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Article

Comprehensive Assessment of Flood Risk and Vulnerability for Essential Facilities: Iowa Case Study

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Abstract: In this study, nine different types of essential facilities in the state of Iowa (such as hospitals, fire stations, schools, etc.) were analyzed on a county level in terms of flood depth, functionality and restoration time after flooding, and damage sustained during flooding. These essential facilities were also analyzed on the state level in terms of their location relative to the 100 y and 500 y flood zones. Results show that the number of essential facilities within the flood extent reached up to 39%, and during the 100 y flood scenario all but one of the six chosen counties lost functionality of 100% of their facilities. Most essential facilities were found to have a flood depth of 1 to 4 ft deep and a restoration time of 480 days. The purpose of this study is to bring awareness to decisionmakers regarding the risk that flooding events pose to essential facilities and to highlight the increasing dangers of flooding on a broader scale. This study will be beneficial to improve mitigation strategies, emergency response plans, and ensuring that emergency services and facilities are available in the event of future floods for the affected areas.

Keywords: floods; flood vulnerability; risk assessment; flood damage; essential facilities; facilities

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1. Introduction

In recent years, the frequency and impact of natural disasters has risen significantly on a global scale [1]. One of the more prevalent of these natural disasters is flood events, as they can leave a great amount of destruction in their wake, affecting not only people and their homes [2], but infrastructure and the surrounding environment as a whole [3,4]. There are many factors that have made flood events more dangerous over the last decades, such as climate change and urban development [5,6]. The United States alone has seen a rise in damages due to flooding, averaging USD 7.96 billion per year from 1985 to 2014 [7]. Additionally, floods may also begin to occur in regions where they might not have before [7–9], and, as such, more city officials and stakeholders need to be made aware of the risk to their communities so they might implement flood mitigation and emergency response strategies accordingly [10].

While drowning accounts for a large portion of deaths caused by flooding, it is not the only way that floods can be deadly. Floods can also lead to deaths caused by physical injury, electrocution, carbon monoxide poisoning and other chemical hazards, and even fire [11]. Therefore, in the event of a major flood, the availability and operation of several types of critical infrastructure is imperative [12]. Critical infrastructures are defined as "assets, systems, and networks that provide functions necessary for our way of life" [13]. The most important critical infrastructures for flood preparedness are those that this article will refer to as essential facilities [14–16]. These include medical facilities, emergency medical stations

(EMSs), fire stations, police stations, schools, shelters, potable water facilities, wastewater treatment facilities, and power plants. Medical facilities and emergency medical service (EMS) stations are needed to provide medical care to those affected by flood damage as quickly as possible [17,18]. Police and fire personnel are needed to help coordinate the public and enact emergency plans, such as evacuations, relocations, roadblocks [19], and other mitigation strategies [20–22], as well as keeping fires and the risks of electrocution caused by downed wires at bay [10].

Power plants provide electricity to other essential facilities so that they can remain operational, such as by ensuring that communications among personnel remain intact and medical equipment remains functional [18,23]. Schools, lodging facilities, and other community buildings, such as churches and event centers, are important for providing shelter to those displaced by flooding [24]. Potable water and wastewater facilities are used to ensure that people and other essential facilities affected by flooding still have access to fresh water during and after a flood [15,23]. While it is of utmost importance to have at least one of each of these essential facilities operational within an area affected by flooding, it is best to have multiple, in the event that the facility loses function or is inaccessible to the public [25,26].

The impact of flood events on infrastructure and essential facilities has been studied in other parts of the world, such as Thailand [27], Australia [28], the United Kingdom [29,30], and the United States [31,32]. In March of 2023, a study was conducted on hospitals impacted by flooding in the state of Florida in the United States by assigning various hazard levels to buildings identified within the hazard zone [31]. In another study, the impact of flooding on essential infrastructure was analyzed in England in 2016 by using spatial network models and quantifying the impact in terms of how the population was affected [30]. While the value of these studies cannot be overstated, there are still many areas susceptible to a high risk of flooding that have not been studied. Furthermore, the studies that have been conducted on flood impact on essential facilities are largely focused on medical facilities specifically and less so on others, such as police stations, wastewater facilities, or shelters.

