Comprehensive Analysis of Riverine Flood Impact on Bridges: Iowa Case Study

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Abstract

Floods often have a catastrophic impact on human life in terms of economic loss, infrastructure damage, and loss of life. Transportation network resilience is one of the critical aspects of supply lines for delivering goods and services during and after disaster events. Understanding vulnerable transportation segments is critical to addressing potential disruptions that may be caused by a flood event. In this study, we provide a comprehensive assessment of flood impacts on Iowa's transportation infrastructure, focusing on bridges, waterways, and traffic disruption. This research adopts a systematic framework, proceeding from a general overview at the state level to large-scale specifics. The initial segment outlines the statewide flood impact, progressively delving into individual bridges, waterways, and traffic ramifications. The research presented here analyzes the impact on inundated bridges across counties for varying flood intensities. Recognizing the disparity in county bridge counts, the inundated bridge ratio gains precedence alongside absolute counts. The southeast region of Iowa comes out as pivotal in flood scenarios, notably during 50-, 100-, and 500-year events. Marion, a moderately populated county in the southeast of Des Moines, stands out as a critical region due to its significant bridge inventory inundation in 100- and 500-year flood cases. The study also investigates bridge conditions, construction years, and their correlation with inundation risk to determine the vulnerability of bridges to flooding events and enhance our understanding of the potential effects of inundation on various bridge features. Furthermore, waterway bridge evaluations for different flood magnitudes and their impact on evacuation plans are explored. Transportation network vulnerability is assessed through closed-bridge effects on traffic. Average daily traffic values and detour lengths elucidate traffic disruption patterns across the state. These insights underscore the intricate interplay between floods and transportation, shedding light on bridge vulnerability, waterway evaluation, and traffic disruption. Overall, the presented research provides crucial information for flood mitigation strategies and resilience-enhancing measures in Iowa's transportation infrastructure.

Keywords: flood impact assessment, risk analysis, riverine flood, bridge, infrastructure

1. Introduction

Floods are one of the most dangerous natural disasters in the world. Climate change, increasing population, and rapid urban development are leading causes of increasing flood events. (Sadler et al., 2017). Floods are caused by various factors, including rainfall quantity and distribution, concentration and severity, land cover, soil moisture, steam network capacity, and tidal impact (Lebbe et al., 2014). Flood risk is substantial in many regions, considering the fact that the majority of the cities are either located near a large waterbody or a stream. Furthermore, flood depths in urban areas tend to rise quickly because of the impermeable catchment regions covered by city development and transportation infrastructure (Lebbe et al., 2014). Due to the nature of the flood, which strikes abruptly and may continue for days, depending on the terrain and drainage system, it might even take weeks, which causes longer recovery times. As a result, effective flood risk management is essential for minimizing potential losses, which should include corrective and preventative measures to decrease flood loss and damage via timely planning and preparation (Alabbad et al., 2022).

Flood events have a significant impact on human life directly (i.e., structural damage and casualties) and indirectly (i.e., disruptions to the transportation of people and products). Most flood events cause direct economic losses, which often result in catastrophic consequences for the public (Wang et al., 2023; Alabbad et al., 2023a). The negative economic and social effects of floods have increased recently due to rising physical risk and population growth in flood-prone areas (Highfield and Brody, 2017). By 2030, there are expected to be 5 billion people living in urban areas worldwide, and a single flood might have a catastrophic impact on millions of lives. (Gaines, 2016). Therefore, floods represent a serious threat to society considering current and projected risks (Li et al., 2020).

As a response to potentially massive impacts on communities, government agencies, such as the Federal Emergency Management Agency (FEMA), support mitigation practices to minimize flood impact on vulnerable communities to increase flood resiliency of the communities (Alabbad et al., 2023b; Yildirim et al., 2023). Simultaneously, decision-makers regularly conduct vulnerability assessments on critical assets within their jurisdictions to identify vulnerable zones (Haltas et al., 2021; Yildirim and Demir, 2022). These proactive strategies aim to adapt and strengthen resilience in order to reduce the current impact of natural hazards and protect vulnerable communities against future challenges for cities (Beck et al., 2010).

Apart from other services, the transportation network is one of the most affected areas during and after a flood since the interruption disrupts access to key facilities such as hospitals and fire stations. Moreover, these closures have an indirect impact on people who do not work from home, causing psychological distress as well as losses in work hours and Gross Domestic Product (GDP) (Botzen et al., 2019). Moreover, many studies demonstrated that bridges are the most crucial components of a transportation network. Bridges play an important role in societal and economic domains by facilitating access to vital services such as schools and hospitals, as well as supporting vital utilities such as pipes, cables, power, water supply, gas, electricity, and communication (Pregnolato, 2018).

Bridges (highways, railways, etc.) have been built for millennia, especially to cross rivers (Dunbar, 1915; Schwantes, 1993), and they are an indispensable element of the community in many ways. On the other hand, they are important features as they allow traversal of physical impediments (e.g. rivers) but they are also vulnerable to flooding effects, primarily waterway bridges, which are directly influenced by hydromechanical impacts, as well as their construction and maintenance costs and potential closure-detour lengths. In addition to their importance, roads and bridges have not been constructed to withstand changing climates, population growth, and economic austerity (Pregnolato et al., 2018). Hence, due to their importance in transportation, crossing structures (bridges and tunnels) cannot be removed or altered in the same way as berms or other floodplain infrastructure (Seigel, 2021).

Most of the bridge-focused flood evaluations are primarily structural-based or hydromechanical-based analyses in the literature. For instance, while Lebbe et al. (2014) deals with the physical impacts of flooding on bridges in his study (i.e., scour on bridge piers, bridge collapses due to the hydromechanical effect of flooding, etc.), Tubaldi et al. (2022) designed and analyzed the debris accumulation model in the laboratory environment to examine the scour and buoyancy effects on the bridges during the flood events.

In addition, Zayed et al. (2007) conducted studies to evaluate the bridge risk index of bridges exposed to flooding by using parameters such as bridge geometry, bridge foundation, and bridge substructure systems. When compared to other natural disasters, the flood is unique. A bridge, for instance, responds differently to an earthquake than it would to flooding. In the absence of collapse or significant damage, a bridge can be considered earthquake safe. However, a bridge closure is not only about collapsing but also about being inundated by water, which prevents safe usage of the infrastructure during a flood. The bridge is inoperable and closed due to flood water overflowing its surface, rendering it indistinguishable from a collapsed bridge.

Floods continue to cause the greatest amount of economic disruption of all the natural disasters that affect the United States (Highfield and Brody, 2017). Annual flood events in the United States cost roughly $3.8 billion in damage between 1980 and 2021 (NOAA, 2021). Over the previous two decades, Iowa has also faced several flood events that have adversely affected its people, infrastructure, and agriculture (Yildirim and Demir, 2019). Moreover, flood disasters affected numerous regions of Iowa in 2019, causing an estimated $1.6 billion in damage (Iowa.gov, 2019).

Furthermore, the 2008 flood affected over 40,000 people and caused an estimated $10 billion in damage across the State of Iowa (Zogg, 2014). The state has also been hit by other major floods in recent decades, including the floods of 1993, 2001, 2008, 2014, 2016, and 2019 (Yildirim et al., 2022). These floods have caused widespread damage to homes, businesses, and infrastructure, and have displaced thousands of people. As a result, Iowa is one of the most vulnerable states in the United States to flooding. Even though several recently developed national guidelines, which are accessible in the UK, Italy, and Japan, have implemented risk-based techniques for regulating hydraulic effects on bridges (Loli et al., 2022), there is no comparable state-wide research on this topic in Iowa.

Due to historical flood events in the state, several studies have been introduced to understand the risk and vulnerability of Iowa (Alabbad and Demir, 2022). In some studies, detailed analyses were carried out based on the watersheds (i.e., Yildirim and Demir, 2021). Meanwhile, several studies were carried out about certain cities and communities (Alabbad et al., 2021). In these studies, the condition of essential facilities, such as hospitals, during 100- and 500-year floods and flood impacts on people and traffic networks were examined.

