7795.68	1.353	0.19	25.67	197.7	0.13	0.898	0.0008023
Bridge Seat El	16156.78	11711.58	1.38	0.181	-4.049	11.895	-0.34	0.737	0.005012
Streambed El	16409.7	11527.71	1.423	0.168	-4.409	11.96	-0.369	0.716	0.005873

Lastly, no statistically significant relationship was found between any of the categorical variables and the cost of pier scour, as shown in Figure 3.19 and Table 3.18.

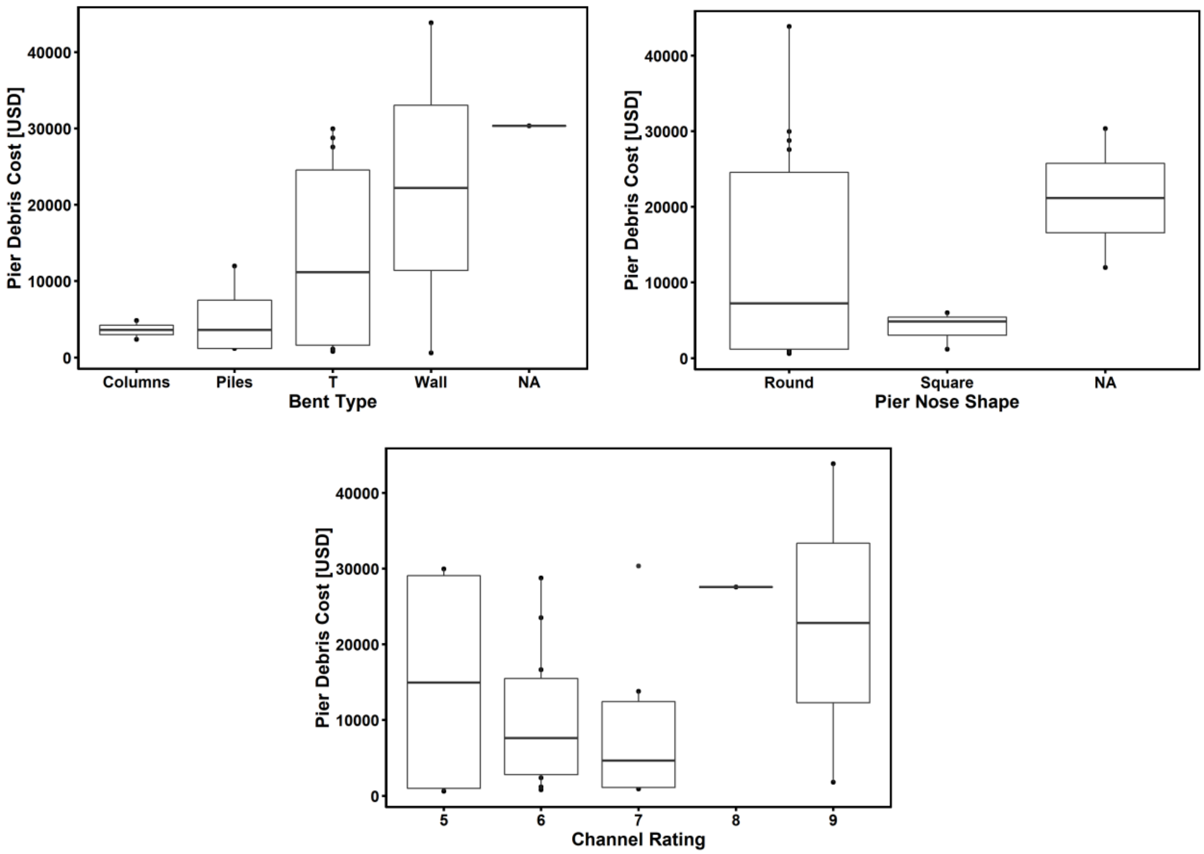


Figure 3.19. Pier debris categorical box plots

Table 3.18. Pier debris categorical variable summary

Parameter	Value	Coefficient	S.E.	T-Stat	P-Value	Overall P-Value	R^2
Bent Type	Columns	3624	8702	0.416	0.682	0.3363	0.1522
	Piles	1472	10657	0.138	0.892		
	T	9147	9230	0.991	0.334		
	Wall	18600	12306	1.511	0.146		
Pier Nose Shape	Round	12619	2837	4.449	0.000222	0.2857	0.05406
	Square	-8604	7854	-1.095	0.285713		
Channel Rating	5	15115	6403	2.361	0.0285	0.4486	0.1617
	6	-4648	7576	-0.614	0.5465		
	7	-6565	7842	-0.837	0.4124		
	8	12462	14318	0.87	0.3944		
	9	7708	11090	0.695	0.495		

3.4.4. Summary of Statistical Methods Based on Historical Damage

Using historical flood damage data to create models to better predict the probability and cost of damage in the future is a very advantageous method. The demonstration of the method in this section showed that several parameters related to bridges can be used to predict the probability of damage from abutment/berm erosion, pier scour, and pier debris. Some of these relationships are intuitive, such as the effects of pier width on the probability of debris accumulation, while others are less obvious, such as the effect of bridge length on the probability of abutment/berm erosion.

It is also beneficial to understand whether certain bridge parameters are related to the cost of flood-related damage to bridges. This can help identify certain bridge characteristics that should be avoided in future designs as well as identify current bridges that may be at greater risk in the event of a flood. Linear regressions were a good starting point for determining the relationships between bridge parameters and the cost of flood damage, but other models could certainly be used for this method.

It was found that age, bridge seat elevation, streambed elevation, abutment type, channel rating, and scour rating were all statistically significant in predicting the cost associated with abutment/berm erosion. For the categorical variables, Tukey HSD pair-wise comparisons were used to determine which specific value in each category was associated with the highest cost. It was found that vertical wall abutments with wingwalls had significantly higher costs for abutment/berm erosion than spill-through or vertical wall abutments. It was also found that a channel rating of 8 was associated with significantly higher costs than a rating of 6, 7, or 9. This finding shows a correlation between channel rating and abutment/berm erosion cost but most likely does not indicate causation. Similarly, a scour rating of 7 was associated with significantly higher costs than a scour rating of 6. Causation should not automatically be assumed here, since a scour rating of 7 should mean that countermeasures to prevent scour were in place. Scour damage still occurred in these instances, so the scour countermeasures were not entirely successful.

For pier scour, it was found that bent type was the only parameter that had a statistically significant relationship to repair cost. Again, the Tukey HSD method was performed to determine which type of bent was associated with the highest cost of repairs. The results showed that no single bent type showed a significantly different repair cost than any other bent type. For this reason, conclusions could not be drawn regarding which bent type was associated with the highest damage cost due to pier scour.

Lastly, no statistically significant parameters were found for predicting the probability of pier debris accumulation.

Several improvements could be made to this study that would potentially improve the results. First, a larger sample size could more clearly define the trends and help explain more variation in the data. It is difficult to get additional data on damage costs, however, because these data are only collected as part of the ER program during major flood events. An option for gaining a larger sample size would be to collect repair cost data for less severe floods as well.

Second, the use of actual flood parameters, such as water elevation and water velocity or discharge rate, would be very useful to correlate to the cost of repairs. The challenge with this is finding gages that measure these data in close proximity to each bridge that will experience damage. Some of these data are available, but they are very limited and were therefore not included in the present study. Lastly, it would be useful to perform multiple linear regressions to determine the effect of two parameters on repair costs. This method would be useful for determining combinations of parameters that may affect the cost associated with each damage mode.

This section, like the section above describing the bridge sensitivity index approach, can provide many proxy indicators for monitoring or analyzing current or future bridges. Unlike the indicators used for the bridge sensitivity index, these proxy indicators are based on real-world events, and the parameters used for the proxy indicators have been shown to have statistically significant relationships with the damage done to bridges. Bridge length, bridge seat elevation, bent type, and other parameters can be all be used as proxy indicators and should be matched according to the damage mode in question.

3.5. Consequence of High Water

Data on the probability of a flood occurrence that detail the flood stage and discharge along major waterways are readily available. The probability of flooding is presented as the percentage chance of occurrence within a year, so a 100-year flood would have a probability of 1:100 of happening each year or will most likely happen once every 100 years. The larger the flood return period is, the lower the probability of occurrence, but the higher the intensity and the greater the likelihood of disruption.

By relating bridge elevation to water elevation for a given flood period, the probability of overtopping can be easily calculated for a given bridge. Damage occurs at lower elevations as well, but a bridge is known to be closed when overtopping occurs.

For this reason, the method described in this section uses the probability of overtopping as the benchmark for the probability of occurrence of a bridge closure due to flooding. Future work will be done for additional water elevations because damage does not only occur during overtopping. The study summarized in this section is presented in more detail in Zhang and Alipour (2019), which proposes an integrated framework for a risk and resilience assessment of the road network under inland flooding.

Iowa District 6, which consists of 12 counties in the eastern part of the state, was used as a sample population in this study. Major cities in this district include both Iowa City and Cedar Rapids, which have both experienced major flooding in recent years due to the Iowa River and Cedar River flowing directly through these cities. (Flooding in Cedar Rapids in 2008 is shown in Figure 1.2.) The primary road system in this area, which comprises a network of 4,599 nodes, 7,512 links, and 603 state-owned bridges, was analyzed. Several data sets have been collected for this district, including terrain, geographical, and historical flooding data, all of which make up the framework shown in Figure 3.20.