Although the impact of flooding has been frequently researched across the United States and other countries, there have been very little studies conducted on its impact in the State of Iowa [33]. Fewer still are studies conducted on the impact of flooding on essential facilities. This study aims to fill that gap in research and to bring more awareness to the effects of flooding in Iowa. Specifically, this study looks at the impact of flooding on essential facilities in Iowa with the intention of informing city officials and stakeholders about the risk associated with flooding in their respective Iowan counties and communicating [34] the flood risk using novel visualization technologies [35]. This is performed in hopes that the public will consider implementing appropriate mitigation strategies and emergency plans if they have not already done so in order to ensure the safety of their communities should a flood event occur.

The remaining sections of this paper are structured in the following manner. Section 2 describes the methodology used in this study. Section 3 reports and discusses the results generated from the study. Section 4 provides the conclusion and discussion of potential future research that could be carried out.

2. Methodology

2.1. Case Study

There were two general areas of interest chosen for this study (Figure 1). The first area was the entire state of Iowa, which is in the midwestern part of the United States. The second area consisted of 6 of the 99 counties within Iowa on which a deeper analysis was conducted (counties colored in blue). These counties were Pottawattamie, Polk, Linn, Johnson, Harrison, and Story counties. Iowa is considered one of the highest at-risk states for flood events, as its landscape is significantly influenced by several major waterways that run throughout the state and its borders are occupied by the Mississippi River in the east and the Missouri River in the west [36].