Moreover, several flood risk analyses and their socioeconomic and geophysical effects have been explored in detail for a limited area within Iowa (Cikmaz et al., 2023). However, a high-profile flood study has not been carried out so far on the bridge infrastructure, specifically across Iowa. In addition, most of the flood studies conducted, not only in Iowa but also in the country, are based on 100-year (1% annual occurrence chance), 200-year (0.5% annual occurrence chance), and 500-year (0.2% annual occurrence chance) flood scenarios. However, the impact of 50-year (2% annual occurrence chance) flood scenarios is not negligible and needs to be examined. Therefore, in our study, we conducted a county-wise bridge-specific flood inundation analysis across Iowa for 50-year, 100-year, and 500-year flood scenarios and evaluated the impacts of these closures on the state.

The remainder of the study is compiled into three main sections: data and methodology, results and discussion, and conclusion. The data and methodology section includes data preparation, methodology, bridge impact analysis, and case study information. In the discussion and results section, we delivered county-wise bridge inundation, age and condition, waterway evaluation, and traffic disruption analysis sections. In conclusion, the general results and inferences from this study and possible future work ideas are presented.

2. Data and Methodology

2.1. Data Collection

Bridge infrastructures are essential for both during and after disaster activities such as evacuation, rescue, and search operations since bridges are critical transportation elements that allow access to impacted regions (Lebbe et al., 2014). Since bridges are the main element in our study, bridge analyzes, and evaluations are carried out and compiled in detail in this section. In this study, all the raw inventory data (including location, structure number, owner, structure type, type of service, construction-reconstruction year, etc.) and the specifications that are used for determining the bridge classifications, and conditions are obtained from the latest National Bridge Inventory (NBI) report. The overall bridge summary of Iowa can be presented in 3 classes: Inventory-based, County-based, and Point-Based.

Inventory Based: With 24,006 bridges, Iowa ranks in the top 10 in the nation but Iowa's bridge infrastructure has its unique challenges. The state ranks first in terms of the number of deficient bridges (Iowa DOT, 2022). Of the 24,006 bridges across Iowa, 4,505 are in poor condition and another 10,134 are in fair condition. Most of Iowa's bridges (93%) are on waterways, making them an essential part of the state's transportation system. The average age of a bridge in Iowa is 43 years old, which poses challenges in terms of maintenance and upgrades. The ownership of Iowa bridges is divided among different agencies, with County Highway Agencies owning 18,602, State Highway Agencies owning 4,154, and City or Municipal Highway Agencies holding 1,213. The remaining 37 are owned by other entities. The service types for Iowa bridges include 22,632 highway bridges, 519 highway-pedestrian bridges, and 647 overpass structures.

The majority (97%) of these bridges can be classified as highway bridges. However, they can also be classified by other parameters including materials, structure types, and ages. Figure 1 shows that the majority of bridges are made of concrete and/or steel and almost all the bridges are in the highway or highway-pedestrian category. In the structure type case, almost half of the bridges are in the Multi-Beam or Girder group, while the other half is split into six groups.

Furthermore, half of the bridges are described as Local bridges, 32% are in the Collector class, and the other 18% are in the Arterial class.

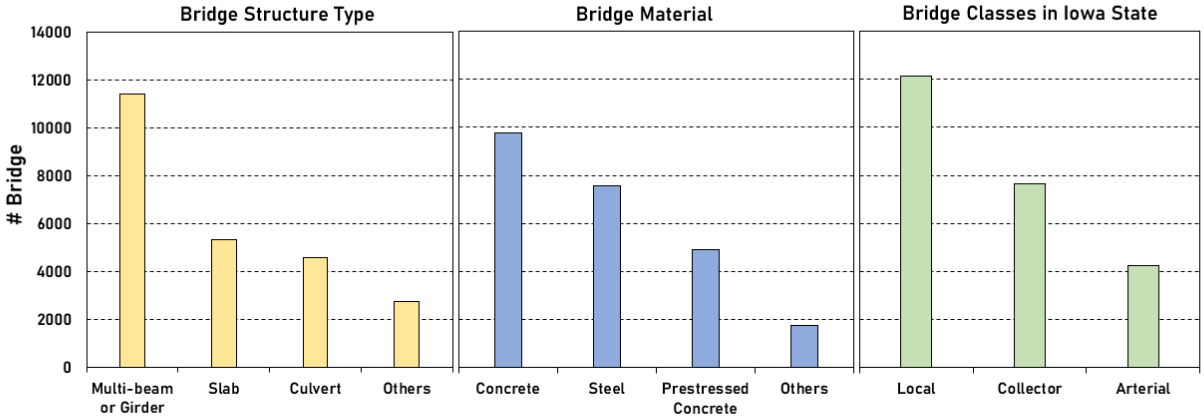

Figure 1. Iowa bridge type and class distribution

<u>County Based:</u> As seen in Figure 2, Polk County has the second-largest bridge inventory in Iowa, with 542 bridges, just after Pottawattamie, with 565 bridges, while Winnebago has only 69. However, Polk's inventory is the youngest in Iowa, with a 33.2-year average bridge age. On the other hand, Boone (63.86) and Clayton (55.93) hold the oldest average bridge ages. In the bridge condition case, Tama County leads the way with 119 deficient bridges. On the other hand, O'Brien has only three poor condition bridges. However, in percentage cases, 43.9 percent of Ringgold bridges are in poor condition, which makes Ringgold the leader in this regard. On the contrary, O'Brien (1%), Clinton (2%), and Sioux (3%) are the counties that have the fewest deficient bridges as a percentage.

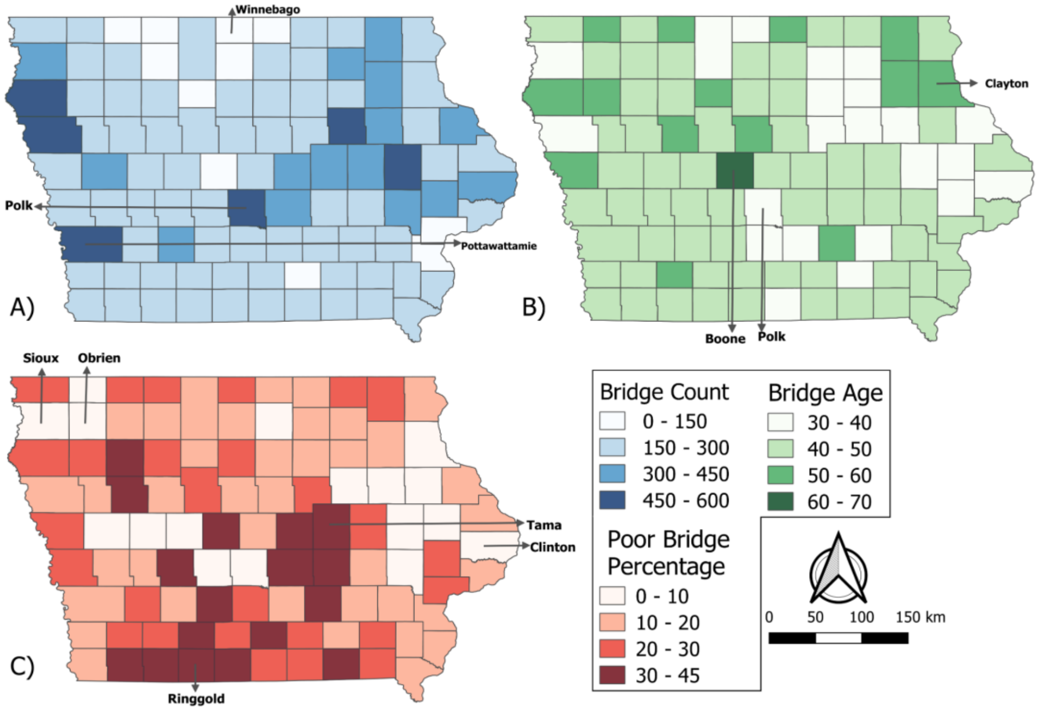

Figure 2. Iowa County-Wise Bridge Distribution Maps: A) Total Bridge Amount; B) Average Bridge Age; C) Poor Condition Bridge Percentage

Point-Based: As demonstrated in Figure 3, most of the bridges in Iowa are clustered southeast of the state center. In addition to that, the majority of deficient bridges in Iowa are located on the southwest and east sides of the state center, whereas the north side of the state center could be stronger in terms of the number of bridges and, accordingly, the number of deficient bridges.

