A Comprehensive Flood Risk Assessment for Railroad Network: Case Study for Iowa

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Abstract

Climate-induced disasters, particularly floods, pose a substantial risk to human well-being. These risks encompass economic losses, infrastructural damage, disruption of daily life, and potential loss of life. This study focuses on understanding flood risks to critical infrastructure, emphasizing the resilience and reliability of essential services during such disasters. In the United States, the railway network is vital for the distribution of goods and services. This research specifically targets the railway network in Iowa, a state where the impact of flooding on railways has not been extensively studied. We employ comprehensive GIS analysis to assess the vulnerability of the railway network, bridges, rail crossings, and facilities under 100- and 500-year flood scenarios at the state level. Additionally, we conduct a detailed investigation into the most flood-affected counties, focusing on the susceptibility of railway bridges. Our state-wide analysis reveals that in a 100-year flood scenario, up to 9% of railroads, 8% of rail crossings, 58% of bridges, and 6% of facilities are impacted. In a 500-year flood scenario, these figures increase to 16%, 14%, 61%, and 13%, respectively. Further, our secondary analysis using flood depth maps indicates that approximately half of the railway bridges in the flood zones of the studied counties could become non-functional in both flood scenarios. These findings are crucial for developing effective disaster risk management plans and strategies, ensuring adequate preparedness for climate change impacts on railway infrastructure.

Keywords: flood, railroad network, railway, flood risk assessment, flood vulnerability

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1. Introduction

Climate-induced hazards, including hurricanes and floods, significantly threaten various societal aspects. These events frequently lead to loss of life, substantial economic losses, infrastructure damage, and disruptions to daily life (Bell et al., 2018). The impacts of these disasters are expected to intensify due to climate change and land-use changes (Pfahl et al., 2017). Rentschler et al. (2022) demonstrate that factors such as population growth, economic development, climate change, and land subsidence are exacerbating flood losses in the world's 136 largest coastal cities. While the estimated average annual cost of flood damage stood at $6 billion in 2005, it is projected to surge beyond $60 billion by 2050 (Rentschler et al., 2022). Understanding the potential ramifications of these natural disasters is crucial. Identifying regions at risk is imperative for implementing measures to mitigate public safety risks, as highlighted by Yildirim et al. (2022).

Decision-makers regularly need to assess the history of the vulnerable sites to determine the level of risk and potential losses (Haltas et al., 2021). They also conduct risk impact analyses to assess potential mitigation options (Yildirim and Demir, 2021). Furthermore, structural or non-structural mitigation options can be evaluated to secure welfare and minimize losses (Alabbad et al., 2023; Yildirim and Demir, 2022). This proactive approach allows for the implementation of targeted protective measures, strategic location choices, and robust emergency response plans, ultimately safeguarding communities and minimizing the cascading disruptions that can result from infrastructure failures during flood events.

In order to ensure the resilience and dependability of critical services during disasters, it is crucial to understand the flood risk to critical infrastructure. The railroad network, a crucial component of delivering goods and services in the United States, is one of those infrastructures. The primary freight and passenger rail network in the US comprises about 140,000 miles in 49 states and serves various sectors of the economy such as agriculture, industrial, wholesale, retail, and manufacturing (AAA, 2022; Chinowsky et al., 2019). The role of the Iowa rail system, a major hub for railway traffic, is to connect Iowa shippers and buyers to markets in the North, in and out of the country (Iowa DOT, 2021). Although freight transport comprises the majority, AMTRAK, which carries passengers, also provides service in the state. Therefore, it becomes vital to assess the railroad network's vulnerability during flooding to maintain services.

One of the pillars of a thriving economy is reliable transportation infrastructure, which provides access to social services, employment opportunities, and marketplaces (Koks et al., 2019; Limao & Venables, 2001). As an example, railway infrastructure is essential for providing both freight and passenger transportation, which enhances social and economic welfare (Kellerman et al., 2015). Besides, railroads play a crucial role in guaranteeing that emergency responders are well-equipped with the essential resources and information to manage hazardous material incidents efficiently (AAA, 2023). They collaborate by sharing resources and information and providing staff and equipment to assist in containing incidents, safeguarding public health and the environment, addressing any negative effects, and ultimately restoring safe operations as part of their comprehensive planning, risk reduction, and response endeavors (AAA, 2023). However, there is a risk that the reliability of railroad networks can be considerably hampered by riverine flooding, which can also seriously disrupt and cause structural damage (Kellerman et al., 2016). Therefore, future urban risk management must address the rail transportation systems' greater sensitivity to flood risk brought on by climate change (Gonzva et al., 2015).

Flooding events can occur for several reasons, such as heavy rainfall, rising sea levels, snow or ice melt, and they can damage structures of railway networks like buildings, bridges, rails, and overhead lines. Each of these potential damages provide an environment for discussion of evaluation, maintenance, and repair costs. Thus, any significant interruption in rail service always attracts attention from the public and puts further pressure on the political and administrative establishment (Hamarat et al., 2021). Furthermore, since railroads are less spatially flexible than other modes of land transportation, they are more susceptible to flooding (Changnon, 2009). For these reasons, rail systems rank among the most crucial infrastructures to protect against major flooding (Bubeck, 2019).