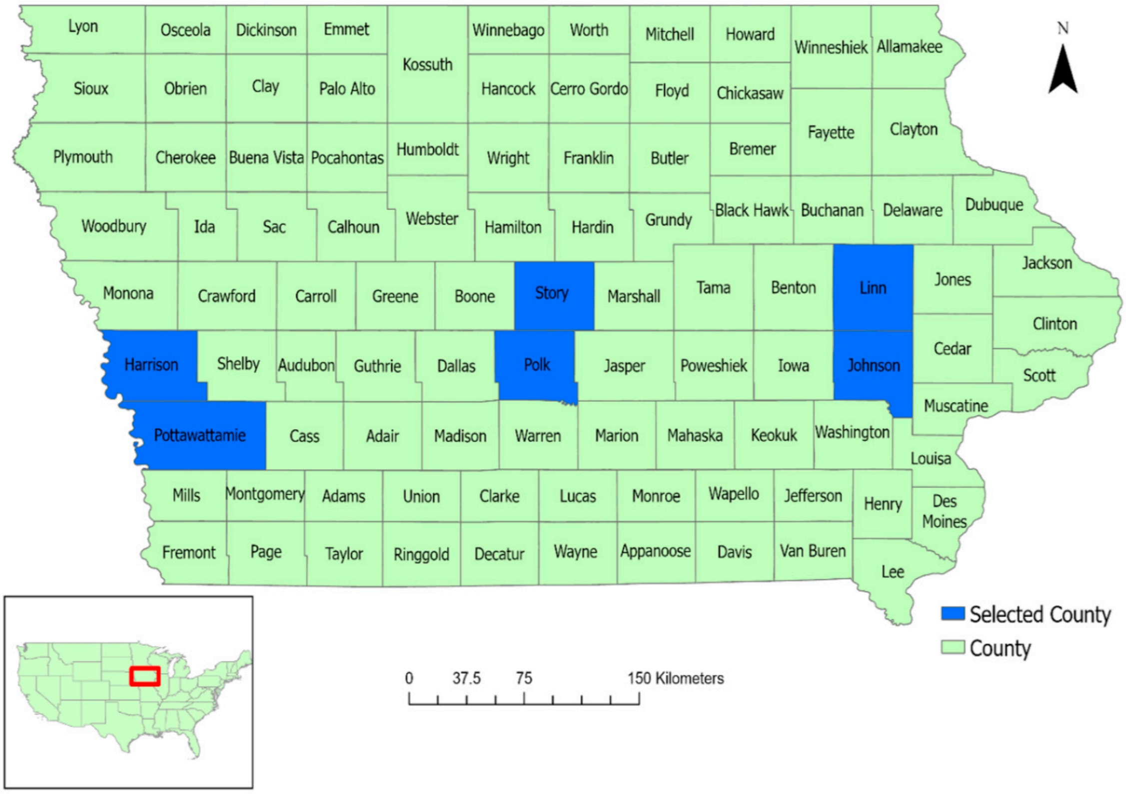

Figure 1. Map of the state of Iowa delimited by county.

One of the largest floods to occur in the state happened in June of 2008 during an onslaught of floods plaguing the entire Midwest. The Cedar River flooded, causing 14% of the city of Cedar Rapids, Iowa, to be flooded, damaging or destroying approximately 6100 structures and displacing approximately 24,000 people [37]. In August of 2016, Freeport, Iowa suffered the second 100 y flood event to occur within 10 years, which caused approximately USD 2.5 million in damage [38].

2.2. Data Collection

In this study, nine different types of essential facilities were observed. These facilities include medical facilities (hospitals, clinics), EMS (emergency medical services) stations, fire stations, police stations, schools (elementary, Jr.–Sr. high, colleges and universities, education and learning centers), shelters (churches, event centers, motels, hotels, and lodges), potable water facilities, wastewater facilities, and power plants. The geographic locations of essential facilities were collected from three different data sources. Initially, the locations of all essential facility types were pulled from each dataset and compared to each other to determine the best source for each facility type. The data source with the highest representation of an individual facility was the source chosen for that facility. In the study, location data on wastewater facilities were pulled from the Inventory National Database [39] within HAZUS (6.1) software [40]; power plants, fire stations, and EMS stations were pulled from individual datasets within the HIFLD database [41–43]; medical facilities, police stations, schools, shelters, and potable water facilities were pulled from the ArcGIS Business Analyst (2019) dataset [44].

HAZUS is a software tool developed by the Federal Emergency Management Agency (FEMA) for the purpose of analyzing the effects of natural disasters, including floods. The Inventory National Database is embedded within the HAZUS software and contains detailed information about various structures, including essential facilities, such as their location, occupancy type, size, and many others. It was last updated in 2023 [45]. The Homeland Infrastructure Foundation-Level Data (HIFLD) database is managed by the Department of Homeland Security (DHS) and is designed to support various homeland security and emergency management activities. This database contains detailed information about the location of essential facilities in the United States. The datasets containing information on fire stations, EMS stations, and power plants were all updated as of 2023 [43].

The ArcGIS Business Analyst dataset is licensed by Infogroup and is accessible through the ESRI Demographics database. The dataset contains basic information on each business in the entire state of Iowa as of 2019, including locations and business types [44]. Building data were retrieved from the National Structure Inventory (NSI), which is a dataset created and maintained by the US Army Corps of Engineers (USACE). It contains data detailing structural aspects of various buildings across the United States and was used in the creation of the Inventory National Database [45]. This dataset was used to retrieve occupancy type, foundation height, structural value, and content value for each essential facility. This dataset was updated as of 2022 [46]. The two-dimensional 100 y and 500 y flood extent maps and the three-dimensional flood raster maps for the six chosen counties were both obtained from Iowa Flood Center in Iowa City, IA. The flood maps available include 2 y, 5 y, 10 y, 25 y, 50 y, 100 y, and 500 y extents and were produced using HEC-RAS models [47,48]. A summary of all data sources used in this study is shown in Table 1 below.