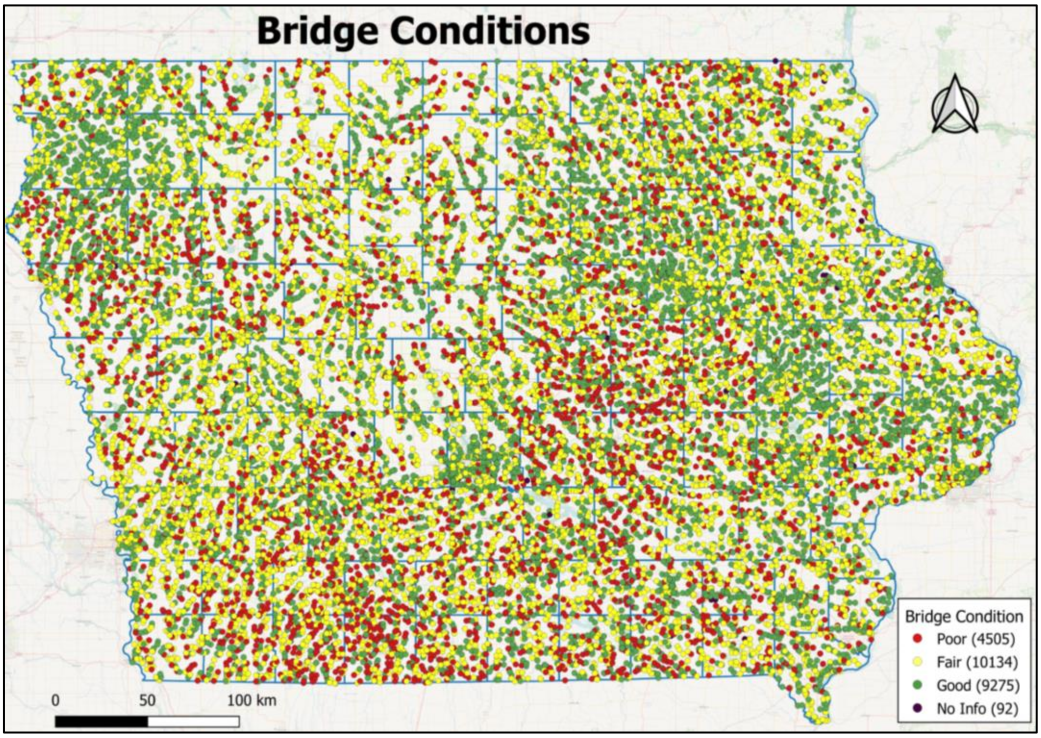

Figure 3. Iowa bridge locations and their current conditions

The extent and level of flooding on the drainage surfaces and floodplain for various return times -in this study, 50-year (2% annual occurrence chance), 100-year (1% annual occurrence chance), and 500-year (0.2% annual occurrence chance) are used as return times- are illustrated on flood inundation maps (1-meter resolution) produced by the Iowa Flood Center and the Iowa Department of Natural Resources based on flow gage, topographical data, and other hydraulic features of the outflow systems. (Gilles et al., 2012). Moreover, the bare earth DEM (Digital Elevation Model) of Iowa and county borders has been obtained from Iowa Geodata Server. To determine whether the bridge is inundated or not under a specific flood case, we utilized bare-earth elevation, bridge deck elevation, and underneath flood depth for all bridges.

2.2. Methodology

In this study, combining and analyzing the bridge inventory data listed above with the flood map created for Iowa's bare earth DEM and three different flood scenarios and map-based one basis of point and county were performed with QGIS software, which is an open-source geographic information system. In addition, county-based bridge distributions, traffic network analysis, and the calculation of the statistics of these analyses (i.e., condition distribution, year of construction distribution, and determination of criticality based on these findings) are also carried out and visualized with QGIS.

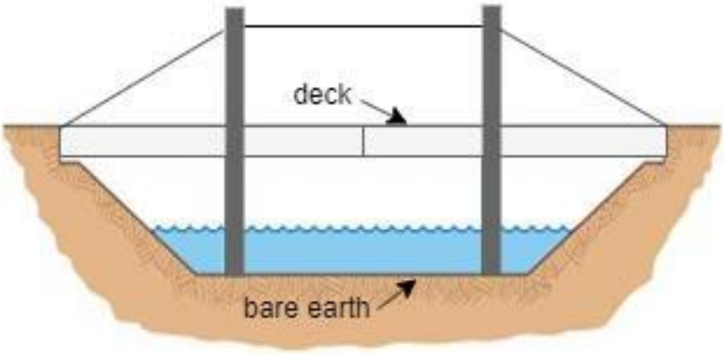

Figure 4. Cross section of a waterway bridge (Alabbad et al., 2021)

The overtopping and closure of a bridge cannot be predicted using basic two-dimensional intersections between flood extents and bridges, so in order to accommodate for bridge design aspects, a three-dimensional analysis has to be used, with additional parameters like bare earth and bridge deck elevation (Alabbad et al., 2021). To detect the elevation of bridges, we used Lidar (Light Detection and Ranging) data from the GeoInformatics Training Research Education and Extension (GeoTree), which is a remote sensing technique that measures the range (varying distances) to the Earth by using light in the form of a pulsed laser. The methodology can be observed in Figure 4 and the equation below. In the formulation below, HBE is bare-earth elevation, HD is bridge deck elevation, and HF is flood depth. The inundation formula 'Fi' can be generated as follows (Eq. 1):

$$\begin{gathered} Fi \ = \ HD - HBE + HF \\ if\ Fi\ > 0, bridge\ is\ inundated \\ if\ Fi < \ 0, bridge\ is\ not\ inundated \end{gathered} \qquad \text{Eq. 1}$$

2.3. Case Study

In our study, we focused on county-level bridge inundation analysis during 50-year, 100-year, and 500-year flood scenarios, their distribution to counties, and impacts on the transportation network of the State of Iowa. In our algorithm, a bridge that closes in a 50-year flood scenario is considered to be closed directly in a 100-year flood and a 500-year flood. Likewise, a bridge that closes in a 100-year flood case is also considered directly closed in a 500-year flood because these values are probabilistic and were determined by using historic flood events, so if a bridge is inundated in a 50-year flood it is definitely closed in a 500-year flood too.

In the following subsection, procedures for waterway adequacy and bridge condition evaluations are provided. Waterway Adequacy Assessment (NBI item 71) is a crucial factor in understanding the status of bridges during floods and taking measures in that direction. This evaluation requires the inspector's assessment of the waterway's sufficiency; hence, this evaluation appraises the waterway opening about flow passage across the bridge (Iowa DOT, 2015). The evaluation parameters can be obtained from Table 1.

Condition ratings are used to define the present mechanical condition of bridge components in comparison to their as-built conditions. The condition codes, used to grade bridge components, should describe the general state of the entire component in order to encourage uniformity among bridge inspectors, so they are not meant to rate localized issues or occasionally occurring cases of wear and tear (Iowa DOT, 2015). Therefore, the proper assignment of a condition score must take into account both the degree of degradation or disrepair and how widely distributed across the component being assessed.