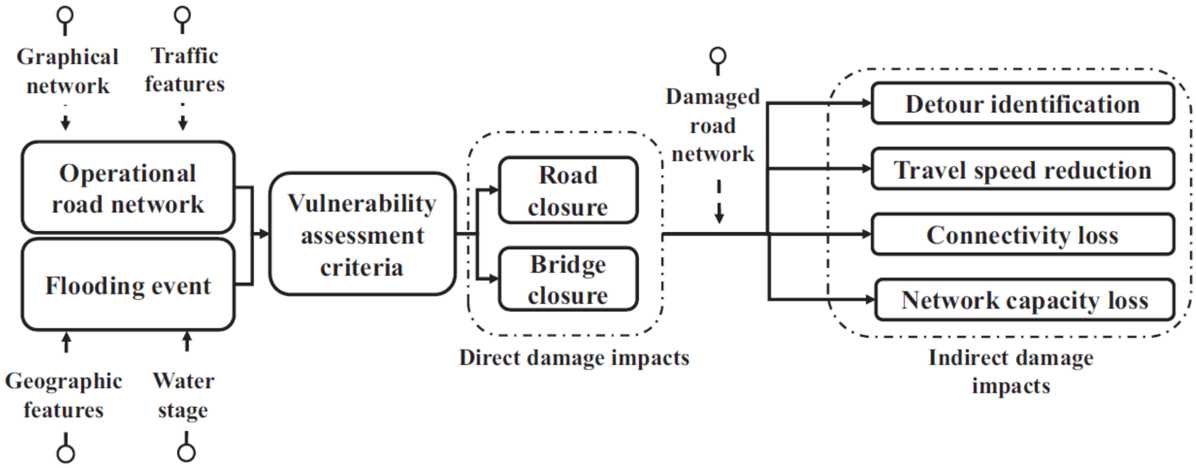


Figure 3.20. Data category and model framework

For this analysis, it was assumed that traffic demands do not change immediately after a flooding event. This assumption also implies that the capacity of the road is not exceeded and that any road closures result in no traffic. If there are detours due to road closures, it is assumed that these longer routes will be followed by road users.

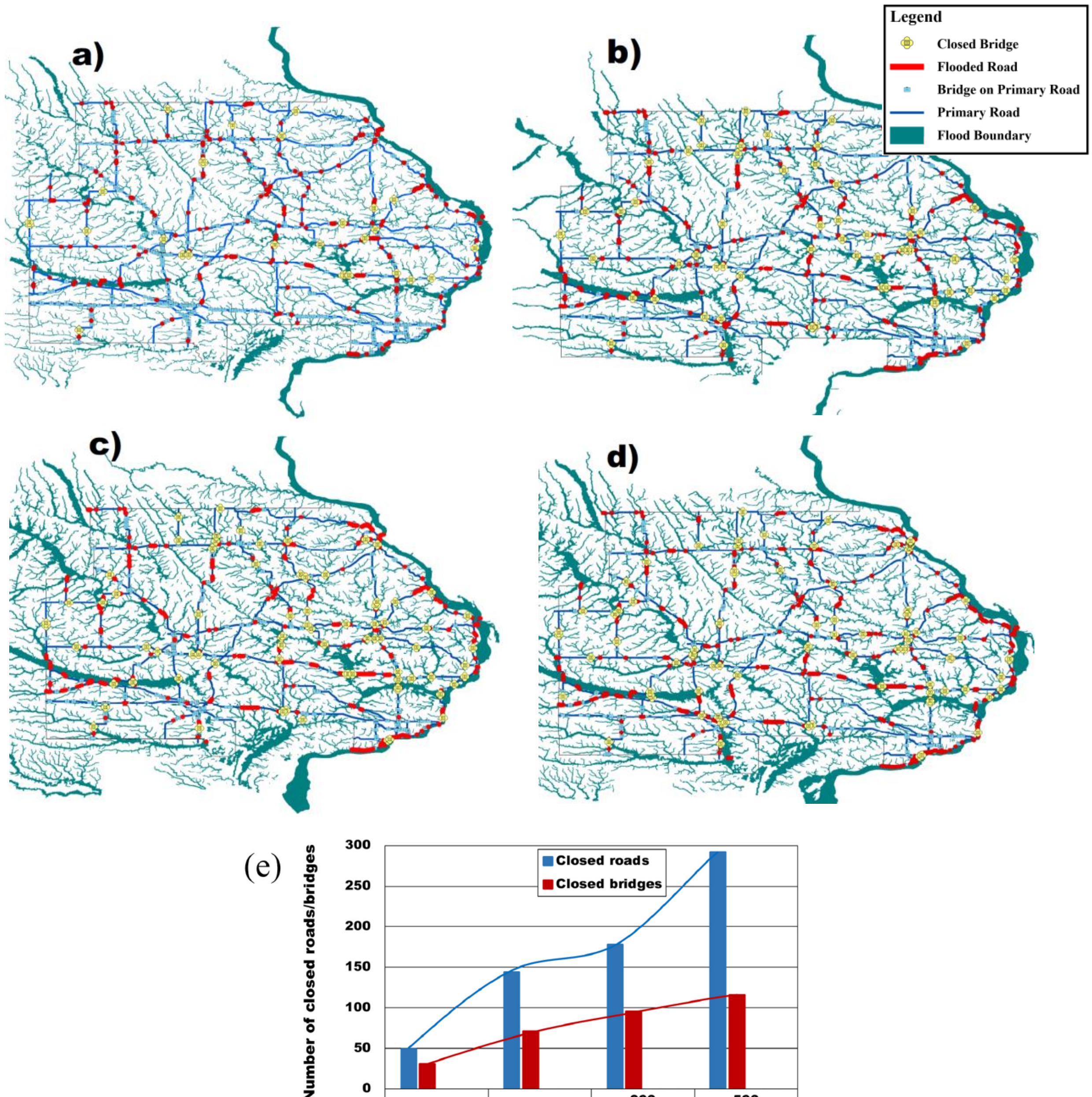
Repair efforts for transportation assets are difficult to assess, especially after a flooding event. It is common for efforts to be directed toward those assets where the flood stage was highest because that is where damage is assumed to be the worst. This study looked into both roadways and bridges and overlaid historic flood frequency stages on top of the elevations of these transportation assets. If the water level was found to be above the roadway elevation or was found to be at or above the low girder elevation (or abutment footing elevation), then that asset was assumed to be closed. In reality, a closure would happen sooner than this threshold due to potential safety concerns. Damage could also occur below these thresholds, as found in the DDIRs mentioned in Section 3.2, which could cause a longer term closure that extends past the flood duration. Long-term closures due to damage were not included in this study; only closures during the flooding duration were considered. The underlying theory used for this study is shown in equation (3.3).

$$\begin{cases} d_{r/b}^{flood} < d_{r/b}^{upper}, \text{road or bridge open} \\ d_{r/b}^{flood} \geq d_{r/b}^{upper}, \text{road or bridge closed} \end{cases} \tag{3.3}$$

where:
$d_{r/b}^{flood}$ = flooding water depth
$d_{r/b}^{upper}$ = upper limit of the tolerance elevation of the road or bridge to flooding

The topological properties of a network are important to evaluate because they are useful for assessing the risk to the road system and comprehending infrastructure functionality during hazard events. Transportation networks consist of links and nodes and therefore have properties that can be measured with topological graph theory. Topological graph theory is based on the physical layout of a graph and several measures of connectivity, which reflects the ease of flow between nodes and links. Indicators used for graph theory in this study include the average number of links passing through each node, the degree of connectivity of a given node to its neighbor nodes, and the average shortest path. These indicators are summarized in more depth in Zhang and Alipour (2019).

Figure 3.21 illustrates the damage to the road and bridge network during flood return periods of 2, 50, 200, and 500 years. The differences among plots are subtle due to the large size of District 6, but the results summarized in Figure 3.21e show the actual number of closed bridges and roadways based on equation (3.3). The number of closed roads in this region is calculated to be 49 during a 2-year flood and increases nearly 600% during a 500-year flood. The number of closed bridges is calculated to be 31 during the same 2-year flood and increases nearly 400% during a 500-year flood. These closures are only due to water overtopping roadways and reaching the girder level of bridges. It is likely that additional closures would be implemented due to additional damage or debris or if the infrastructure assets are otherwise deemed unsafe for travel.



	2 years	50 years	200 years	500 years
Closed roads	49	144	178	292
Closed bridges	31	71	95	116
Max depth (feet)	10.31	17.20	22.45	24.79
Mean depth (feet)	4.84	6.43	6.91	6.75

Figure 3.21. Network maps and closure information under four 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

The results for the three indicators used to assess the topological losses at the network level are summarized in Table 3.19. The average number of links per node decreases with larger flood frequency periods, as seen by the average nodal degree of the network, d_{ave}. The average cluster coefficient, C_{ave}, does not change significantly with flood frequency, which indicates that most clusters form after lower intensity flooding. Lastly, the average shortest path, P_{ave}, also does not show a significant association with flood intensity, possibly because as flooding intensity increases, more paths are removed from the network, which can then create longer paths as a result. The number of residual shortest paths, SP_{num}, however, declines with increasing flood intensity, which indicates the disconnection of some origin-destination pairs.

Table 3.19. Values of topological indices under different flooding events

Flooding years	No flood	2 years	50 years	200 years	500 years
d_{ave}	0.0252	0.0250	0.0249	0.0248	0.0244
$d_{ave}^{0.1}$	0.0023	0.0022	0.0019	0.0017	0.0011
C_{ave}	3.76×10^{-4}	3.76×10^{-4}	3.76×10^{-4}	3.76×10^{-4}	3.24×10^{-4}
Tri_{num}^{3}	3,899	3,835	3,702	3,673	3,522
P_{ave}	0.3988	0.3974	0.3952	0.3966	0.4006
SP_{num}	3,888,348	869,636	327,714	388,103	250,838

The performance of the transportation network was found to decrease with flood intensity. Assuming 100% performance when no flooding is present, the performance decreases to 84.7% with a 2-year flood and continues to decrease with higher intensity flooding. Similar results can be seen for traffic delay times and travel times, both of which increase with flooding intensity. These results are summarized in Table 3.20.