Iowa is one of the most vulnerable states and has experienced several major flood events in the United States (FEMA, 2023a; Cikmaz et al., 2023). The state is also in the top ten federal grant assistance beneficiaries, which is primarily due to flood events (FEMA, 2023b). Historically, floods in the Midwest during 1922, 1991 (Eash & Koppensteiner, 1996), 2008 (Zogg, 2014; Changnon, 2009), and 2019 (Flanagan et al., 2019) severely damaged railroads and disrupted train movement, and Iowa's rail network had also been affected by these floods. Figure 1 demonstrates that one of the railroad bridges in downtown Waterloo, Iowa, was partially swept away by Cedar River floodwaters on June 10, 2008 (Zogg, 2014). According to Changnon (2009), the 2008 flood caused the railroads in the Midwest substantial damage and costs as well. On the Iowa side, six rail bridges and three train wrecks were destroyed or badly damaged; additionally, 24 rail lines were closed in total.

Figure 1. Photo by The Waterloo-Cedar Falls Courier. (Zogg, 2014)

Although the consequences of floods cause serious economic losses, there are a limited number of rail flood risk assessments in the literature using the methods and methodologies suggested in damage assessment studies during and after floods at spatial scales. Nonetheless, using historical data and a Geographic Information System (GIS) analysis, Hong et al. (2015) suggested a thorough technique to statistically evaluate the railway system's vulnerability to floods for the Chinese railway system. In 2015, Kellermann et al. proposed the Railway Infrastructure Loss (RAIL) model, which is for the railway transportation sector, by developing a flood damage model for the estimation of both structural damage to railway infrastructure and incurred direct economic losses. Kellermann’s methodology is based on data collected during and after past flood events (Kellermann et al., 2015; 2016). This methodology was applied to the Austrian Northern Railway and Mur River catchment areas, respectively. Bubeck et al. (2019) utilized the same method for the European railway network. Despite previous research efforts, a comprehensive analysis of railway assessments during flooding remains limited and needs more attention, especially in light of the challenges posed by climate change (Tanir et al., 2024).

Specifically, even though railroads in Iowa play an essential role in the state's economy and the region's ability to compete on the global stage (Iowa Rail Toolkit, 2019), the state is lacking a thorough examination of the rail network's vulnerability to flooding. Many existing studies on small- and large-scale flood disaster risk models have predominantly focused on damaged buildings, affected populations, or road networks. (Alabbad & Demir, 2022; 2023). To the best of our knowledge, this is the first Iowa-wide assessment of future flood risk to railway infrastructure.

This research aims to assess the impact of flood risk on the railroad network in Iowa by performing state-level analyses of railroads, railroad bridges, intersections of railroads, and public roads, as well as some county-level analyses using floods of 100- and 500-year return periods. The study outcomes on the assessment of future flood risk for rail infrastructure can help develop policies and plans for effective disaster risk management and adequate preparedness for climate change. At the same time, the results obtained from the study can be used to identify which locations are risky and need prioritized transportation investments and resources to reduce the risk of flooding.

The organization of the article is as follows: The materials and methods applied in this article are provided in Section 2. Section 3 presents and discusses the results regarding 100- and 500-year flood risks to railway infrastructure in Iowa. Section 4 concludes the investigation of our findings regarding assessing and managing flood risk for railroads in Iowa.

2. Materials and Methods

This research delved into examining how railroads are impacted by flooding at both the state and county levels. By considering the extent of the flood, we were able to assess a specific geographical area and pinpoint areas where rail transportation is vulnerable to flooding. Figure 2 illustrates the various elements of the analysis conducted to assess the railways’ vulnerability to flooding.

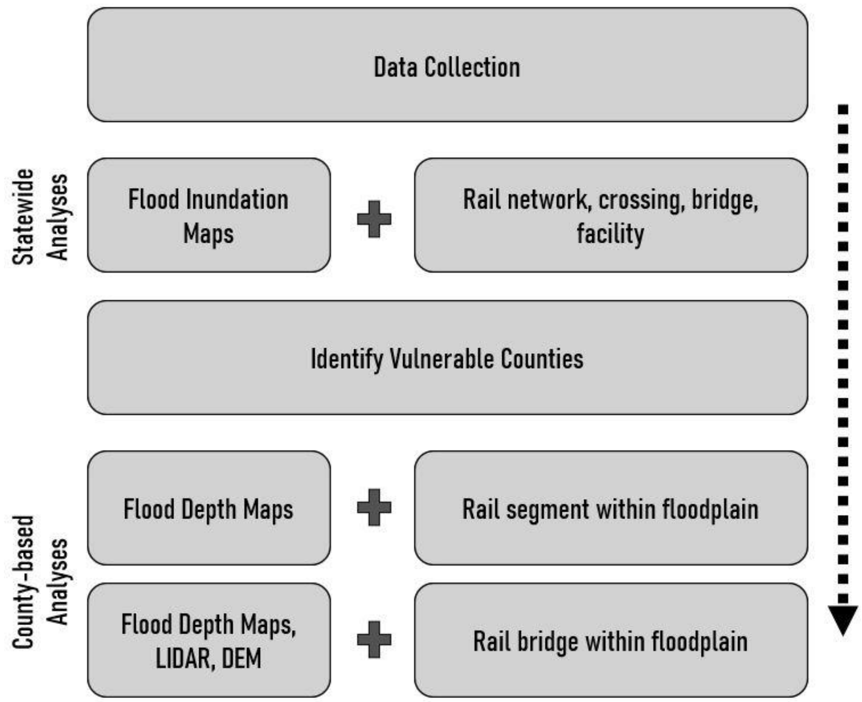

Figure 2. Overall workflow of the flood impact assessment on Iowa rail

2.1. Data Collection

This study utilizes various datasets by acquiring publicly available data sources and requesting Iowa Department of Transportation (Iowa DOT). Information about the origin, content, and format of each data set used in this research is explained below. Using these datasets, we aim to provide a comprehensive understanding of the impact of floods on freight and passenger services in Iowa.