Table 1. The graphical representation of all data sources used in this study.

Facility Type	Examples	Data Source	Year
Medical Facilities	Hospitals, clinics	ArcGIS Business Analyst	2019
EMS Stations	EMS stations	HIFLD Database	2023
Fire Stations	Fire stations	HIFLD Database	2023
Police Stations	Police facilities	ArcGIS Business Analyst	2019
Schools	Schools, colleges	ArcGIS Business Analyst	2019
Shelters	Churches, motels	ArcGIS Business Analyst	2019
Potable Water Facilities	Water treatment	ArcGIS Business Analyst	2019
Wastewater Facilities	Treatment plants	HAZUS Inventory National Database	2023
Power Plants	Power generation	HIFLD Database	2023
Building Data	Structural details	National Structure Inventory	2022
Flood Maps	100 y and 500 y extents	Iowa Flood Center	2023
Raster Maps	Flood depths	Iowa Flood Center	2023

2.3. Vulnerability of Essential Facilities to Flooding

2.3.1. Flood Exposure

The first analysis is conducted to determine which essential facilities were within the 100 y and 500 y flood extents. This was performed over the entire state of Iowa using flood maps from both flood extents. These flood maps were layered individually over a map of Iowa delimited by county for each analysis using Geographic Information Systems. All three datasets were then loaded into ArcMap (10.8.2) software and were added as a layer on top of the 100 y and 500 y flood maps. To determine which essential facilities were within each flood zone, the “Select by Location” tool was used to run an intersection between the essential facility data points and the flood map. If the data points intersected with the flood map, they were considered to be within the flood extent and were recorded and organized in Excel by facility type and county.

Schools often combine multiple education levels into one building. If multiple schools shared the same address and mostly the same name, they were considered to be one school. For example, Lynnville-Sully Middle School and Lynnville-Sully High School shared the same address, and, thus, were considered as one facility. Similarly, if a sheriff station shared the same address as a police station, it was considered to be one facility. However, if two different facility types occupied the same location, they were considered to be two separate facilities, such as EMS stations and fire stations or EMS and medical facilities located in the same building. Wastewater facilities often had duplicates of the same facility within the dataset, of which only one copy was chosen.

In this research, we analyzed the impact by calculating the percentage of essential facilities within each flood zone out of the total number of essential facilities within each county. The counties with the highest percentages of essential facilities within the flood zones were considered the most impacted. Pooling the analyses at the county-level spatial scale is advisable, given that the majority of disaster declarations and funding allocations are made at that level. The remaining analyses were conducted on the selected counties, and, therefore, only took into consideration Pottawattamie, Polk, Linn, Johnson, Harrison, and Story counties. These counties were chosen because they had the highest number of essential facilities within the 100 y flood zone.

2.3.2. Flood Depth Analysis

The next analysis performed was that of flood depth across the six selected counties for both the 100 y and 500 y flood extents. These data were obtained by using flood depth raster layers of each county in QGIS (3.34.0) software. Flood depth analysis was conducted on each of the six counties individually, first by layering the essential facility data over the county map, followed by the raster layer, then by using the "Sample raster values" tool in QGIS to extract the flood depth measurements of each essential facility per county. The flood depths were retrieved to be utilized with depth–damage functions used later in the study. For this analysis, the foundation height of each facility was not taken into consideration.