Table 3.20. 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%

This method presents a very straightforward approach to determining bridge and road closures. Data for flood period years can simply be overlaid on a current transportation network map and compared with the elevations of the infrastructure to determine whether overtopping has occurred. In this way, the minimum number of closures can be accurately calculated for a known flood elevation. This number is likely to be higher than presented in this study because closures often occur before the water elevation reaches road or girder level. With the closures calculated from this method, the transportation network can be analyzed to determine the average shortest path, travel times, and delays, all of which is useful for transportation users.

4. DEVELOPING PROXY INDICATORS FOR ROADS

4.1. Road Flooding and Pavement Types

The previous section began to look at the consequences of flooding for roads by determining closures due to high water. Inundated roads are inaccessible for traveling and are therefore affected by flooding during the time period of the flood. Damage to the pavement, however, can result from flooding and therefore have long-term effects for affected road segments. It is important to understand which types of pavements will be affected by flooding because different pavements suffer different degrees of damage and strength loss after flooding.

Post-flooded pavements have been found to be weaker than pavements that have not been affected by flooding. This was found to be true for various pavement types, including asphalt concrete, portland cement concrete, and composite pavements (Gaspard et al. 2007). The strength of an HMA pavement will begin to become compromised if it is submerged by flood waters for longer than six hours, and the pavement can even begin to weaken within two hours of submersion (Mallick et al. 2017). Flexible pavements suffer a loss of structural strength more rapidly than other pavement types after being affected by a flood. It was found that the subgrade CBR for flood-affected flexible pavements decreased by up to 67% and the structural number decreased by up to 50% (Sultana et al. 2015). Helali et al. (2008) found that submerged HMA pavements that had experienced prior distortion and cracking, including alligator, map, transverse, and longitudinal cracking, deteriorated significantly more rapidly than non-flooded HMA pavements. In the same study, similar results were found for PCC pavements that had experienced prior distortion and transverse cracking. Flooding accelerates the deterioration of roads, especially those with higher pre-flood rutting (Sultana et al. 2016b).

To develop proxy indicators for the effects of flooding on roads, the primary roadways in Linn County were analyzed. Linn County is a heavily populated county in Iowa DOT District 6 and has a history of flooding around Cedar Rapids. Using ArcGIS mapping, the primary road network was imported into the software with the elevations of each road section. The roadway surface and base layer materials were known for each segment and were overlaid in the network. Flooding scenarios ranging from 2-year to 500-year periods were then imported into the map to evaluate the overtopping of roads.

Figure 4.1 illustrates this method, with each primary road shown in gray and segments closed due to overtopping shown in red. In this figure, only the flooding scenarios for the 2-year, 10-year, 100-year, and 500-year periods are presented to show the distinctions among them.

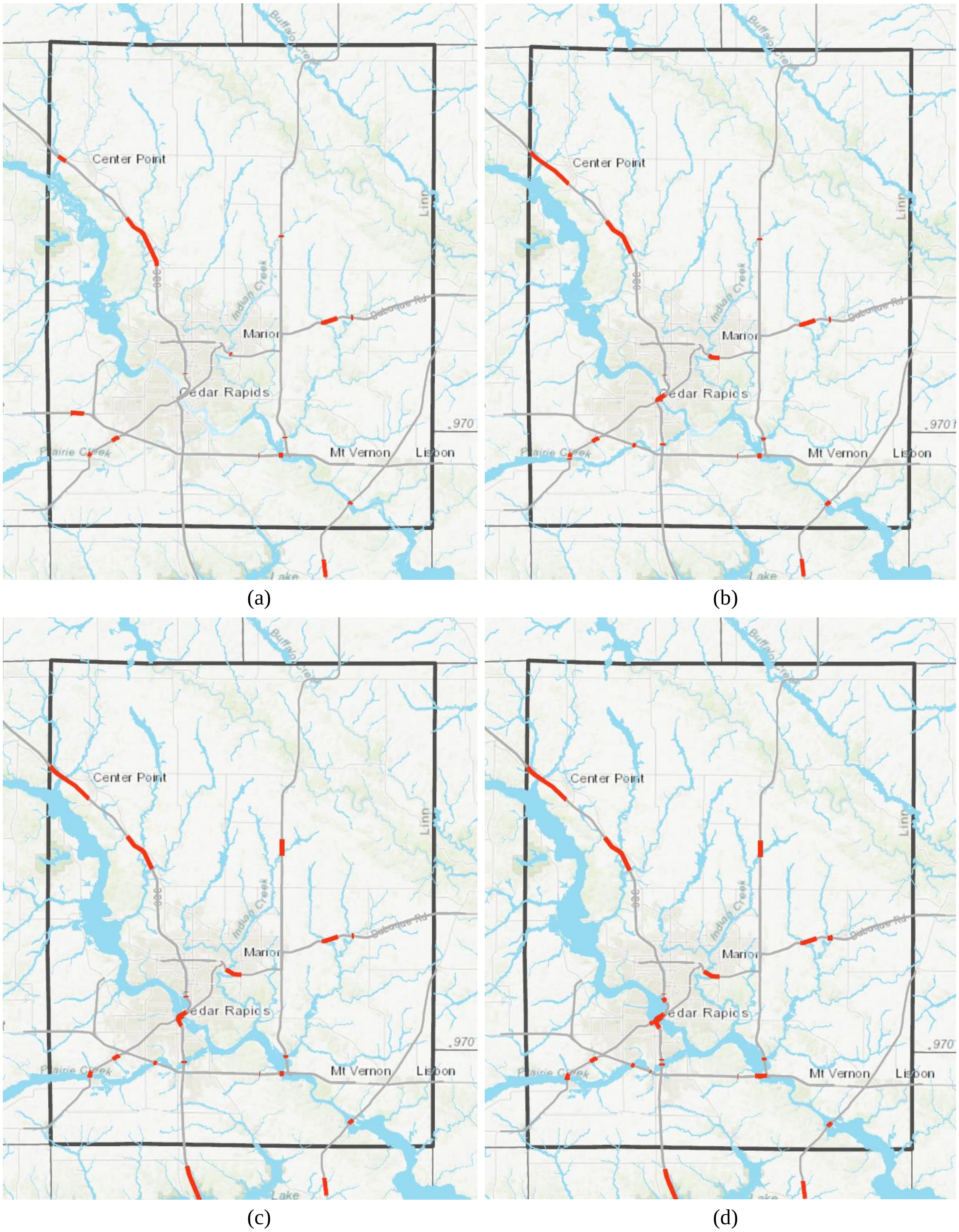


Figure 4.1. Road closure scenarios for (a) 2-year (b) 10-year (c) 100-year, and (d) 500-year flood periods

Each segment of road has data for the type of base pavement and surface pavement. If the water overtopped any part of a particular segment, it was assumed that the entire segment length was closed because through traffic would not be able to use this segment. The mileage lengths of road closures for different pavement types are summarized in Table 4.1 for flood frequency periods of 2 years through 500 years. The surface material of over half of the pavements in flooded segments was PCC, and base material for the majority of segments, besides those for which the base material was listed as "unlisted," was HMA.

Table 4.1. Pavement miles closed by pavement type

Flood Period [yr]	2	5	10	25	50	100	200	500
Surface Material								
Type A Asphalt Cement Concrete	1.62	2.1	4.78	6.43	4.25	6	7.29	7.07
Type B Asphalt Cement Concrete	0	0	0.17	0	0.17	0.17	0	0.24
Hot Mix Asphalt (HMA)	7.98	8.98	8.86	10.42	4.75	16.84	16.22	18.34
PCC Concrete Slab	2.93	2.93	2.98	2.93	1.98	3.08	2.93	3.08
Portland Cement Concrete (PCC)	12.93	16.3	21.48	26.75	16.28	31.68	33.61	34.12
Base Material								
Unlisted	9.03	9.03	9.93	10.46	5.35	11.44	11.32	12.79
Type A Asphalt Cement Concrete	0.53	1.01	3.6	5.25	3.07	4.82	5.76	5.54
Asphalt Treated Base	0.13	0.13	0.75	0.64	0.24	6.17	6.41	6.52
Cement Treated Base	0	0	0	0	0	0.48	0	0.93
Econocrete Base	5.13	7.86	12.5	14.81	9.98	14.77	15.01	15.58
Granular Subbase	2.66	2.66	3.15	4.25	3.46	3.77	4.98	3.96
Hot Mix Asphalt (HMA)	6.76	7.76	7.55	9.11	4.54	15.53	14.56	16.68
Portland Cement Base	1.02	1.66	0.44	1.66	0.44	0.44	1.66	0.5
Special Backfill	0.2	0.2	0.35	0.35	0.35	0.35	0.35	0.35
Total roadway flooded [mi]	25.46	30.31	38.27	46.53	27.43	57.77	60.05	62.85

Because the majority of the surface material was PCC, the road system could be expected to deteriorate faster if the flooded pavements already show signs of transverse cracking or distortion. The strength of the roads could begin to decrease within two hours of submersion because the majority of the base layer material was comprised of HMA. These data can help identify areas where routine maintenance practices need to be changed. For example, if a road segment comprised of HMA is particularly susceptible flooding, maintenance could be suggested that would ensure that any form of cracking is not present prior to inundation. Being proactive on inspections and maintenance can help agencies avoid more costly repairs after flooding events.

4.2. Road Flood Water Depths

In Section 3.5, the transportation network in District 6 was analyzed for both bridges and roads. In the analysis, the probability of overtopping for each bridge or road segment was calculated for different flood periods. Similarly, in Section 4.1 the effects of the submersion of roads were analyzed based on flood period, but this analysis included the pavement type to understand the specific vulnerabilities of roads in flood areas based on the roads' base and surface materials. In this section, a third subnetwork is analyzed to examine the effects of flood period on road overtopping.