Flood Inundation Map: After the devastating 2008 flood in the state of Iowa, the Iowa Flood Center has been established to develop advanced tools and provide resources for better flood management, including creating 2- and 3-D flood models for various return period scenarios (i.e., 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year) (Gilles et al., 2012). These floodplain maps were generated by analyzing the hydrologic and hydraulic characteristics of basins and streams, employing high-resolution input data such as a 1-meter digital elevation model, and utilizing MIKE FLOOD and HEC-RAS software. Access to the generated flood inundation maps is available through the Iowa Flood Information System (IFIS, Demir and Krajewski, 2013). While comprehensive flood map models are critical for this study, data-driven approaches for flood map generation (Li and Demir, 2022; 2024) can be used for resource constraint communities.

Railroad Network: The Iowa DOT data is the main source for the rail networks and relevant information. Data covering the last 10 years of railroad data includes current active rail lines, abandoned rail lines, and historic rail lines for the State of Iowa. However, at the analysis stage, only actively used railways were taken as a basis in order to be up-to-date and consistent. The total active rail length in Iowa is 11,927 kilometers.

Railroad Crossings: It presents the location of the intersection of railway and public roads, and its data type is a point geometry. The feature class contains rail crossing information, and it was generated using the Federal Railroad Administration's (FRA) US DOT Crossing Inventory Form 6180.71 (Iowa DOT, 2020). Nonetheless, the data include all railway crossings that can be at road level, under the road, or over the road. If the rail crossing is over the road, it will not be affected by the flood. For that reason, we eliminated this crossing class from the open attribute table based on FRA's data entry field description report. Eventually, the number of crossings in Iowa that are road-level and under the road was found to be 5,503.

Rail Bridge: Railroad bridges are collected from Homeland Infrastructure Foundation-Level Data (HIFLD, 2023). These bridges are represented as point geometry and include the intersections of railroads with roads, waterways, and other railroads. There are 2,652 rail bridges located statewide.

Rail Facilities: The Iowa DOT provided information on several rail facility types, namely warehouses, grain facilities, and transload facilities. A warehouse is a type of commercial building used for storing commodities, which can be anything from raw materials to packing supplies to spare parts to finished products used in manufacturing and production. The purpose of grain storage facilities is to store grain like warehouses, and they must have either a state or federal license. Lastly, a transload facility is where bulk freight shipments are transferred from a truck or container in one mode to another at a terminal interchange point. In total, Iowa has 14 warehouses, 324 state- and federally licensed grain facilities, and 46 transload facilities.

Digital Elevation Model (DEM): This dataset contains a digital elevation model (DEM) of the geographical surface of Iowa (Iowa Geodata, 2020). The DEM has a 3-meter horizontal resolution and was created by combining one-meter-resolution elevation data acquired by Iowa's LiDAR program between 2007 and 2010. Under predetermined standards, the Iowa Light Detection and Ranging (LiDAR) Project (GeoTREE, 2007) gathers position and elevation (X, Y, and Z) data for the entire state of Iowa. The data is cleaned to remove any man-made structures and tree cover to display bare earth. In Iowa, the highest elevation point, Hawkeye Point, is about 510 meters, whereas the lowest elevation point, the Mississippi River, is 146 meters (USGS, 2023).

2.2. Case Study

The study is carried out on the rail network in Iowa, which consists of a total of 99 counties located in the Midwest region of the United States. It is the only state that is bordered by two major streams: the Missouri River to the west and the Mississippi River to the east. Furthermore, Iowa has a history of recurrent flood events that have caused significant damage to infrastructure, crops, and human life during the past two decades (Alabbad & Demir, 2022).

According to rail infrastructure information (Iowa DOT, n.d.), there are 18 freight railroad companies that run 3,825 miles of track in Iowa. These railroads are divided into 4 classes: Class 1, regional, short line, and tourist railroads. Eighty-three percent of Iowa's total route miles, including most of its grain collection network, are covered by Class 1. It also has a passenger rail line called AMTRAK that runs east and west through the southern part of Iowa (see Figure 3).

This line includes two different AMTRAK routes and has a total of six stations. However, these stations do not pass through big cities such as Des Moines, Iowa City, and Cedar Rapids. In addition to them, from the rail line data provided by the Iowa DOT, we can access the building information of networks which shows that the rail networks were built between 1855 and 2003.

Figure 3. Passenger and freight railway network in the State of Iowa.

2.3. Flood Impact Assessment on Iowa Railroads

This section presents the methods used to assess the impact of the 100- and 500-year floods on the railway system using the data we have described above. Analyses were carried out at the state and then county levels using geospatial analytical software such as Quantum Geographic Information System (QGIS) and ArcGIS Pro. The data has three different types of geometric structures and raster images. Among the geometric data, flood inundation maps, which illustrate the extent of the flooding, have polygon geometry, whereas the rail network data has line structure. Rail crossings, nodes, rail bridges, and rail facilities are presented as point geometry. Besides, flood depth, LIDAR, and DEM data are stored as raster data.