2.3.3. Functional Analysis of Facilities in Flooded Areas

Results from the flood depth analysis were used to perform the next analysis, which was to determine the functionality of essential facilities that had been considered flooded for both the 100 y and 500 y flood extents. Functionality was determined by comparing the flood depth of each essential facility to that of the standard functionality threshold of each facility type provided in the HAZUS Inventory Technical Manual, while taking into account the first-floor height and assuming no basement was present [49]. For example, as shown in Table 2 below, medical facilities are considered to have a first-floor height of 3 ft and functionality depth of 0.5 ft. This means that the flood depth would have to be 3.5 ft for a medical center to be considered nonfunctional. For the functionality threshold of each facility type, the default option was chosen if present. If there was no default option, the medium level was chosen instead. Because the HAZUS documentation does not have a depth functionality threshold for shelters or EMS stations exclusively, the threshold for schools was used for shelters and the threshold for fire stations was used for EMS stations instead. If the flood depth was below the threshold provided in the manual, the essential facility was considered to be functional. If it was at or above that threshold, the facility was considered nonfunctional. For this analysis, the foundation height of each facility was taken into consideration. Essential facilities with flood depths less than 0.5 ft were considered to have a flood depth of 0 and were not included in this analysis.

Table 2. Default medical functionality information provided by the HAZUS Inventory Technical Manual.

Medical Care Facilities						
HAZUS Label	**Occupancy Class**	**Default Building Type**	**Basement**	**First-Floor Height (ft)**	**No. of Stories**	**Functionality Depth (ft)**
MDFLT	Default Hospital	Concrete	Yes	3	Mid	0.5
EFHS	Small Hospital	Concrete	Yes	3	Low	0.5
EFHM	Medium Hospital	Concrete	Yes	3	Mid	0.5
EFHL	Large Hospital	Concrete	Yes	3	Mid	0.5
EFMC	Medical Center	Concrete	Yes	3	Low	0.5

2.3.4. Estimation of Restoration Time for Affected Facilities

Results from the flood depth analysis were also used to determine the restoration time of essential facilities that were considered flooded for both the 100 y and 500 y flood extents. Restoration time was determined by comparing the flood depth of each essential facility to that of the standard restoration time threshold range of each facility type, which was also provided by the HAZUS Inventory Technical Manual (5.1). For the restoration time threshold range of each facility type, the default range was chosen if present except in the case of power facilities, for which the restoration time threshold for the occupancy type IND2 was used, which corresponds to light industrial building. If there was no default range, the medium-level range was chosen instead. As there was no information in the HAZUS documentation regarding restoration time estimates for wastewater and potable water facilities, these facility types were not considered for this analysis. Flood depth ranges are split into tiers that correspond to the number of days it would take for that facility type to be restored after flooding occurred, as shown in Table 3 below. The number of days for restoration time required per facility was determined by looking at its flood depth and then assigning it the number of days for restoration that corresponded to that flood depth as described in the HAZUS Inventory Technical Manual.

Table 3. Default medical restoration time information provided by the HAZUS Inventory Technical Manual.

HAZUS Label	Description	Minimum Flood Depth (ft)	Maximum Flood Depth (ft)	Maximum Days to Restoration
EFMC	Medical Clinics and Labs	−4	0	360
EFMC	Medical Clinics and Labs	0	4	480
EFMC	Medical Clinics and Labs	4	8	630
EFMC	Medical Clinics and Labs	8	12	720
EFMC	Medical Clinics and Labs	12	25	900

2.3.5. Damage Analysis of Facilities in Flood-Prone Areas

In this study, four types of damage analysis were performed per essential facility for both the 100 y and 500 y flood extents. These analyses were the structural damage cost, percentage of structural damage, content damage cost, and the percentage of content damage. The structure value, content value, and occupancy type code were all provided by the building data from the NSI dataset, and the flood depth was provided by the previous analysis. If no building data were available for a facility, the default values for structure and content values and occupancy type code provided by the HAZUS Inventory Technical Manual were used instead. These values were then used in a depth–damage function provided by HAZUS, which is used to determine the mathematical relationship between damage percentages and flood depth [50].