This section describes a method for mapping the spatial and temporal pattern of floods and the water depth of local floods. Three sources of geographical information system (GIS) data were used to perform the analysis. The first two included Iowa flood water depth maps and Iowa floodplain maps. These two types of flood-related data were obtained from the Iowa Flood Information System (IFIS), developed by the Iowa Flood Center with reference to the Earth's ground surface using the Geographic Coordinate System (GCS) and North American Datum of 1983**.** The last source was a county-level elevation map for the state of Iowa in GeoTIFF format that was developed based on the National Elevation Dataset (NED) from the USGS National Map. Additionally, geographical data on the local road network under analysis and the location of cities in the analysis area were also useful for the study.

IFIS flood maps are derived from complex, space- and time-dependent historical hydrological pattern records. To cover flood intensities ranging from regular floods to extreme floods, five types of flood return periods were selected: 2-, 5-, 10-, 50-, and 200-year floods. Figure 4.2 shows the analysis subnetwork extracted from the Iowa primary and secondary road network, with Cedar Rapids shown in the upper right. This subnetwork spans District 1 and District 6.

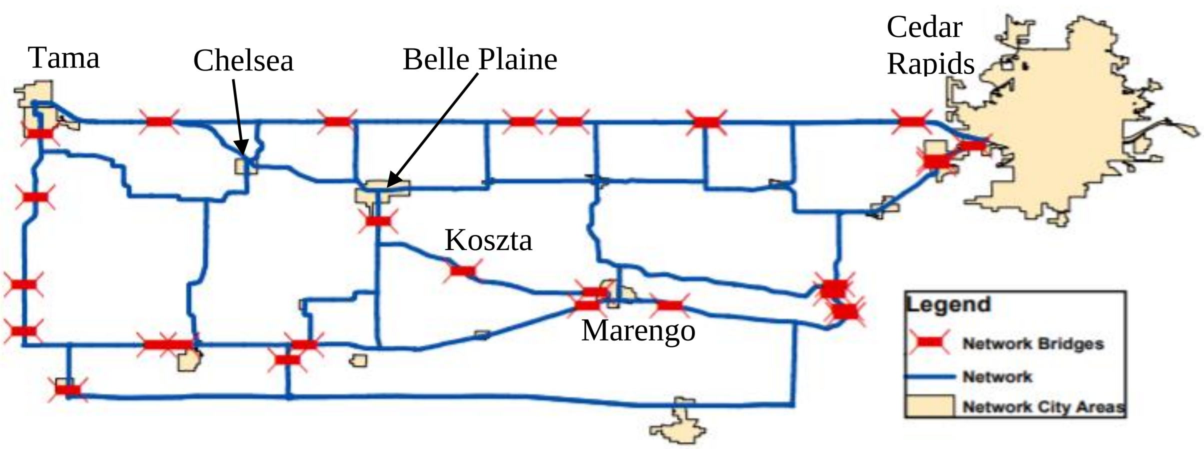


Figure 4.2. Iowa subnetwork used to analyze flood depth

Due to the inclusion of flood water depth data, the model is time consuming to implement and requires specialized ArcGIS skills and data tool knowledge; however, the resulting information is relatively simple to interpret. Figure 4.3 through Figure 4.7 show the flood depth distribution outcomes for the Iowa subnetwork for the five flood return periods examined. In the maps presented in these figures, the colored areas show the floodwater depth based on an analysis of the IFIS flood risk areas. The lightest shading on each map indicates a depth between 0 and 0.1 ft, and the darkest shading indicates a depth greater than 5 ft.