Graph theory has been beneficial in the analysis of transportation networks (Alabbad et al., 2021). In this theory, a graph *(G)* is represented as $G = \{N, E\}$ and it consists of vertices *(N)*, referred to as nodes or points, connected by edges *(E)*, also described as links or lines. In this research, we looked at the path length exposure for flood probabilities of 1% and 0.2%. For all railways, we identify segments to be affected by overlaying flood maps on railway networks using the intersection tool in QGIS. It is assumed to be closed if the rail section partially or completely intersects the floodplain. In addition, considering the theory that bridges (vertices) connect the railway networks segments (edges) to each other, additional data at the county level is used to calculate the flood depths on a particular railway bridge and examine whether that bridge is inundated. In our analysis, a railway bridge is considered inaccessible and submerged if it is connected to fully flooded roads.

2.3.1. State-wide Analysis

In the first part of the study, a statewide analysis is conducted by utilizing flood inundation maps intersecting with the rail network, crossings, bridges, and facilities. For the rail crossing, bridges, and facility analysis, we have identified the inundated points by overlapping 100- and 500-year polygon layers from the intersection algorithm in the ArcGIS Pro software. As the next step, using point counts in a polygon as one of the analysis tools, we calculated the total number of these point geometries that will be affected by the flood in each district.

Similar to point analysis, the railway network analysis is combined with the railway layer and flood inundation maps using the intersection algorithm. We aimed to show the ways in which infrastructure will be directly affected. However, since the rail networks are connected to each other, the flood that will occur in a small place will also affect the remaining lines, according to graph theory. Since the data is too large to be broken down into separate segments, the percentage and overall length of submerged rail segments are computed by utilizing a field calculator tool in QGIS based on 99 counties in the state of Iowa.

2.3.2. County-based Analysis

Following, a comprehensive county-based analysis is performed using flood depth information for three counties. These counties are Pottawatomie, Harrison, and Linn, which are the top three impacted counties depending on railroad length. At this stage, two separate analyses are carried out. First, the flood depth information of the railways within the floodplain in these areas has been examined. Another method is a three-dimensional analysis used by Alabbad et al. (2021) and Mount et al. (2019), calculating how many railway bridges will be inundated. To assess the condition of rail bridges during flooding, the LiDAR dataset is first used to determine the elevation of the bridges. To calculate inundation, the bridge elevation is compared to the combined digital elevation model (DEM) of the bare earth as well as the flood depth at a particular bridge position.

The bridge is considered inundated if its elevation is less than the total elevation of the DEM and the flood depth. It should be noted that there are some stages before using this methodology. Firstly, bridges over waterways were selected from the dataset. We identified that certain bridge locations were not aligned with the railways. To address this, we utilized Google Satellite Maps within ArcGIS to accurately realign the bridge points to the center of the railway. Then, after obtaining the lidar, elevation, and flood depth information at the locations of those bridges, the three-dimensional analysis was applied.

3. Results and Discussion

This section presents the results of the flood impact assessment on a comprehensive case study and discusses these results. In section 3.1, state-wide analysis results utilizing flood inundation data are given and discussed, while section 3.2 covers the result of the analysis of most impacted three counties using primarily flood depth data.

3.1. State-wide Analysis Results

Table 1 summarizes the rail components that were flooded in the state of Iowa during the 100- and 500-year flood scenarios. Our analysis reveals that up to 15% of Iowa railroads are at risk of flooding. This ratio is approximately the same at the intersection of public roads and railroads, and facilities such as rail warehouses. Considering the railway bridges, the result shows that they can be exposed to flooding up to 60%, but this rate is only according to the extent of the flood. According to the county-based flood depth analysis that we conducted in the next stage, this rate decreases, but still, flooding will cut off the accessibility of the bridges to a great extent. The ratios mentioned are calculated by dividing the exposed elements in every county by the ratio of the total element counts. This means that equal importance is given to all of them, regardless of whether they are small or overpopulated counties.

Table 1. Summary of rail elements exposed to flooding in Iowa State

Flood Scenario	Railroad Length (km)	# of Railroad Crossings	# of Rail Bridges	# of Rail Facilities
Baseline	11,927	5,503	2,652	384
100-yr flood	1,040	437	1,551	23
500-yr flood	1,952	793	1,622	51

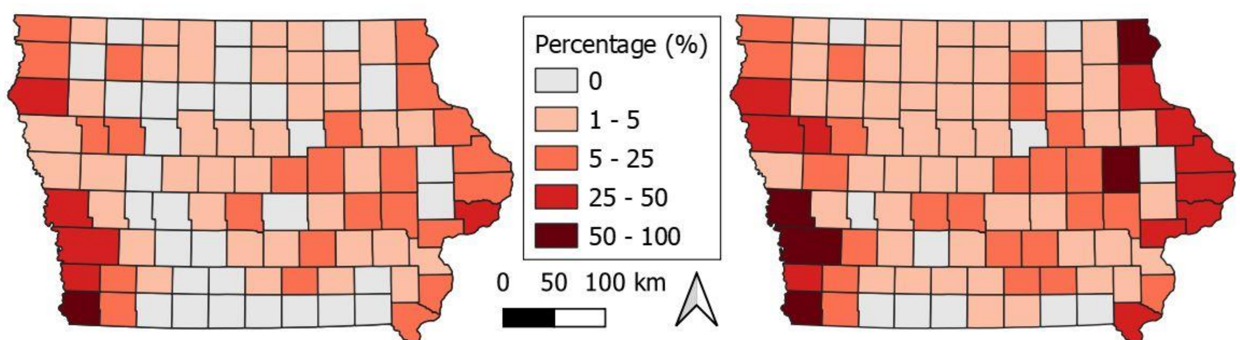

Figure 4. The percentage of inundated railroad length per county during 100-yr (a) and 500-yr (b) flood scenarios.