Table 1. Evaluated values for waterway adequacy (Iowa DOT, 2015)

Classification Description	**Functional Classification Codes**		
	Principal Arterials – Interstates, Freeways, or Expressways	**Other Principal and Minor Arterials and Major Collectors**	**Minor Collectors, Local Roads**
Bridge not over a waterway.	N	N	N
Bridge deck and roadway approaches above flood water elevations (high water). Chances of overtopping remote.	9	9	9
Bridge deck above roadway approaches. Slight chance of overtopping roadway approaches.	8	8	8
Slight chance of overtopping bridge deck and roadway approaches.	6	6	7
Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with insignificant traffic delays.	4	5	6
Bridge deck above roadway approaches. Occasional overtopping of roadway approaches with significant traffic delays.	3	4	5
Occasional overtopping of bridge deck and roadway approaches with significant traffic delays.	2	3	4

Table 2. Group of Descriptive Conditions (Iowa DOT, 2015)

Grade	**Condition**	**Description**
7. 8. 9	Good	Component defects are limited to only minor problems.
5, 6	Fair	Structural capacity of the component is not affected by minor deterioration, section loss, spalling, cracking, or other deficiency.
0, 1, 2, 3, 4	Poor	Structural capacity of the component is affected or jeopardized by significant deterioration, section loss, spalling, cracking, or other deficiency.

According to the NBI and Iowa DOT Bridge Inspection Report, the general condition value was determined using the superstructure, substructure, deck, culvert, channel, and channel protection (NBI items 58–62). The Iowa DOT used the Structure Inventory and Inspection Management System (SIIMS) to classify the grouping of these scores as good, fair, and poor. Classification scores are provided in Table 2.

3. Results and Discussion

The results are presented in a general-to-specific order, beginning with an overview of the statewide impact of the flood on bridge and transportation infrastructure, and then providing more detailed information on the impact on individual bridges, waterways, and traffic. This organizational structure allows readers to gain a broad understanding of the flood impact before delving into more detailed information.

3.1. Statewide Evaluation

In this section, the ratio and counts of inundated bridges, and their structural distributions are analyzed for each county on the statewide scale. Comparing the number of inundated bridges in different counties after different flood events can be misleading, as the total number of bridges in each county can vary significantly. Therefore, the inundated bridge ratio (See Figure 5) is preferred to be delivered along with the inundated bridge counts (See Figure 6). For instance, in the 500-year flood case, Pottawattamie has 94 inundated bridges, which makes the county the second-critical county in the inundated bridge count. However, this number is only 17% of the total number of bridges in this county, and that makes Pottawattamie 38. place in the percentage case for a 500-year flood scenario.

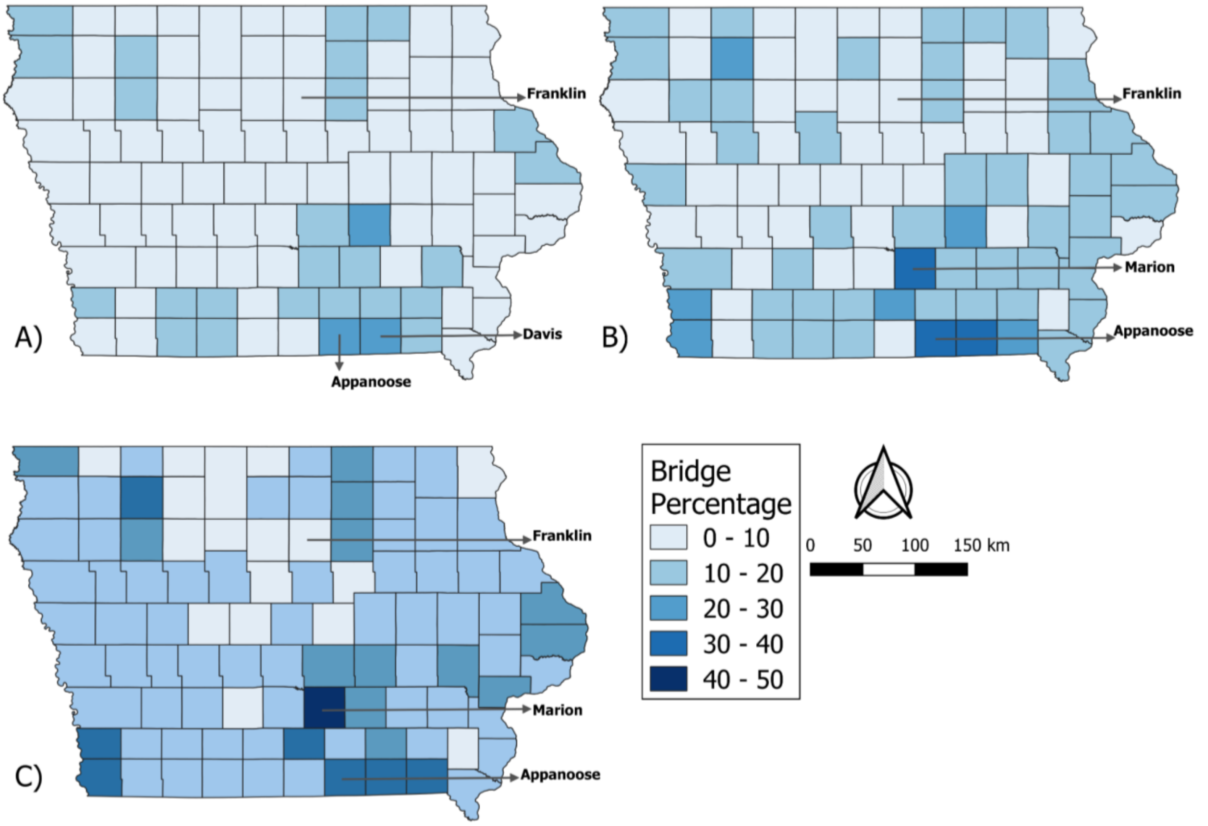

Figure 5. Percentage of the bridges closed during flood events for each county under A) 50-year; B) 100-year; C) 500-year flood scenarios.

As demonstrated in Figure 5, the southeast side of Iowa's center is more vulnerable than the other parts of the state in 50-, 100-, and 500-year flood scenarios. Moreover, Davis, with 28% of the bridge inventory inundated, is the most critical county for 50-year flood scenarios, while Marion has the greatest impact for both 100-year and 500-year flood cases with 38% and 47% of the bridge inventory inundated, respectively. However, in inundated bridge percentage, Appanoose is placed in the top 3 for both flood scenarios, while Franklin is placed in the last 3 for both cases.

In Figure 6, the pie charts placed on each county represent the closed bridge type distribution while the map itself represents the inundated bridge number on a county scale. Our statewide analysis suggests that there are 1,966, 2,697, and 3,904 bridges that are inundated under 50-, 100-, and 500-year flood scenarios, respectively. Although the majority of Iowa bridges are located in the northwest and northeast regions, most of the inundated bridges in different flood scenarios are located southeast of the center. Considering the structure, nearly half of the inundated bridges are in stringer/multi-beam or girder type under 50-year flood scenario while this percentage is 48% and 45% for 100-year and 500-year scenarios. According to the inventory data, 47% of the total bridges are in stringer/multi-beam or girder type. This means that even though Iowa has chosen to build these types of bridges for most locations, such bridges have the highest risk of flooding.