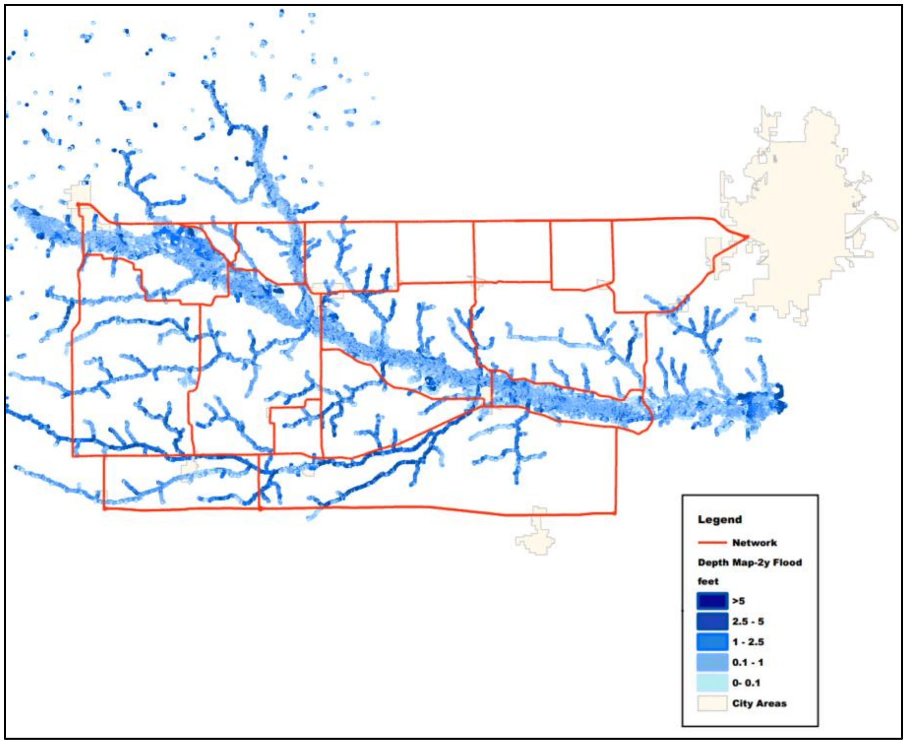


Figure 4.3. Map of 2-year flood water depth for the Iowa subnetwork

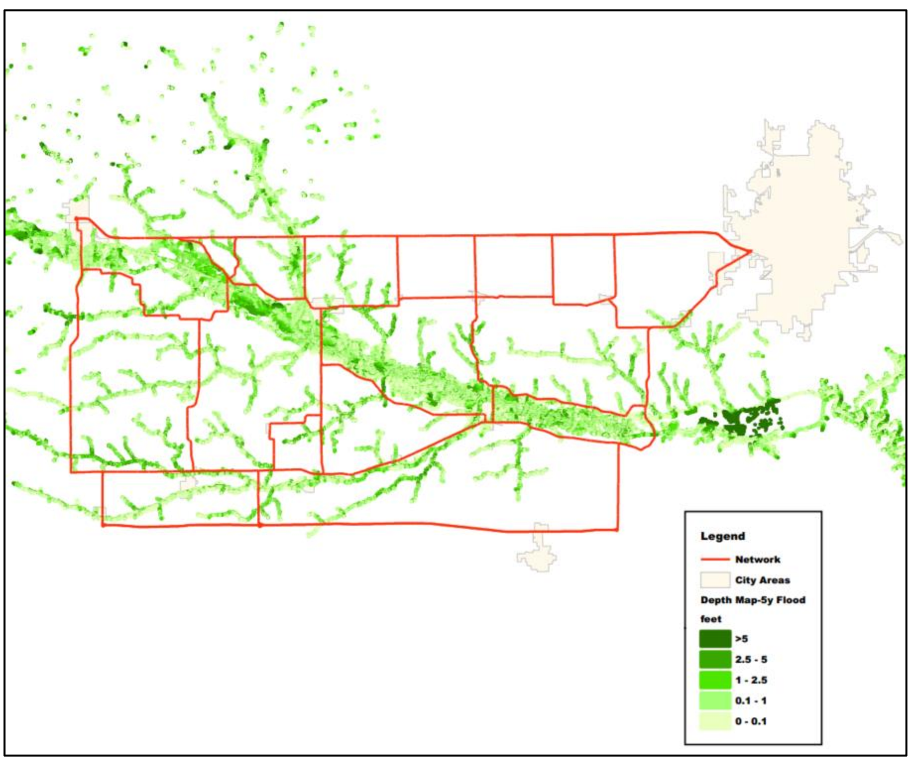


Figure 4.4. Map of 5-year flood water depth for the Iowa subnetwork

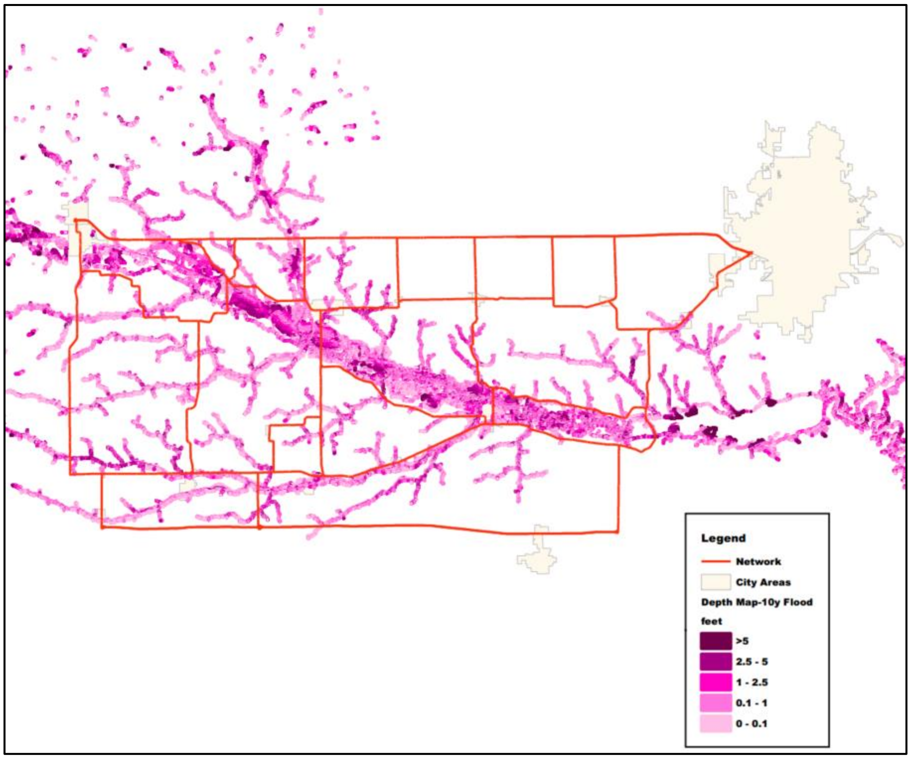


Figure 4.5. Map of 10-year flood water depth for the Iowa subnetwork

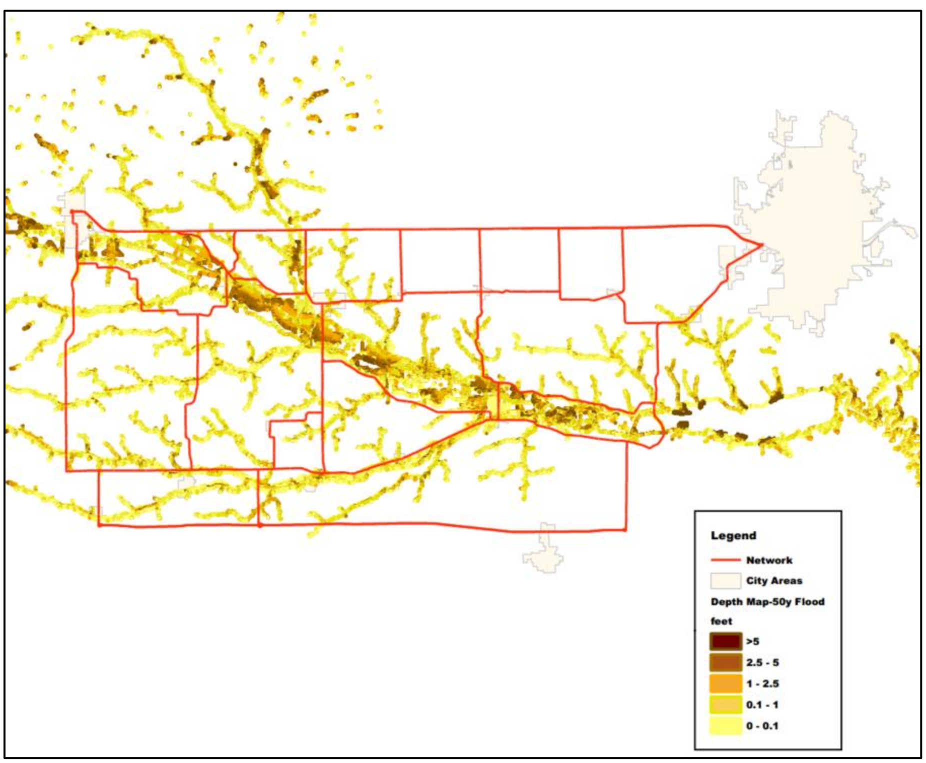


Figure 4.6. Map of 50-year flood water depth for the Iowa subnetwork

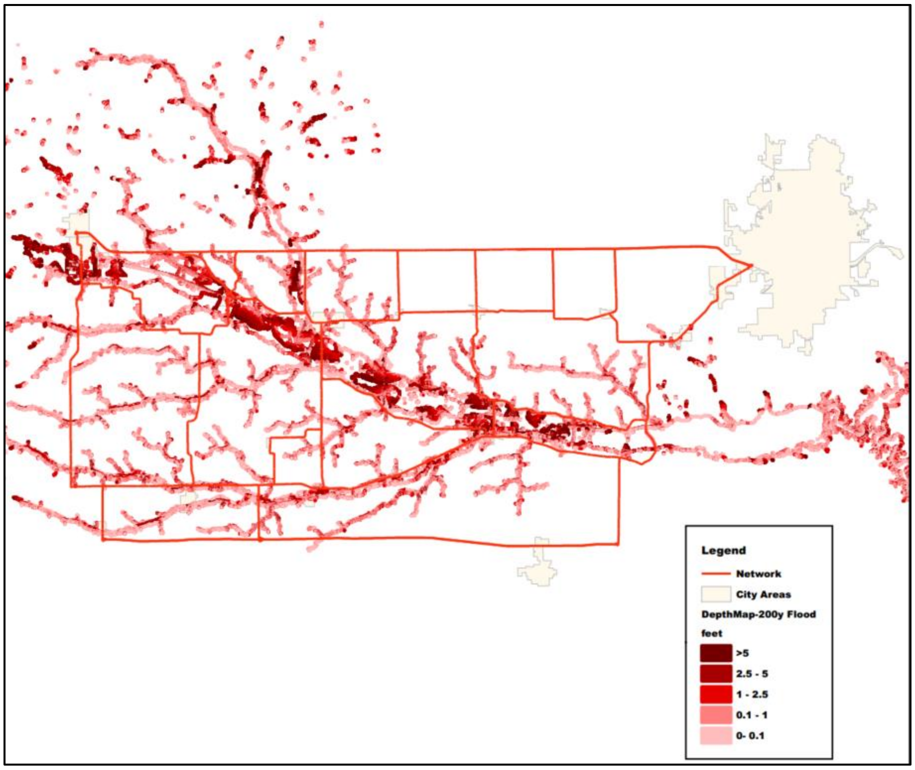


Figure 4.7. Map of 200-year flood water depth for the Iowa subnetwork

From Figure 4.3 through Figure 4.7, it is clear that as the flood intensity increases, the shading in each flood water depth map continuously darkens, which means that the flood water depth continuously rises. To evaluate the extension of the flood water boundary together with the growth in flood intensity, two comparison maps were generated. To highlight the contrasts, the maps in Figure 4.3 and Figure 4.6 were merged into a single map in Figure 4.8, and the maps in Figure 4.4 and Figure 4.7 were merged into a single map in Figure 4.9. The comparisons clearly show that an increase in flood intensity can not only cause an extension of the flooded area but also bring a higher flood water depth.

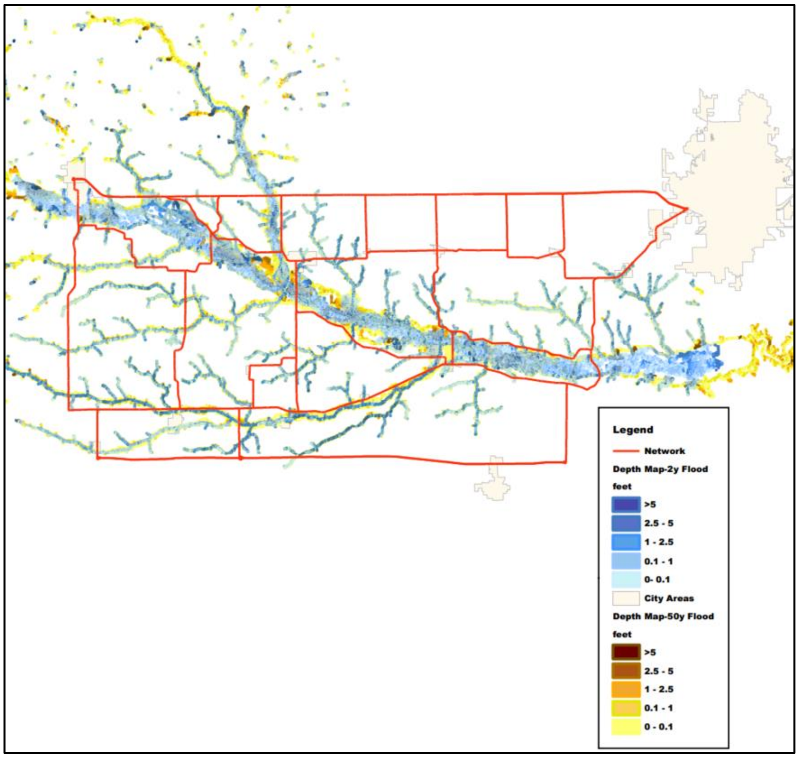


Figure 4.8. Comparison map combining a 2-year flood water depth map and a 50-year flood water depth map for the Iowa subnetwork

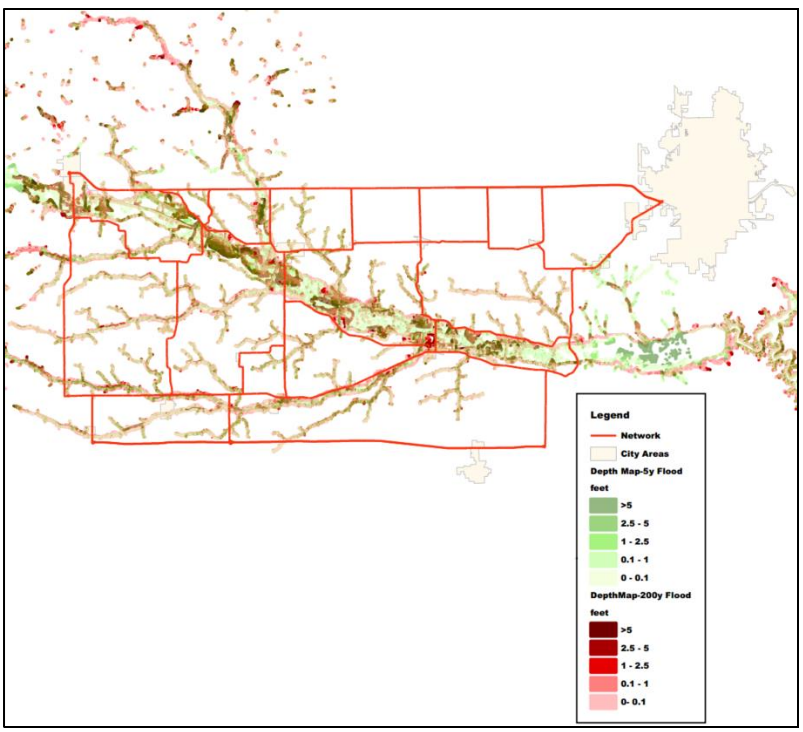


Figure 4.9. Comparison map combining a 5-year flood water depth map and a 200-year flood water depth map for the Iowa subnetwork