Figure 4 shows the percentage of impacted railway length per county during the 100- and 500-year floods. The railroad length was evaluated instead of the number of railroad segments in order to analyze the direct effect of flooding on the railroad. Considering the length of the railway that will be affected is an essential factor in estimating reconstruction or repair costs. Briefly, we calculated the inundated railroad length within each county and extracted the county damage percentage (Figure 4). Most counties have damage levels of up to 5%. Moreover, under the 100-

year flood event, Fremont County, located in the lower-left corner of the Iowa boundary, would be experiencing major inundated railways exceeding 50% of its railway length, while under the 500-year flood, four more counties (Pottawatomie, Harrison, Linn, and Allamakee) are impacted by that percentage. In general, it has been concluded that some counties, such as Pottawattamie, Mills, Plymouth, and Harrison, which are located along the Missouri River, as well as every other county along the Mississippi River, except Louisa, will suffer remarkable rail damage (5–50%). On the other hand, there are a few counties that have zero percent damage. This means that either the railway network does not pass through those counties, or the railways do not overlap with the flood extent in both scenarios.

Table 2. Top 15 counties based on impacted railroad length (km) sorted by 500-year.

County	**Crossover**		**Main**		**Siding**		**Spur**		**Turnout**		**Yard**		**Total**		
	100	500	100	500	100	500	100	500	100	500	100	500	100	500	All
Pottawattamie	0.6	0.6	68.7	108.0	9.3	10.4	28.2	33.7	1.4	1.5	101.4	144.5	209.6	298.7	445.0
Linn	-	0.8	24.3	56.3	1.1	2.3	12.1	23.4	0.6	1.4	34.1	83.3	72.5	167.5	335.6
Harrison	-	-	63.4	98.3	0.9	1.9	-	-	1.9	5.2	5.9	10.8	72.4	116.6	231.7
Scott	-	-	23.1	42.6	2.4	8.2	1.6	2.2	-	-	25.5	30.2	52.6	83.1	177.3
Lee	-	-	16.9	35.6	-	-	0.5	1.2	-	-	29.8	39.6	47.6	76.9	196.7
Polk	-	-	28.8	40.6	1.7	2.8	10.3	12.8	0.7	1.1	13.8	13.8	55.6	71.4	309.3
Plymouth	-	-	39.4	64.5	2.7	3.7	-	-	-	-	-	-	42.2	68.8	166.8
Allamakee	-	-	10.5	62.1	-	2.8	-	-	-	-	-	-	10.5	65.3	71.8
Clinton	-	-	20.2	41.5	1.9	4.0	-	3.3	-	-	2.0	14.0	24.3	62.8	238.0
Dubuque	-	-	9.1	34.2	0.6	1.3	-	7.4	-	-	-	19.0	10.0	62.0	145.2
Woodbury	-	-	1.5	16.7	-	0.7	-	13.2	-	1.0	-	28.8	1.8	60.8	193.0
Mills	-	-	40.2	45.1	3.0	3.1	-	-	4.1	4.1	3.3	3.3	50.9	55.9	122.4
Fremont	-	-	37.8	38.1	8.2	8.2	3.6	3.7	1.2	1.2	-	-	51.0	51.3	57.1
Clayton	-	-	7.9	35.8	1.3	3.0	0.8	0.8	0.8	0.8	0.5	5.0	11.3	45.4	108.2
Muscatine	-	-	9.8	21.8	3.1	4.9	2.6	8.0	-	-	-	4.4	15.5	39.1	156.1

According to the Iowa Rail Toolkit (Iowa DOT, 2023), a total of six railway class groups derived from the data can be briefly explained as follows:

Main: The primary railway route where uninterrupted train travel occurs between terminals and rail yards within the rail network.

Turnout: A configuration of tracks that allows a train to change its path from one track to another.

Crossover: A relatively brief section of track that redirects train traffic from one parallel line to another.

Siding: A brief additional track connected to the main track at both ends using turnouts, allowing trains to meet or pass. It runs parallel to the main route.

Spur (or stub in): A shorter, often dead-end portion of track constructed to provide specific facilities like loading and unloading ramps access to the main or secondary line. It can also serve as temporary storage.

Yard: A network of supplementary tracks is used for tasks such as organizing railroad cars based on their cargo or destination, assembling trains, storing cars, or conducting equipment repairs.

Although Fremont County has a high flood risk in both flood scenarios, looking at only percentages, Pottawattamie County ranks first when we look at the length of railroads that will be affected by flooding. Table 2 summarizes the information for the top 15 counties based on length of the railway that will be affected by the flood with different railroad type classification. At the same time, this table gives the total length of the railroad network for each of these impacted counties in the last column. The range of total impacted length during the 100- and 500-year flood events for the studied counties fluctuated from 10 to 209 km and 39 to 299 km, respectively. During a 500-year flood event, the total impacted length increased dramatically, often doubling or even exceeding the impacted length observed during 100-year flood events, as seen in areas such as Linn, Clinton, and Dubuque. Among the top 15 counties affected, the main class is the railway type that every county will be inundated with, with a range of 8–108 km. In contrast, the crossover class comes out as less vulnerable to flooding.