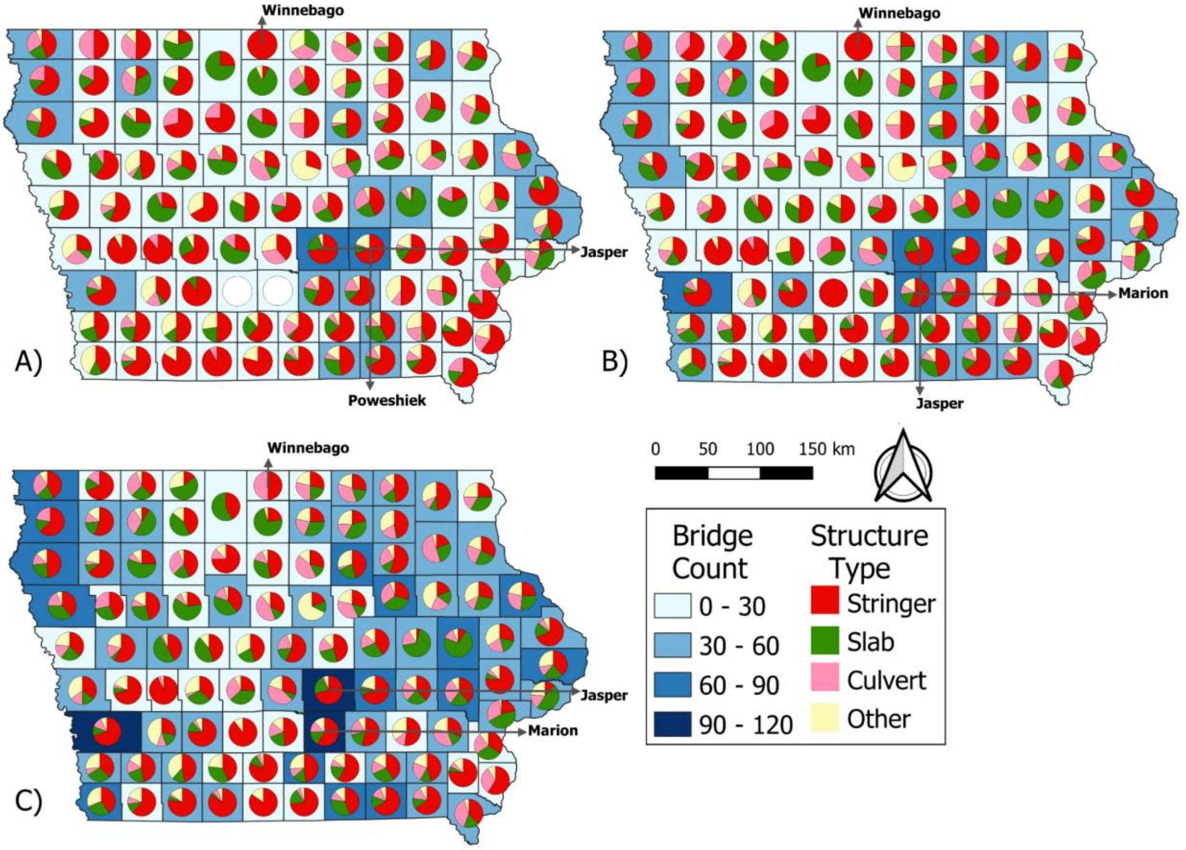

Figure 6. The number of closed bridges and their structure types in Iowa for A) 50-year; B) 100-year; C) 500-year flood scenarios

Considering the number of inundated bridges, Poweshiek (67) is the most vulnerable county for 50-year flood scenarios, while Marion (82; 103) leads the way for both 100-year and 500-year flood scenarios. Even Marion is the 52nd county in bridge count, with 217 bridges. That makes Marion one of the most vulnerable counties for flood hazards. On the other hand, in the inundated bridge count, Jasper (64; 75; 93) is placed in the top 3 for both flood cases, respectively, while Winnebago (2; 2; 4) is placed in the last 3 for both scenarios.

Table 3. Top ten counties (ordered by closed bridge counts in 500-year flood scenario) and their inundated bridge conditions for 50-, 100-, and 500-year flood scenarios.

County Name	**Total Bridge**	**Flood Type**	**Closed Bridge Condition**		
			Good	**Fair**	**Poor**
Marion	217	50 Year	12	17	8
		100 Year	24	40	18
		500 Year	36	46	20
Pottawattamie	565	50 Year	17	14	7
		100 Year	31	22	8
		500 Year	41	36	17
Jasper	381	50 Year	15	14	34
		100 Year	19	18	36
		500 Year	21	25	45
Sioux	448	50 Year	28	15	3
		100 Year	34	18	4
		500 Year	51	33	5
Clinton	372	50 Year	26	10	0
		100 Year	35	14	0
		500 Year	61	19	0
Poweshiek	263	50 Year	10	28	29
		100 Year	10	30	31
		500 Year	11	33	33
Lucas	196	50 Year	7	4	14
		100 Year	14	8	32
		500 Year	22	18	37
Johnson	364	50 Year	2	11	13
		100 Year	11	19	16
		500 Year	23	32	17
Woodbury	458	50 Year	18	5	6
		100 Year	25	12	8
		500 Year	37	22	13
Lyon	278	50 Year	18	14	14
		100 Year	19	16	17
		500 Year	27	20	22

3.2. Bridge Infrastructure Evaluation

In this section, the condition and construction year distribution of the inundated bridges for 3 different flood scenarios are analyzed. The analysis allows decision-makers to investigate the average age of at-risk infrastructure as well as its specific properties, such as building materials. In this analysis, the condition distribution of inundated bridges for the top ten counties that have the most inundated bridges under the 500-year flood scenario is determined. However, all three flood scenarios share six of the top ten counties (Poweshiek, Jasper, Lyon, Sioux, Pottawattamie, and Marion), which are the most affected by flood events. The color code we use indicates that the bridge counts have increased from light colors to dark colors. If the number of bridges was determined to be 0, white color was used for that cell.

As illustrated in Table 3, in both scenarios, Jasper County has the highest number of closed bridges in poor condition. While Clinton has no closed bridges in deficient condition in all cases. Moreover, although Marion leads the way in 100- and 500-year flood cases, it is in 9th place in the 50-year scenario. This means that Marion becomes critical at a higher rate than the other counties as the size of the flood increases. Another county whose criticality is increasing from a 50-year flood scenario to a 500-year flood scenario is Pottawattamie. This county ranks 8th in the number of inundated bridges in the 50-year flood case, 4th in the 100-year flood case, and 2nd in the 500-year flood case.

With an average age of 43, Iowa has one of the oldest inventories in the United States. This situation puts Iowa in a troubled position on many issues. In this analysis, we determined the inundated bridge age distribution of Iowa for 50-year, 100-year, and 500-year flood scenarios and whether the bridge closure is relevant to the bridge age or not. For rebuilt bridges, the construction year is accepted as their reconstruction date.

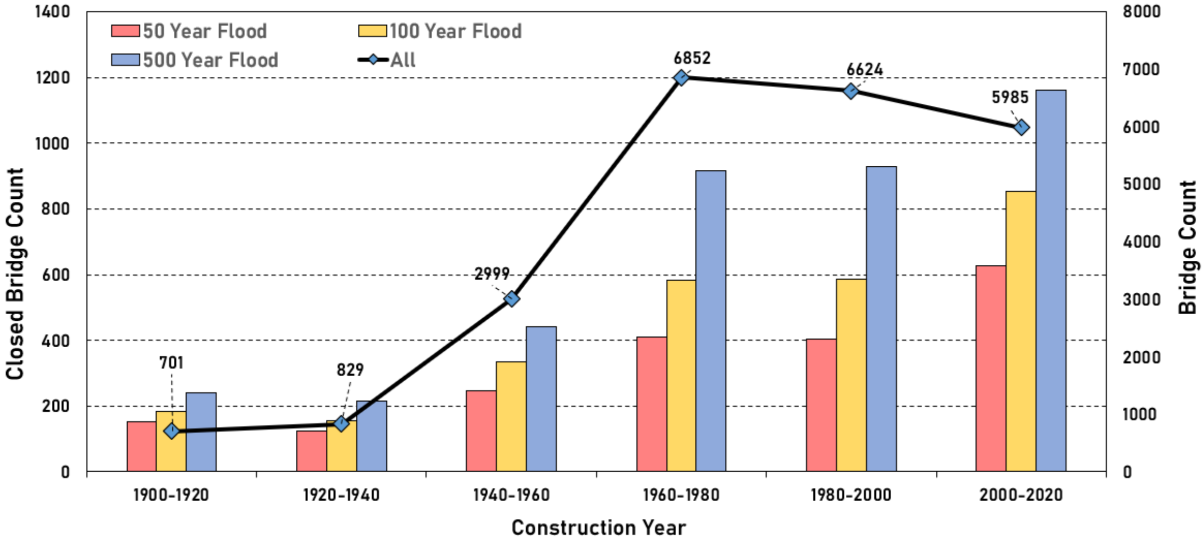

Figure 7. Construction year distribution of total and inundated bridges for multiple flood scenarios for Iowa

As can be seen in Figure 7, up to the 2000s, both constructed total bridges and closed bridges in different cases increased proportionally. However, after the 2000s, the number of inundated bridges increased while total bridge numbers decreased slightly. While the average age of bridges closed in the 50-year flood scenario is 46, this number drops to 45 in the 100 and 500-year flood cases. So, newer bridges are more vulnerable to flooding closure than older bridges (up to the 1960s), even though they were built with more advanced engineering methods and tools (software, construction machinery, etc.). On the other hand, 15 bridges were constructed before 1900. One of them is inundated for 50- and 100-year flood cases and two of them (including the first one) are inundated for 500-year flood cases.