4.3. Road Infrastructure Flood Risk Assessment Framework

The objective of this section is to investigate flood risk on a selected road segment and provide a data-driven approach to proactive asset management in terms of flood risk mitigation. Pavements are particularly vulnerable to flood damage because they are not designed to withstand such extreme environmental conditions. All types of pavements are susceptible to flood damage, with rigid pavements generally having relatively higher resilience under flooding conditions (Oyediji 2019, Khan et al. 2017a). Flood damage to pavement includes damage on the surface caused by flood-carried debris and structural damage that initiates in the sublayer when the unbound sublayer soil is substantially weakened and/or eroded by flooding (Oyediji 2019, Mallick et al. 2018). In general, the most important negative effect of flooding on pavements is to reduce the strength/stiffness of the bulk geomaterials (i.e., aggregates and soil) that provide structural strength to the pavement's foundation (Mallick et al. 2018, Sultana 2017). The resilient modulus that characterizes the pavement's elastic response to loading is severely affected by moisture content. The resilient modulus decreases at a constant rate as water saturation increases above an optimum value. For example, the resilient modulus of gravelly soil can decrease by 50% if saturation increases from 70% to 96%; note that post-flooding saturation is likely to be about 100% (Mallick et al. 2018).

The damage that flooding causes to a road's structure is exacerbated when the inundation duration is longer (TxDOT 2019), which can lead to pavement slab dislocation and deformation-induced damage to the pavement (Oyediji 2019, Mallick et al. 2018). When flooding inundates a road, water may persist in the underlying layers for an extended period of time, weakening the subgrade's support for the pavement and making the pavement vulnerable to structural damage under loading (Mallick et al. 2018). As a result, pavements are susceptible to unnoticed damage from service loads after being flooded because the subgrade is weakened by inundation (Oyediji 2019, Mallick et al. 2018). Such damage may also be caused by loading from post-flood operations such as repair, reconstruction, and cleaning activities (Oyediji et al. 2019). The factors that affect flood water drainage, such as the road's base course material characteristics, trench backfill materials, and drainage system design, are known to have a considerable effect on the extent of damage to a pavement (Mallick et al. 2018). It is therefore imperative to base the pavement infrastructure flood risk assessment on the potential duration of inundation. The topology of the infrastructure in terms of the likely flood depth and available drainage channels can provide grounds for estimating inundation duration.

Regarding the post-flood vulnerability of pavements to damage, as described above, it is imperative for decision makers to perform thorough assessments to determine whether to close or open roads after flooding. A road condition assessment for this purpose can be performed through a combination of hydraulic analysis and structural analysis (Mallick et al. 2018). One of the latest efforts to address this important concern has been attempted by Qiao et al. (2017), who proposed an approach that utilizes Bayesian decision trees to incorporate nondestructive testing, uncertainties in the structural state of the pavement, and associated costs in the process of deciding whether to close a given road after flooding or keep it open. The method is meant to answer two fundamental questions: (1) whether the road can be opened or should be closed and (2) whether FWD testing should be performed. FWD testing may be required based on the degree of uncertainty in the estimated structural condition of the pavement. The study assumes that a pavement's structure and condition before flooding are unknown, and thus the approach is applicable to all roads independent of their type, design, or condition. Other decision making methods have been proposed, but unlike the approach of Qiao et al. (2017), they are mostly based on inspections and tests and do not include quantitative risk assessment. Examples are the decision making matrix developed by the Florida DOT (Applied Research Associates, Inc. 2013) and the post-flooding infrastructure repair and mitigation solution framework developed by Vennapusa et al. (2013).

The recommended approach to pavement flood management is proactive flood risk assessment. Road inundation risk assessment involves assessing the likelihood of flooding, the vulnerability of the road structure to flood damage, the severity of the consequences of flooding for the road network, and possible mitigation strategies (TxDOT 2019, Khan et al. 2017b, Khan et al. 2017c, Blandford et al. 2019).

The method proposed in the present study encompasses analyzing spatial and temporal flood information, infrastructure topology data, the structural response of pavements to flooding, pavement life-cycle performance, the network-level impacts of potential flood damage, and candidate mitigation strategies. To develop this method, this study used publicly available data and established a data management framework to treat the available data and link them to analytical tools. A flood risk assessment framework was produced that quantifies the resilience of the existing road infrastructure to flood events and provides recommendations for a proactive risk-aware asset management approach.

Once climate data (i.e., flood likelihood and depth) are obtained, the next immediate step in evaluating the impact of flooding on a network of pavements is to classify the existing pavements as nonvulnerable, potentially vulnerable, or vulnerable based on their structure. To this end, general structural information on the pavements is required to categorize them according to the groups shown in Table 4.2.

Table 4.2. Classifications of pavement structure

Class	General Structural Information
Nonvulnerable	Continuously reinforced concrete pavement (CRCP)
	Jointed reinforced concrete pavement (JRCP)
	Jointed plain concrete pavement (JPCP)
	Thick asphaltic concrete pavement (thickness > 5½ in.)
Potentially vulnerable	Intermediate thickness asphaltic concrete pavement (2½ in. < thickness < 5½ in.)
Vulnerable	Thin-surfaced flexible base pavement (thickness < 2½ in.)
	Thin-surfaced flexible base pavement (surface treatment-seal coat combination)

Considering this categorization scheme, the road segment to be studied should possess one of three layer structures that are either vulnerable or potentially vulnerable to flood damage. The general layer structure of such pavements is shown in Figure 4.10.

Modified from TxDOT 2019

Figure 4.10. General layer structure of pavements that are either vulnerable or potentially vulnerable to flood damage (CTB = cement-treated base, LTSG = lime-treated subgrade, FB = flexible base)

The impact of flooding on pavement performance can be categorized into four groups, according to Lu et al. (2020):

1. Acceleration of pavement deterioration rate as a result of the flood occurrence without significant immediate damage
2. Immediate performance deficiency following the flood occurrence with an unchanged or marginally increased degradation rate afterwards
3. Significant immediate damage as a result of the flood occurrence with a considerably accelerated degradation rate afterwards
4. Structural failure to the degree that the pavement is no longer functional

As these flood damage modes indicate, the deterioration rate over the pavement's service life is an important factor in assessing flood damage. Therefore, a pavement's vulnerability to damage should consist of two aspects: (1) potential for immediate damage and (2) change in service life.

Flood damage generally occurs through either water saturation, flood currents, or flood-carried debris. The major causes of flood-related pavement damage are pavement layer material degradation, interlayer bonding loss, and surface texture loss; these are largely caused by saturation, the force of the flood, or flood-carried debris. Long-term flood damage is mostly caused by moisture and thermal effects. Flood-related loads include depth, duration, velocity, debris, and contaminants. Because of the pavement's potential to absorb flood water, flood depth and duration are significant factors affecting the extent of damage. Flood velocity describes the force exerted on the pavement by the flood's movement (Lu et al. 2020). The flood loading types and associated damage mechanisms presented in Lu et al. (2020) are shown in Table 4.3.

Table 4.3. Flood load types and damage mechanisms

Load type	Damage mechanism
Depth	Absorption of water
Duration	Absorption of water
Velocity	Flood force
Debris	Debris impact, debris deposition, increased erosion
Contaminants	Chemical/biological causes

Source: Lu et al. (2020)

AASHTOWare Pavement ME Design can simulate pavement performance under flooding based on pavement design characteristics and climate regime. Thermal and moisture effects are modeled in the software by a component named Enhanced Integrated Climate Model (EICM). Pavement performance characteristics such as permanent deformation and rutting, fatigue cracking, thermal cracking, and roughness are predicted. These performance measures are summarized in Table 4.4 (Lu et al. 2020).

Table 4.4. Performance measures predicted by AASHTOWare Pavement ME Design

Performance Measure	Pavement Type	Measurement Unit
Alligator (bottom-up fatigue) cracking	New AC or replacement with AC or resurfacing with AC	% lane area
Transverse cracking		ft/mi
Total rutting		in.
Longitudinal (top-down fatigue) cracking		ft/mi
Transverse (fatigue) cracking	New JPCP or replacement with JPCP or Resurfacing with JPCP	% slabs cracked
Transverse joint faulting		in.
Punchouts	CRCP	No. of punchouts/mile
Crack width (average)		in.
Crack load transfer efficiency (LTE)		%
Smoothness (IRI)	All	in./mi

Source: Lu et al. (2020)

The effects of flooding can be incorporated into the mechanistic-empirical model through the approaches used by TxDOT (2019) or by Oyediji (2019) or through a combination of the two methods for practical advantages. TxDOT's (2019) method uses TxME software and adjusts the layer material properties for flood events. Oyediji's (2019) approach uses AASHTOWare Pavement ME Design and adjusts the climate input files of the software to represent flood events through extreme precipitation.

To evaluate the vulnerability of pavement segments in Iowa to flooding, a possible approach would include adjusting climate data for AASHTOWare Pavement ME Design based on the flood occurrence scenarios at the target road segments. To this end, the flood depths under given flood scenarios would be calculated through superimposing flood data on pavement topology data. Then, a virtual weather station would be created in AASHTOWare Pavement ME Design to represent the location-specific climate. Aerial characteristics may need to be adjusted accordingly. A tentative path to performance simulation is given in Figure 4.11.