Additionally, we estimated the total length affected and the percentage of affected segments across the state by rail type (Table 3). The state of Iowa is overall threatened with losses of up to approximately 8% and 16%, respectively, in 100- and 500-year flood events, and the class most affected during these two floods is the "main" class in terms of road length, while the "yard" class has the highest share when we look at their percentages.

Based on Tables 2 and 3, as well as the description of railway types given above, it can be interpreted that two railway tracks, which are essential in terms of being main and complementary tracks, will be interrupted in the event of a flood. In particular, a class of yard that has the function of repair and maintenance should normally be a railway line that should be least affected in an emergency situation. Therefore, when we examine these results, it can be concluded that there is a deficiency in this regard.

Table 3. Impacted railroad length (km) for different railroad types sorted by the total length.

Railroad Types	**100-yr**	**Percentage**	**500-yr**	**Percentage**	**Total Length**
Main	658.9	4.97%	1,289.0	9.73%	13,247.5
Yard	245.2	19.35%	431.2	34.04%	1,266.9
Siding	50.4	6.57%	82.4	10.75%	766.7
Spur	72.8	10.90%	127.7	19.12%	667.8
Turnout	11.7	14.64%	19.3	24.14%	79.9
Crossover	1.3	9.90%	2.4	18.24%	13.2

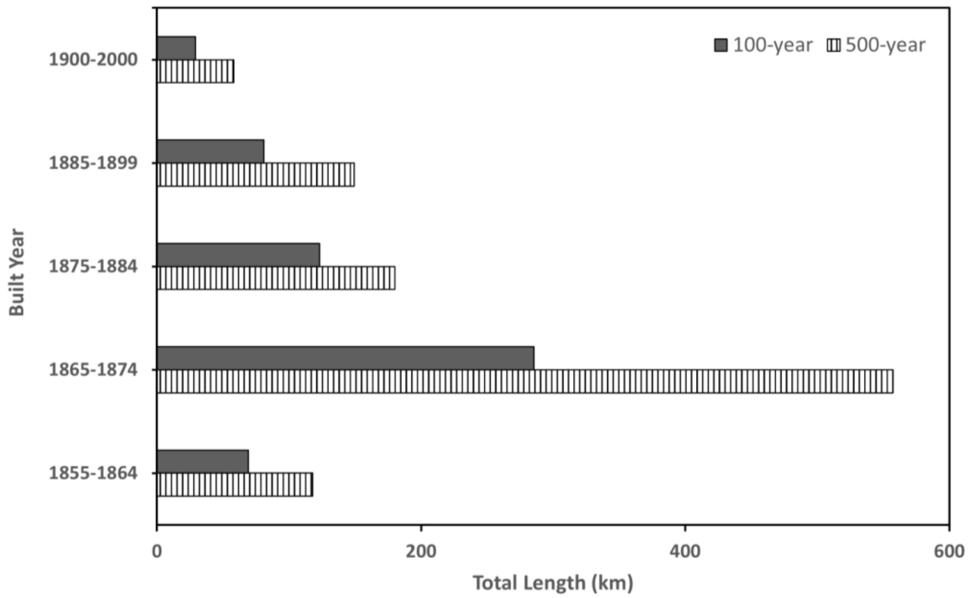

Figure 5. The total inundated railroad length in Iowa sorted by built year.

In Figure 5, we have investigated the total inundated length over the entire state while considering the year of construction. Relying on the rail-built-year information provided by the Iowa DOT, railroads that will be inundated during 100- and 500-year flood scenarios are relatively older built railroads. In Iowa, the first railroad was built in 1855, and the railroad lengths that are expected to be most affected in both 100 and 500-year flood scenarios were built between 1865 and 1874 with an estimated length of 285 km and 557 km, respectively. That could potentially be attributed to the oversight of not factoring in flood scenarios during the construction of these older railways. We also noticed that the length of the railway impacted by a 500-year flood is almost twice the length impacted by a 100-year flood, for each construction period. On the other hand, the railroad lengths that are expected to be the least affected in both scenarios are the recent railways made in 1900 and 2000. From these findings, it can be stated that the railways built in recent years were built considering the flood risk.

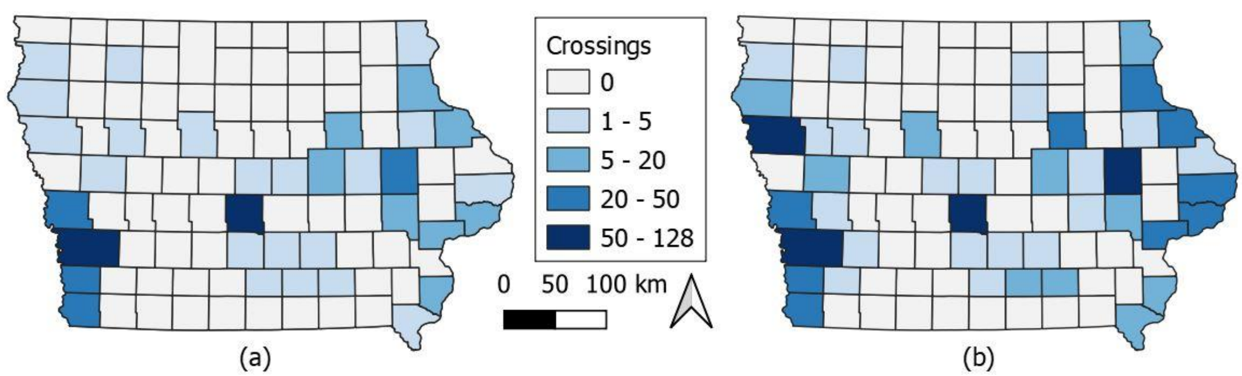

Figure 6. The number of impacted crossings between the railroad and public road per county during 100-yr (a) and 500-yr (b) flood scenario.