3.3. Waterway Evaluation

In this section, the inundated bridges by county for 3 different flood scenarios and their dedicated waterway evaluations were determined. As can be obtained from Table 4, waterway bridge evaluation is carried out for three different groups according to their functionality classes. Therefore, it is not possible to talk about a general average of waterway evaluation because the definitions to which the assigned values correspond are different. Therefore, in this analysis, the average waterway assessment calculations were made separately based on the bridges closed in three different flood scenarios and their functional classes. Of the color codes used in the background of the average waterway evaluation values under the 50-, 100-, and 500-year flood scenarios, red indicates that the value is higher than the overall average, and green indicates that it is equal to or lower than the overall average for that bridge class.

Table 4. Average waterway evaluation value of inundated bridges for 50-, 100-, and 500-year flood case and their functional classifications

Bridge Classes and Parameters		**Waterway Bridge Flood Scenario**			
		All	**50-yr closed**	**100-yr closed**	**500-yr closed**
Principal Arterials Interstates, Freeways or Expressways	Bridge Count	328	9	26	32
	Average Waterway Evaluation	7.19	8.89	8	7.94
Other Principal and Minor Arterials and Major Collectors	Bridge Count	6,258	247	375	603
	Average Waterway Evaluation	7.23	7.32	7.23	7.25
Minor Collectors, Local Roads	Bridge Count	15,613	1,680	2,249	3,209
	Average Waterway Evaluation	7	6.67	6.71	6.77

As can be seen in Table 4, there are 328 waterway bridges, which include principal arterials, interstates, freeways, and expressways. Although the average waterway evaluation averages of inundated bridges decrease as the flood magnitude increases -which is unexpected because these scores are based on the probability and frequency of bridge closures- these values are still higher than the overall average in three different flood scenarios. In other words, for this specific bridge class, inundated bridges generally have higher waterway adequacy scores, which is a critical situation for determining evacuation and rescue plans and taking action against flooding. Inundation of a bridge with a high waterway adequacy score instead of a bridge with a low score may damage the confidence in these evaluations.

Moreover, 6,258 waterway bridges contain the other principal and minor arterials and major collectors. While the average waterway adequacy scores of inundated bridges are not that high, the average for bridges closed in any flood scenario is not lower than the overall average. On the other hand, in the minor collector and local road cases, which contain the majority of the inventory with 15,613 bridges, the average waterway adequacy scores of the different flood cases are lower than the overall average for this functional class.

The average values increase with the criticality of the flood as expected. However, this class includes most of the inundated bridges for every scenario, so it is still crucial to consider the inundation risk for that class. To ensure consistency, we have assigned a rating of 9 to all road types. This rating falls under the category of "Remote overtopping bridge deck, and roadway approach's chance," which means that the chance of overtopping occurrence is greater than once in 100 years. The county-wise analysis results can be seen in Figure 8.

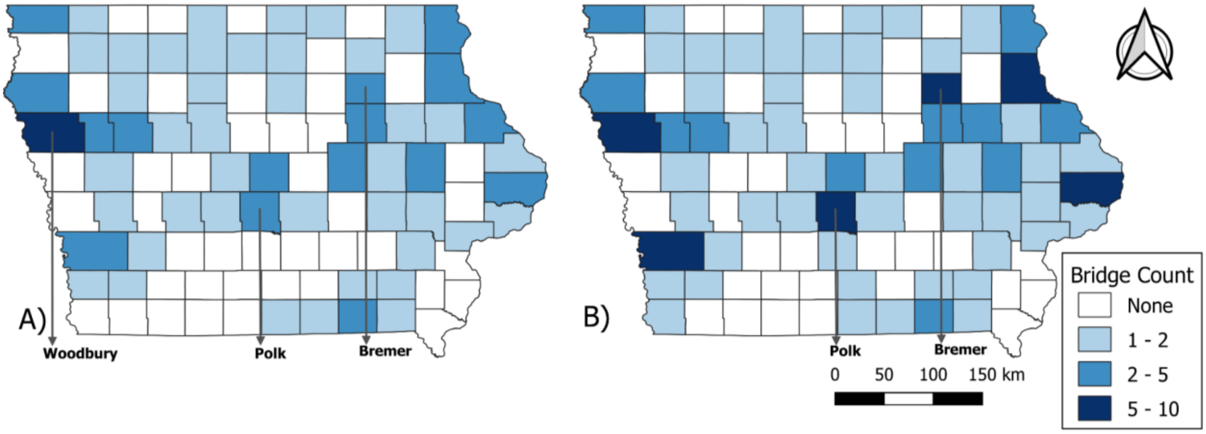

Figure 8. Inundated bridge counts that are classified as remotely overtopping chance for A) 50-year; B) 100-year flood scenarios.

In the State of Iowa, 1,064 of the waterway bridges have been designated with a score of 9 (frequency of occurrence is greater than 100 years) in waterway evaluation. However, there are 119 and 150 bridges that have a score of 9 in the waterway evaluation that are inundated under 50-year and 100-year flood cases, respectively. This is a risky situation because the closure of bridges that are not expected to be closed during the flood hazards may upset the rescue plans and cause instant changes in evacuation routes. On the other hand, 56 waterway bridges have no current waterway evaluation score. However, only 8, 11, and 14 of them are inundated by 50-year, 100-year, and 500-year flood cases, respectively.

As can be obtained from the previous section, Marion is the most critical county in both inundated bridge count and percentages for 100-year flood cases. However, none of these bridges were evaluated as remote-frequency waterway bridges. In contrast to other counties, Marion's evaluation can be said to be consistent, considering the county's vulnerability. Furthermore, in the 50-year flood scenario, Woodbury leads the way with six inundated bridges with a score of 9, while Polk ranks first with 10 bridges in the 100-year flood scenario. From 50-year Case to 100-year Case, the Inundated Bridge count in Polk County increased by 5 and reached 10. In addition, the number of inundated bridges in Bremer doubled, from 3 to 6.

3.4. Traffic Disruption

The transportation network is normally anticipated to uphold the prescribed minimum levels of functionality under normal and even disrupted conditions because any interruption to the network would have a negative impact on the continuous flow of traffic elements such as pedestrians, goods, and vehicles. (Ghasemi and Lee, 2021). Bridges, nevertheless, cannot be ignored, as they are the most vulnerable elements of a traffic network. Thus, the impact of closed bridges on the Iowa traffic network in 3 different flood scenarios is analyzed and discussed in this section.

The average daily traffic value may be represented as counting the number of vehicles (including cars, trucks, busses, etc.) traveling by a certain spot (i.e., a bridge) 24 hours a day, 365 days a year, and then dividing the total number of counts by 365 (Huntsinger, 2022). In this section, a county-wise summation of average daily traffic values of inundated bridges in 50-, 100-, and 500-year flood scenarios is calculated and mapped.