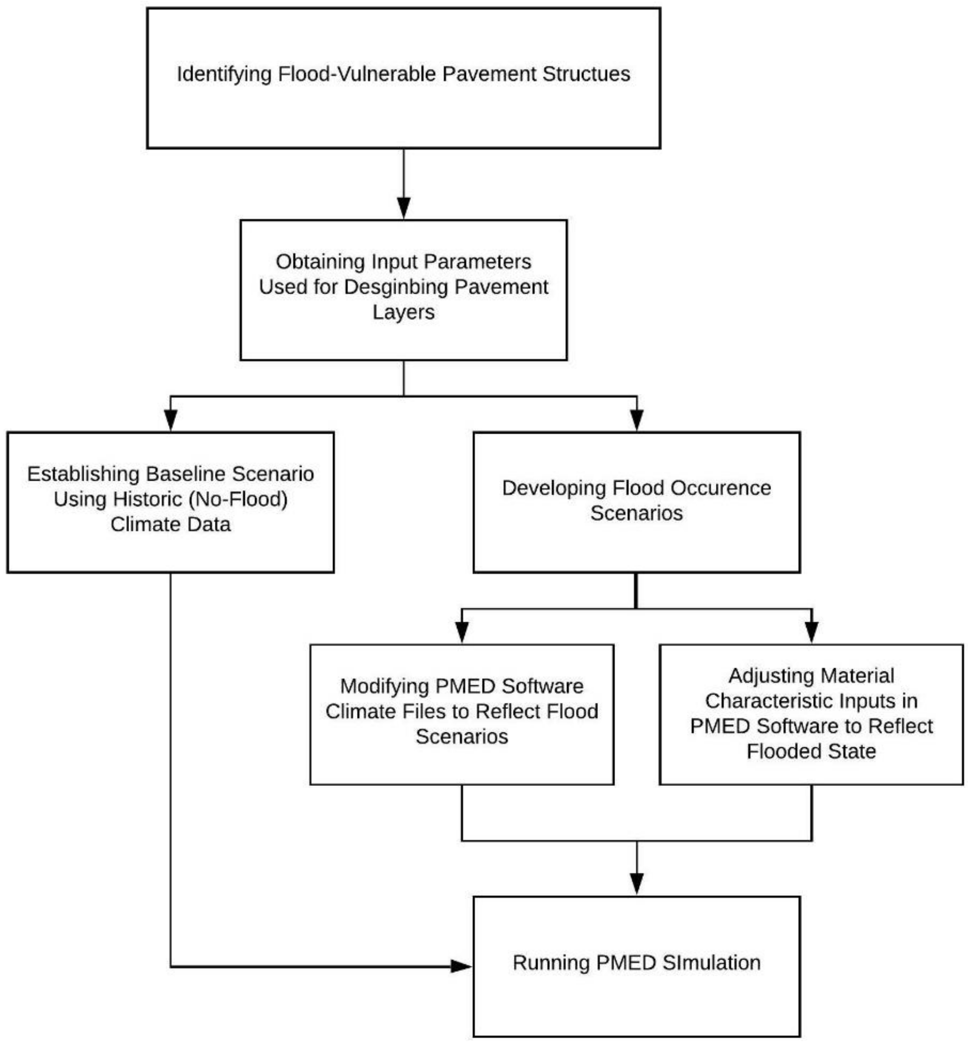


Figure 4.11. Tentative path to simulating the impact of flooding on pavement performance

The following parameters are critical for incorporating the effects of flooding into the model:

- Depth of the water table – Flooding is defined as the complete inundation of the subgrade material
- Precipitation
- Adjusted subgrade and subbase resilient moduli – The resilient modulus of the subgrade layer is a major factor in modeling the effects of flooding. The subgrade layer's long-term weakening by moisture content is a major cause of flood damage; therefore, adjusting the subgrade resilient modulus is required to model flooding.

- Rutting parameters – The rutting parameters of the unbound layers should be defined. The rutting parameters of the AC layer can be assumed to be unchanged by flooding.
- Drainage time after the flood event – The stiffness and stress states of the pavement layers change significantly as a function of saturation. The model should account for the approximate time it takes for the subbase and subgrade layers to recover and regain strength after flooding.

The main pavement design and characteristic inputs required by AASHTOWare Pavement ME Design are presented below.

4.3.1. General Project Information (Including Performance Criteria)

- Calibration coefficients for transfer functions
- Design type
- Design life – Typical design lives are shown in Table 4.5, but other design life specifications can be interchanged and considered in the analysis.
- Base construction month (if applicable)
- Pavement construction month
- Traffic opening month
- Initial IRI – Initial IRI is needed as an input criterion for pavement design. This initial value should be determined from construction records of previously placed AC or PCC surfaces under comparable conditions.

Table 4.5. Typical pavement design life values

Pavement type	Design Life (Years)	Long-Life Design Life (Years)
Flexible	20	40
Rigid	30	40
AC Overlay	15	NA
PCC Overlay	30	40
Restoration JPCP	15	NA

Source: Lu et al. (2020)

4.3.2. Traffic

- Two-way average annual daily truck traffic (AADTT)
- Number of lanes in the design direction
- Percent of trucks in the design direction, or directional distribution factor (DDF). If sufficient truck volume data are unavailable, a DDF value of 50% should be used.
- Percent of trucks in the design lane, or lane distribution factor (LDF). If sufficient truck volume data are unavailable, the values listed in Table 4.6.6 should be used.
- Operational speed, taken as the posted speed limit or the average truck speed
- Vehicle class distribution (VCD) information

- Growth rate of truck traffic. Based on Iowa DOT practice, this can be selected from the three options provided by AASHTOWare Pavement ME Design: no growth, linear growth, and compound growth.
- Monthly adjustment factors (MAF) and hourly distribution factors (HDF). These factors represent truck traffic distribution over the months of the year and hours of the day, respectively. MAF and HDF tend to vary with location, and it is recommended to use local values that can be acquired from the Bureau of Public Roads (BPR). If these factors are not known, carefully selected software-recommended values can be used.
- For other inputs, software defaults can be used, unless their values in the segment are especially important.

Table 4.6. LDF values for AASHTOWare Pavement ME Design

Number of lanes (two-directions)	LDF (%)
2	100
4	90
6	80
>6	60

Source: Lu et al. (2020)

4.3.3. Climate

- Location and/or climate station
- Depth of the water table, which shows the average distance between the pavement surface and the free water table. AASHTOWare Pavement ME Design allows average annual or seasonal values for water table depth.

4.3.4. Design Features

HMA

- Rutting calibration parameters. These can be the same for all HMA layers or be defined separately for each layer if local calibration has been done.
- Surface shortwave absorptivity. The default value can be used.
- Endurance limit. This is not necessary unless it has been defined in the initial pavement design as a mixture property.
- Layer interface friction. Use 1 to represent full friction.
- Condition of existing (underlying) pavement. In the case of new pavement design, this information would be the condition of the existing underlying pavement. For evaluating existing pavements, access is needed to the condition data of the underlying pavement at the time of the existing layer’s construction.

JPCP

- Surface shortwave absorptivity. The default value can be used.
- Joint spacing. AASHTOWare Pavement ME Design allows two options for joint spacing in JPCP: a constant or random joint spacing ranging from 10 to 20 ft.
- Sealant type
- Doweling direction (usually all transverse joints)
- Dowel diameter
- Dowel bar spacing
- Widened or non-widened slab
- Whether tied PCC shoulders are used and their load transfer efficiency (LTE)
- Erodibility index. This is determined by the type of base material, which is classified into one of the five categories shown in Table 4.7.
- PCC-base interface. Full friction is assumed, but depending on the base material, the friction may degrade over time. Therefore, for some types of base materials, AASHTOWare Pavement ME Design has a recommended length of time after which there is a possibility for the loss of full friction.
- Permanent curling/warping effective temperature differential. A default of -10°F is used.
- Condition of existing pavement

CRCP

- Shoulder type
- Percent longitudinal steel
- Bar diameter
- Depth of longitudinal steel reinforcement
- Base/slab friction coefficient. This is selected based on the base material.

Table 4.7. Erodibility indices for different base materials

Erodibility Index	Category	Base Materials
1	Extremely Erosion Resistant	Asphalt-stabilized layer or AC and permeable asphalt or permeable cementitious treated base.
2	Very Erosion Resistant	Cement-treated or lean concrete base layer
3	Erosion Resistant	Dense-graded crushed stone base materials with less than 8% fines.
4	Fairly Erodible	Dense-graded or granular aggregate base materials with more than 8% fines.
5	Very Erodible	Silts and other non-cohesive fine-grained soils and cohesive soils.

Source: Lu et al. (2020)

4.3.5. Structure (Including Material Properties)

- Pavement layer structure. This includes all layers and their thicknesses from the surface to the subgrade.
- Material properties. The average values from historical construction records for a specific type of pavement can be used for this purpose. The inputs of the software are as follows:
  - AC – Unit weight, effective binder content, air voids (%), Poisson's ratio (default), aggregate gradation, dynamic modulus (determined based on aggregate gradation), reference temperature, asphalt binder grade, indirect tensile strength at 14°f, creep compliance, thermal conductivity, heat capacity, thermal contraction.
  - PCC – Unit weight, Poisson's ratio (default), coefficient of thermal expansion, thermal conductivity, heat capacity, cement type, cementitious material content, water/cement ratio, aggregate type, reversible shrinkage (default), time to develop 50% of ultimate shrinkage (default), curing method, strength property (selected from different available level options).
  - Base and subgrade – Type of base or subgrade, i.e., whether it is unbound material base or subgrade, cement-aggregate mixture base, stabilized subgrade, or bedrock. Resilient modulus is the most important characteristic. Conversion factors to convert laboratory-measured resilient modulus values to layer values for Iowa sites, Poisson's ratio (by type of material), coefficient of lateral earth pressure, hydraulic properties of soil (saturated hydraulic conductivity and soil-water characteristics curves). Site-specific characteristics: Atterberg limits, density, gradation, optimum water content or in-place water content at the time of construction.