The railway system is linked to land transportation. Disruption in one place on the railway will also affect the public-use road connected to that road. Figure 6 demonstrates the number of impacted crossings between the railroad and public road per county. According to results, while Polk and Pottawatomie counties have the highest crossings inundated due to the 100-year flood, Linn and Woodbury counties will share the same range between 50 and 128 crossings with others in the 500-year flood scenario. It means that crossings in most counties are out of the hazard area.

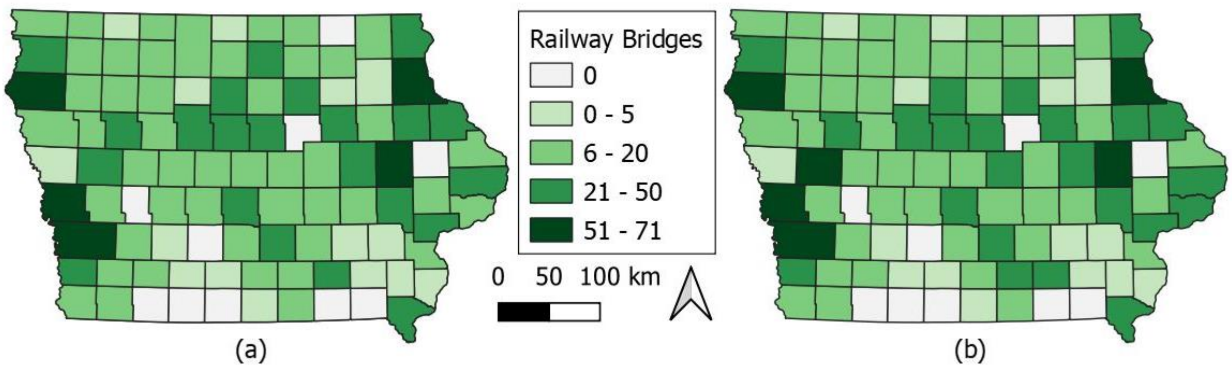

Figure 7. The number of railway bridges within the floodplain per county during 100-yr (a) and 500-yr (b) flood scenario.

A railway bridge is a specially constructed structure to carry the rail traffic flow across an obstacle, including rivers (Pipinato, 2022). However, flooding can cut off access to bridges and create challenges to freight and passenger transport. Figure 7 gives information about the number of railway bridges within the 100 and 500-year flood zones. A total of 87 counties in Iowa have railroad bridges within the two flood extents. It has been found that the highest number of 66 (100-year) and 71 (500-year) railway bridges within the floodplain were in Plymouth County, and some western and eastern counties have a major share. Linn County, where there is a large city like Cedar Rapids, also has a high number of railway bridges in flood zones.

However, it should be noted that these results were created using only 100- and 500-year flood maps, so we cannot say that all these affected bridges will be inundated during the flood. Nonetheless, our analysis can provide a comprehensive examination of rail bridges, enabling the identification of counties that may be susceptible to the inundation of rail bridges. Additional data, such as flood depth, is needed for bridge closure information, and the analysis on this subject is explained in more detail in the next part.

When we compare the Iowa DOT's railway facility locations with the 100- and 500-year flood maps, it appears that some of the storage facilities would be affected by flood scenarios, and Table 4 summarizes that analysis. When we evaluate the percentage of facilities that will be inundated in general, it can be said that there will not be a major loss. Almost every flood probability scenario is below 30%, even in the 100-year scenario, it has been revealed that no warehouse will be affected. Yet, when we evaluate the facilities' capacity and their location information that will be affected by the flood, the losses will be high and this may seriously affect other cities, perhaps even other states. For instance, among the grain facilities, the city that will suffer the most damage storage capacity is Hamburg (Fremont County) with 10,238 bushels. The second most damaged city is Council Bluffs, Pottawattamie County with a total storage capacity of 8,210 bushels, and Davenport (Scott County) will be ranked third city with 4,795 bushels of storage capacity.

Table 4. Rail facilities within floodplain

	Warehouse		**Federal Grain**		**State Grain**		**Transload Facility**	
	100yr	500yr	100yr	500yr	100yr	500yr	100yr	500yr
Inundated	0 (-%)	4 (29%)	13 (6%)	24 (12%)	5 (4%)	11 (9%)	5 (11%)	12 (26%)
Total	14		206		118		46	

3.2. County-based Analysis Results

In this section, depending on statewide analyses, the top 3 vulnerable counties, namely Harrison, Linn, and Pottawattamie County, were selected to carry out a detailed analysis using the flood depth maps as additional data because the standard approach for estimating the cost of flood damage usually relies on flood depth as the primary measure of the extent of damage severity (de Moel, 2012; Gerl et al., 2016; Koket et al., 2004; Wagenaar et al., 2016; Martello et al., 2023).