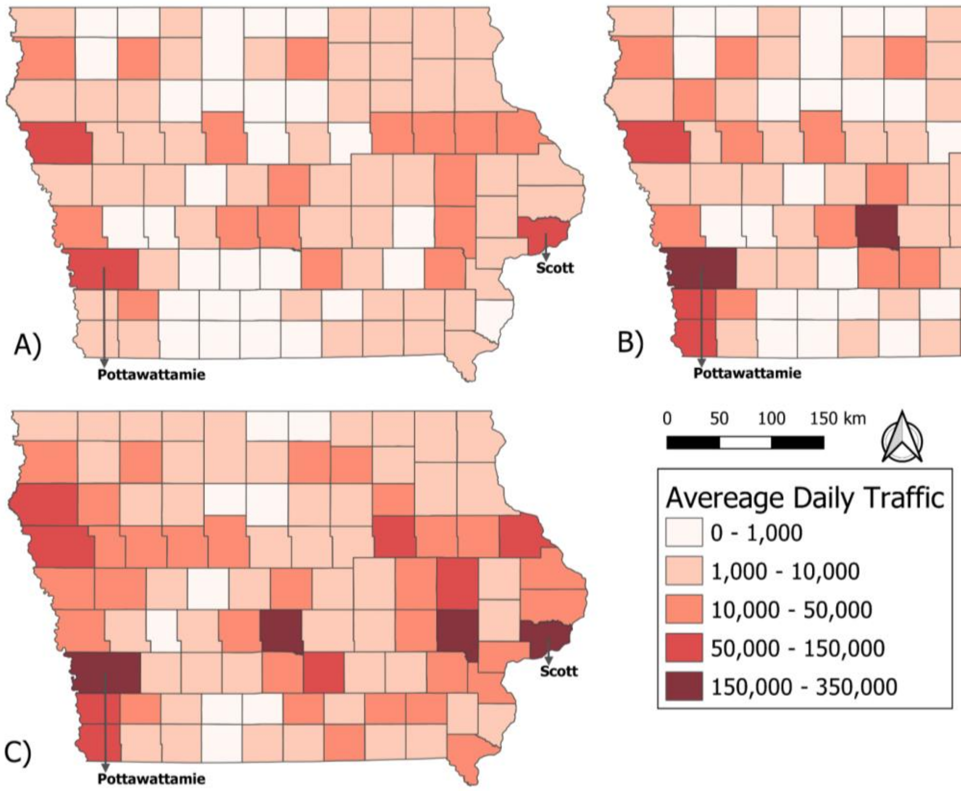

Figure 9. Total average daily traffic load for inundated bridges in A) 50-year; B) 100-year; C) 500-year flood scenarios

As shown in Figure 9, Pottawattamie is the county most affected by bridge closures in all three flood scenarios, based on average daily traffic. However, the county is not the leader in terms of the total number of inundated bridges in any flood scenario. Since the county is on the border with Nebraska, Pottawattamie has a crucial role not only for Iowa but also for transportation between these two states. As a consequence, it is obvious that, in the event of a possible flood, it will have a negative impact on the traffic between these two states. Another critical county is Scott, which is similar to Pottawattamie and is a border county (with Illinois). In all three flood scenarios, this county takes its place in the top 4 in average daily traffic disruption. However, the county is not among the top 10 counties that have the most inundated bridges in any flood scenario.

The detour length should indicate the overall length of the additional trip for a vehicle as a result of the bridge closure (US DOT, 1995). The ability to move cars around the structure should be considered when deciding if a bypass is accessible at the site. For example, if the structure can be bypassed at ground level or if the structure is a diamond interchange, the detour length is 0. However, if one of the twin bridges is closed, some part of the other twin may be used as a bypass. According to the FHWA Guide, this represents a 1-kilometer detour.

Additionally, in this guidebook, if the possible detour is higher than 199 km or the structure is on a dead-end road, it is accepted as 199 km. There are only 9, 13, and 19 bridges in this situation that are inundated under 50-year, 100-year, and 500-year flood cases, respectively. However, we did not include them in our county-based detour analysis to avoid ambiguity.

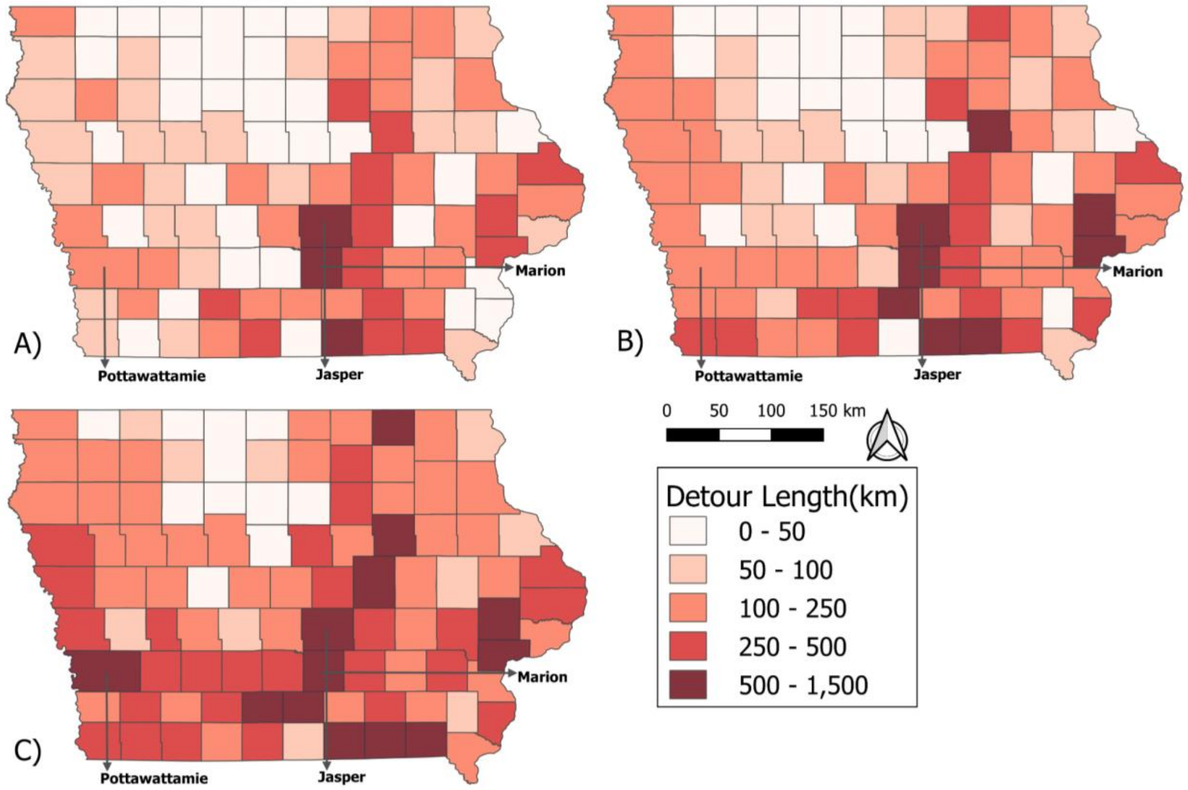

Figure 10. Total detour length due to bridge inundation for A) 50-year; B) 100-year; C) 500-year flood scenarios

As can be seen in Figure 10, on the basis of detour length, the eastern part of the state is more affected than the western part for both 50-, 100-, and 500-year flood cases. In terms of gasoline consumption and maintaining productive working hours, this situation has a negative impact on this county’s traffic network. Nevertheless, despite being in the western part of the state, Pottawattamie's number of closed bridges, total detours, and daily traffic on these bridges are high. That takes that county to a critical place in terms of traffic disruption.