Occupancy type is used to assign structure and content values to each essential facility. These values are then used with the depth–damage curve, as shown in Figure 2, to estimate flood both structural and content damage [51]. For wastewater facilities and power plants, structural and content values were not used in the calculation, and the default replacement values per facility size provided in the HAZUS Inventory Technical Manual were used instead. This was performed for consistency because the wastewater and power plants often had multiple buildings and, therefore, multiple NSI data points. The foundation height of the essential facilities was taken into consideration for this analysis. This analysis also operated under the assumption of essential facilities not having basements. This was performed for the simplicity of the study, as the foundation height provided in the dataset did not account for whether or not the facilities had basements. However, this could be a limitation since hospitals tend to keep their power supply in their basements and loss of power is one of the top reasons that hospitals are forced to evacuate during a flood [52–54]. Additionally, if the flood depth exceeded 10 ft, the facility was considered to be 100% damaged. A flowchart of the methodology used in this study is shown in Figure 3 below.

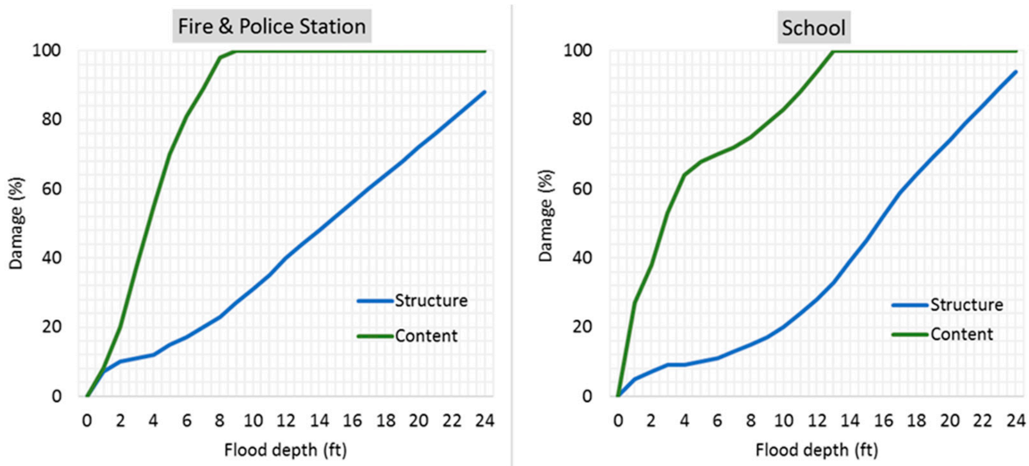

Figure 2. An example of the structural and content flood depth–damage functions used in the study, provided by HAZUS (adapted from [51]).

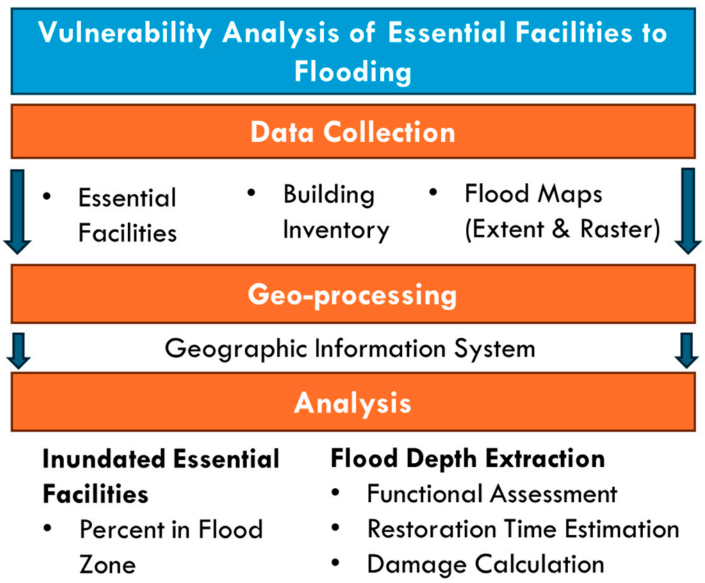

Figure 3. The flowchart of the methodology of the study.