The classification of rail lengths according to flood depth originated from Bubeck et al. (2019) study that used the RAIL method for the railway network in Europe. From those methodologies, flood damage classification begins with classification of the first damage class when floodwater levels reach up to 20 cm along the track portion. In the standard framework, the second damage class pertains to water heights ranging from 21 to 140 cm, while the third damage class is designated for water levels over 140 cm.

Table 5. Affected railway length (km) for the top three counties within the floodplain for different damage classes (cm).

	100-yr Flood Scenario			**500-yr Flood Scenario**		
County	**<20 cm**	**20-140 cm**	**>140 cm**	**<20 cm**	**20-140 cm**	**>140 cm**
Pottawattamie	66.5	135.0	8.1	6.9	175.2	118.2
Linn	18.7	47.3	6.5	22.2	108.2	37.1
Harrison	16.3	53.5	2.5	12.7	86.8	16.0

In Table 5, we assessed the various damage classes and their potential impact on railway lengths. Our analysis indicates that the second damage class predominates in both considered scenarios, representing the most significant share compared to other classes. Notably, while the low damage class ranks as the second most impactful in the 100-year scenario, it falls to third in the 500-year scenario. A closer examination of the second and third damage classes, which are more prone to severe impacts, reveals that Pottawatomie County exhibits the highest rate of rail length among the three counties analyzed. Consequently, given its leading position in terms of rail length, repair costs in Pottawattamie are anticipated to be substantial. These findings provide a realistic basis for estimating repair costs associated with damage. While quantifying the risk of damage is essential, identifying the precise locations of highest risk remains a challenge, and this aspect could not be meaningfully addressed in our study.

Table 6. Railway bridges in the top 3 impacted counties

		# of Bridges in Floodplain		**# of Inundated Bridges**	
County Name	**# of Bridges**	**100-yr**	**500-yr**	**100-yr**	**500-yr**
Pottawattamie	97	59 (61%)	64 (66%)	29 (30%)	37 (38%)
Linn	72	18 (25%)	36 (50%)	0 (0%)	12 (17%)
Harrison	82	56 (68%)	63 (77%)	27 (33%)	39 (48%)

According to one of the Iowa DOT (2008), some railway companies commonly adopt a practice where they place loaded train carriages on specific bridges when there is high water. This is for increasing the bridge's stability by adding extra dense materials such as rocks, ballast, scrap metal, or other heavy and non-reactive substances. In order to identify the location of these bridges, it is important to know which bridges will be inundated, and which will be open.

Table 6 shows how many railway bridges would be in floodplains and inundated based on 100- and 500-year scenarios for the top 3 impacted counties. Even though almost more than half of the bridges seem to be in the floodplain in both scenarios, the rate of bridges to be closed is less than 50% according to the method used in this research. Nonetheless, it should be noted that about half of the bridges in the flood zone will become non-functional. It has been noticed that the railway bridges in Pottawattamie and Harrison counties will be affected more than Linn County. Especially in Pottawattamie and Harrison, it was concluded that 30–50% of the rail bridges would be inundated in both flood scenarios.

4. Conclusion

This research aims to analyze the railway network, railway bridges, rail crossings, and facilities by using 100 (1% chance) and 500 (0.2% chance) year flood return periods at the state and county levels utilizing spatial analytical software (i.e., GIS). Also, the three most affected counties (Pottawattamie, Linn, and Harrison) were selected to carry out more detailed investigations using flood depth maps. The results of the statewide analysis table demonstrate that during 100-year flooding, the percentage of affected rail length, rail crossings, bridges, and facilities could be 9%, 8%, 58%, and 6%, respectively. On the other side, during a 500-yr flood scenario, these results could reach up to 16%, 14%, 61%, and 13%, respectively. As a major outcome, main and yard railroad types, which are vital in terms of being the primary and complementary lines, would be most affected in terms of percentage and rail length. In addition, in the second analysis stage using the depth maps, we observed that in both scenarios, the affected railways in the top 3 counties would suffer mostly second-class damage, and about half of the railway bridges in the flood region would become submerged.

This study faces challenges and uncertainties, and consequently, there is a demand for future research. This research is based on publicly available data, which we cannot rely on to be up to date since many studies cannot afford commercial data sources. There is an opportunity in remote sensing based imagery for flood map extraction (Li and Demir, 2023) and reduce cost on advanced modeling studies. On the other hand, another issue arises from the lack of data collection and analysis on economic and physical losses required for the calibration and validation of our damage models. Presently, such damage and repair information are not gathered in the majority of counties, nor at the state level, in the US. A systematic effort to collect knowledge on damage to railway infrastructure can make a significant contribution to how natural processes damage railway infrastructure, the relative contribution of various natural hazards to total economic losses, and the improvement of strategic risk management.

Our models in the evaluation of future flood risk to railway infrastructure are crucial for the creation of efficient disaster risk management and sufficient preparation for coping with climate change. In other words, it has the potential to assist specific stakeholders in pinpointing regions of vulnerability and guaranteeing a fair allocation of investments and resources for flood mitigation (Alabbad et al., 2022) initiatives (e.g., flood barriers) within the railroad infrastructure industry. However, as there are some limitations in data and studies parameters, this research could be extended to delve deeper into the factors that make areas vulnerable to flooding and to calculate the repair and freight and passenger cargo loss costs of damaged rail segments.

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