However, in all three flood scenarios, the total detour length of the covered bridges in Marion is the highest, at 753, 1,097, and 1,310 km, respectively. It's unusual for Marion to lead the way in a 50-year flood scenario, as the county is not even in the top 5 for inundated bridge counts in the 50-year case. Considering the previous analysis, it can be observed that this county is vulnerable to flooding. On the other hand, another critical county is Jasper. In terms of the detour length of inundated bridges, Jasper County ranks in the top 3 for all flood scenarios as well as the total number of inundated bridges.

Emergency evacuation is considered to be the most crucial disaster response activity in order to ensure community safety against catastrophic events (Irsyad and Hitoshi, 2022). Due to this, it is essential to determine the evacuation routes to be used as a safe passage in case of natural disasters and to direct the rescue teams and civilians to these routes with road signs or announcements. However, in some cases, especially in disaster situations such as floods that directly affect the traffic network, even if a road or bridge is not closed or damaged, the closure of the network elements on the route to which it is connected may cause that element to lose its function. In this section, bridges that were open across Iowa during different flood scenarios but lost their accessibility due to the surrounding inundated road or bridges are analyzed.

Although a comprehensive analysis is not carried out due to data limitations, it is important to present the effects of flood disasters on the traffic network, especially bridges, from another perspective. In this analysis, we disregard inundated bridges and only focus on non-inundated bridge inventory to evaluate whether the connected transportation network is inundated or not. Our analysis reveals that Pottawattamie, Black Hawk, and Polk counties are particularly vulnerable in the case of inaccessible bridges. Those counties were also identified as having at-risk infrastructure due to the possible bridge inundations. More details about the inaccessible bridge inventory for the state are provided in Figure 11.

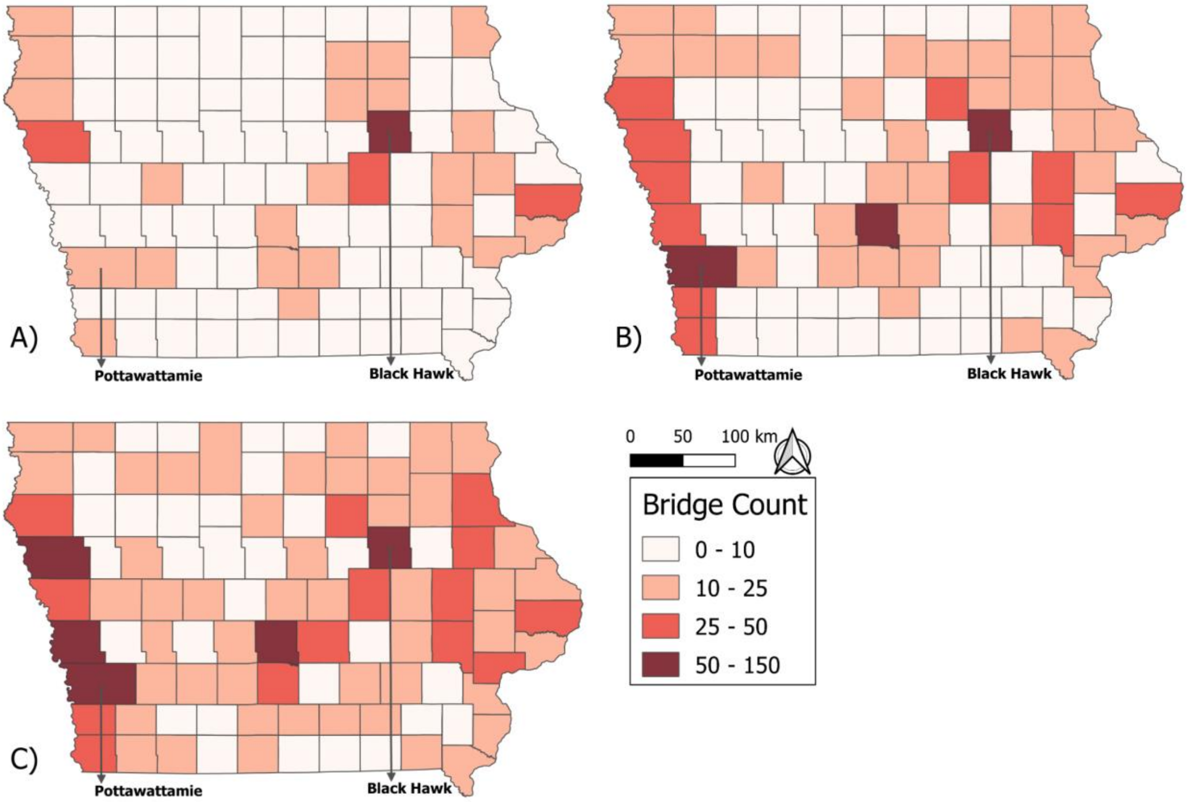

Figure 11. Functional but inaccessible bridge counts for A) 50-year; B) 100-year; C) 500-year flood scenarios

Contrary to other analyses, the western side of the state, especially the counties that are located on the border of Nebraska, is more critical than other regions. While Pottawattamie County is in the top 5 in the number of inaccessible bridges in all flood scenarios, it holds the first place with 121 and 136 inaccessible bridges in 100- and 500-year flood scenarios, respectively. Another critical county, Black Hawk, ranks in the top three for inaccessible bridges in all three flood scenarios and ranks first with 61 inaccessible bridges in the 50-year flood scenario. Another common feature of these two counties is that the open but inaccessible bridge counts in these counties is higher than the number of inundated bridges in all three flood scenarios, and this situation should be comprehensively examined and analyzed in future studies.

4. Conclusion

The study presents a systematic approach, progressing from a high-level overview to in-depth assessments of the impact of floods on Iowa's transportation infrastructure by particularly focusing on bridges. The research initiates by delivering a comprehensive understanding of the statewide flood consequences, followed by detailed analyses of individual bridges, waterways, and traffic disruptions. This structural arrangement facilitates readers' comprehension of the broader flood impact before delving into finer details.

Focusing on the vulnerability of Iowa's bridges, the analysis examines the ratio of inundated bridges, their structural distribution, and the complexities across counties. It emphasizes the importance of considering the inundated bridge ratio in conjunction with absolute counts, particularly due to variations in county bridge totals. The findings underscore the southeastern region's heightened susceptibility in different flood scenarios, while also highlighting specific counties with critical vulnerability, such as Davis, Marion, and Pottawattamie.

The study explores the age distribution and structural conditions of inundated bridges, aiding decision-makers in assessing the resilience of at-risk infrastructure. Furthermore, an evaluation of waterway adequacy reveals crucial insights for evacuation and rescue planning during flooding events. However, the analysis has limitations, such as focusing primarily on structural aspects and neglecting socio-economic and environmental factors that could influence flood impact. The study can be integrated to a data analytics system (Xu et al., 2019; Sit et al., 2021) with real-time mapping capabilities (Li et al., 2022; Li and Demir, 2023) to support informed decision support for small communities.

Additionally, the study does not explore potential adaptation strategies to enhance flood resilience, nor does it consider broader transportation network disruptions beyond bridges. The impact of floods on the accessibility of bridges in Iowa is analyzed, focusing on bridges that remained open but became inaccessible due to surrounding inundated bridges. The analysis identifies vulnerable counties like Pottawattamie, Black Hawk, and Polk, highlighting their susceptibility to inaccessible bridges. Notably, the western side of the state, especially bordering Nebraska, is deemed more critical. These counties have more open but inaccessible bridges than inundated ones, raising the need for further investigation.

In the assessment of traffic impact, the study scrutinizes average daily traffic disruptions and detour lengths caused by bridge closures. It identifies critical counties, like Pottawattamie and Scott, based on average daily traffic disruptions, underscoring their importance in regional transportation networks. The detour length analysis reveals significant disruptions, particularly in the eastern part of the state, impacting fuel consumption and productivity. Overall, the study provides valuable insights into the multifaceted impacts of floods on Iowa's transportation infrastructure, while acknowledging the need for a more comprehensive consideration of socio-economic and environmental factors.

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