Some of the parameters and inputs required for pavement performance modeling in AASHTOWare Pavement ME Design are not easily available. Some of the parameters can be found in the Iowa Pavement Management Information System (PMIS) database. The data available in PMIS are shown in Table 4.8.

Table 4.8. Data items required for AASHTOWare Pavement ME Design modeling found in the Iowa Pavement Management Information System

Category	AASHTOWare Pavement ME Design Input
General	Pavement type
	Year of construction or reconstruction
	Year of last resurfacing
	Number of years since last resurface/construction
	Design life
	Initial IRI
Traffic	AADT (by direction)
	No. of Lanes
	ADT truck
	Speed limit
Design Features	Widened or not widened slab (JCPC)
	Inside/outside shoulder type (JCPC)
	Inside/Outside shoulder width (JCPC)
	Inside/Outside shoulder tied/not-tied (JCPC)
	Pavement Width (JCPC)
	Widened Driving Lane Indicator (JCPC)
	Erodibility index (JCPC)
Structure and Material Properties	Layer structure and thicknesses
	Pavement thickness
	Total construction base depth
	Modulus of subgrade reaction
	Granular materials durability class

Some other data items can be found in non-PMIS sources such as previous studies, or software-recommended values can be used (Table 4.9).

Table 4.9. Input parameters found in sources other than PMIS or for which default values can be used

Category	Default or Obtained from Other Sources
General	Rutting calibration parameters (HMA) [from previous studies]
	IRI calibration parameters (HMA, JPCP) [from previous studies]
Traffic	VCD
	MAF and HDF
	LDF
Design Features	Surface shortwave absorptivity (HMA, JPCP)
	PCC-base interface (JCPC)
	Permanent curl/warp effective temperature difference
Structure and Material Properties	Layer interface friction (HMA)
	Joint spacing (JPCP) [AASHTOWare Pavement ME Design allows two options – refer to Iowa practice]
	Endurance limit (HMA)

Climate data are available for Iowa. Potential flood depths can be calculated by superimposing topology maps obtained from LiDAR data onto flood data using flood maps from USGS. However, processing LiDAR data is a challenging task because of large data volumes, data formats, and compatibility problems. Some critical data items that are required for pavement performance modeling in AASHTOWare Pavement ME Design are not readily available. These unavailable items are primarily related to material properties, as shown in Table 4.10.

Table 4.10. Data items required for AASHTOWare Pavement ME Design modeling but not found in the PMIS or other readily available databases

Category	AASHTOWare Pavement ME Design Input
General	Calibration coefficients for transfer functions [may not be required]
	Base construction month
	Pavement construction month
	Traffic opening month
	Underlying layer condition
Design Features	Sealant type (JCPC)
	Dowel information (JCPC)
Structure and Material Properties	AC material properties: dynamic modulus, unit weight, thermal properties, heat capacity, binder grade, strength characteristics
	PC material properties: unit weight, thermal properties, mixture components, strength characteristics
	Granular materials gradation
	Subgrade material resilient modulus
	Site-specific base and subgrade material properties: Atterberg limits, density, optimum water content

Using the process described in this section, a flood risk assessment framework can be developed that quantifies the resilience of existing road infrastructure. This method is based on several publicly available data sources. The pavement structure data can be extracted from the Iowa PMIS. LiDAR digital elevation models are preferred for their high resolution as sources for topology data. Topology data are available from several sources, including the University of Norther Iowa's GeoTREE, the Iowa Department of Natural Resources, and Iowa State University's ArcGIS Gallery. With these data available, a proactive risk-aware asset management approach can be developed.

5. FUTURE WORK

This study can be expanded to obtain additional results and provide further support for current data. While a small sample size can be advantageous for focusing on a specific area, a more clearly defined trend may be seen by utilizing a sample size spanning the entire state of Iowa. Additional data collection is needed for an analysis of road and bridge elevations outside of District 6, which is the only district analyzed in Section 3.3. A potential way to expand this study would also be to use lower flood stage elevations to analyze the probability of flood-related bridge damage. Damage can occur to bridges when the water stage is below the girders, so the probability of the occurrence of damage should reflect this accordingly.

The other study presented in this report that included a small sample size was the set of analyses using statistical methods described in Section 3.4. Only bridges for which damage was recorded due to a natural disaster since 1998 were included in the data set, so the data were limited. Several of the raw data records did not have a direct match to the SIIMS database, so those records were disregarded. However, additional efforts should be made to extract usable data out of these records, possibly using a different database. Also in that section, the use of water elevation and water velocity data is needed to more accurately determine the relationships between these parameters and the cost associated with repairs.

The bridge sensitivity index scores should include more geomorphic data about the streams themselves to improve the stream channel instability index. SIIMS currently records qualitative data about the streams that need to be compiled and coded to help improve this index. In addition to the data collected, the bridge sensitivity index may be more appropriately presented as a matrix rather than a linear scale. This would involve placing the composite bridge sensitivity index score along one axis and the minimum structural rating along the other, which would ensure that the weighted averages used for the bridge sensitivity index do not overshadow any structural deficiencies with the bridge.

This recommended future work is summarized as follows:

- Collect elevation data and physical descriptor data for the entire state of Iowa rather than only District 6
- Include additional instances of bridge damage if data can be found outside of SIIMS
- Extract and code qualitative data for stream channels from SIIMS for use in the stream channel instability index
- Use flood water elevation and velocity to determine correlations with repair costs
- Revise the bridge sensitivity index into a matrix rather than a linear scale
- Include other flood elevations than overtopping elevations

6. CONCLUSIONS

Data already being collected for the NBI can provide excellent insight into the sensitivity of a bridge to flooding. In this study, this insight was obtained using geomorphic data that provide information about the stream channel that a bridge spans, such as the overall condition of the channel, the scour risk, and the waterway adequacy under the bridge. The bridge's superstructure, substructure, and deck condition were also used to provide a snapshot of the bridge's structural condition. Lastly, several parameters were used to determine the criticality of the bridge to the network if damage or closure were to occur. Each parameter was weighted according to previous analyses that identified how each parameter contributes to its respective index. Multiple sensitivity indexes were then created: a geomorphic index, a structural index, a criticality index, and a combined sensitivity index. These indexes show the distribution of bridges across the state according to different metrics and can be used evaluate how a particular bridge compares with the overall bridge population. Several proxy indicators were also obtained from this method, such as the bridge sensitivity index and specific minimum or maximum parameter values.

Historical data are very useful in understanding the probability of flood-related damage to bridges based on prior damage to bridges caused by flooding. A set of bridges affected by flooding was compiled, and each damaged bridge was evaluated for parameters that may have influenced the damage. Data collected since 1998 from ER reports show that the three most frequent types of flood-related damage occurring to bridges is due to abutment/berm erosion, pier scour, and pier debris. Using variables from empirical formulas or other parameters that are easily accessible from the NBI, trends were determined relating various parameters to the cost of repair from these types of damage.

It was found that the length of a bridge was a significant predictor for whether abutment/berm erosion occurred. A significant relationship was also found between the cost of repair and the parameters of the age of the bridge, bridge seat elevation, streambed elevation, abutment type, channel rating, and scour rating. Evaluating these relationships further showed that there is a significant difference between the cost of repairs for bridges with vertical wall abutments with wingwalls compared to bridges with spill-through or vertical wall abutments.

The results for pier scour showed that the length of a bridge, type of pier foundation, and substructure rating were all parameters that showed a statistically significant relationship to whether pier scour was present. The bridge bent had a statistically significant relationship with the cost of repairs of pier scour, but significant differences were not found between each different type of bent and the overall cost of repairs.

An empirical formula that included parameters for analysis was not available for the probability of pier debris accumulation. Several NBI parameters were nevertheless included in this study that were assumed to be related. Of those, pier width and the type of bent had a statistically significant relationship to whether debris accumulation was present. No parameters showed a statistically significant relationship to the cost of repair for this damage. By analyzing the relationships between damage cost/occurrence and various bridge parameters, clear proxy indicators were determined using parameters associated with each damage mode.

High water can affect both bridges and roads without necessarily causing damage. When water levels become high enough to overtop these assets, the closures dramatically affect the surrounding communities. Flood elevation data for several flood period scenarios were overlaid on a transportation subnetwork from Iowa DOT District 6. As the intensity of these flood periods increased, the number of bridge and road closures and the travel time within the subnetwork also increased. A similar study was also performed on a subnetwork of roads and bridges spanning District 1 and District 6. This study showed the effects of flooding periods of 2 to 200 years.

In addition to closures due to overtopping, damage can occur to pavements solely due to submersion. The same procedure of overlaying flood period data on a transportation subnetwork was performed, but in a smaller area within Linn County, Iowa. In this way, details regarding the overtopping and closure of road segments could easily be seen. The pavement type of each road segment was then overlaid on each flooded segment. This analysis was designed to identify the total length of road that would be flooded by different flood events as well as which pavements would suffer the most from flooding.

This report presented several methods for developing proxy indicators for both roads and bridges of their sensitivity to flooding. These proxy indicators can be used to identify vulnerable assets, monitor those assets, and help plan for the appropriate maintenance. These methods can be integrated into the Iowa DOT’s TAMP procedure to create a more resilient, cost-effective, and better quality transportation network that is prepared for future flooding events.

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