3. Results and Discussion

3.1. Statewide Flood Exposure Analysis

Figure 4 shows the percentage of essential facilities across the state of Iowa that are within each flood zone. Some counties had no essential facilities affected, while Pottawattamie was impacted the most in both the 100 y and 500 y flood events, with 36% and 39% of its essential facilities affected, respectively. The majority of percentages of essential facilities affected per county fell within the 1–5% range. There were 19 counties in the 100 y extent whose facilities were unaffected by flooding in the context of this study, and 11 counties that were unaffected in the 500 y extent. Only three counties in the 100 y flood extent had more than 11% of their essential facilities affected by flooding, while the 500 y extent saw nine counties with more than 11% of its facilities affected. The overall percentage of facilities affected by flooding in the 100 y flood plain was 3%, while those affected in the 500 y flood plain was 5%.

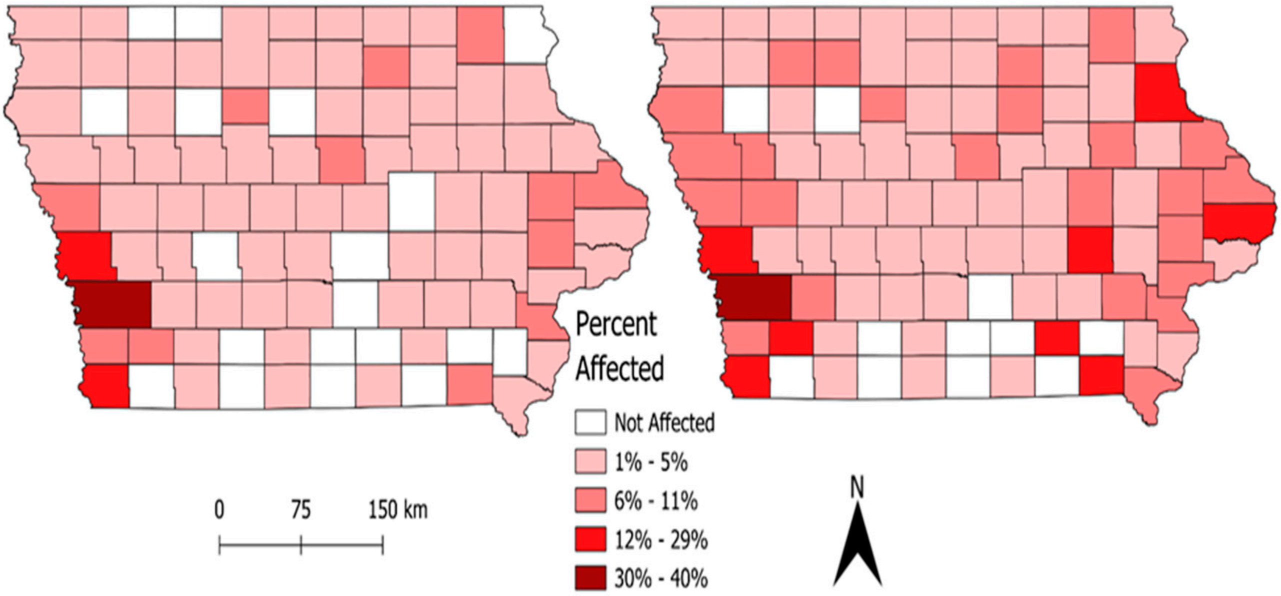

Figure 4. The percentage of essential facilities within the 100 y (**left**) and 500 y (**right**) flood extent in Iowa for each county.

Figure 5 shows the percentage of essential facilities affected across the entire state of Iowa based on the type of facility. The chart also shows a comparison between these percentages between the 100 y and 500 y flood extents. Results show that in both the 100 y and 500 y flood plain, wastewater facilities were by far the most affected facility type, at 17% and 22%, respectively. Schools overall were the least affected at 2% for both flood extents. However, within the 100 y flood extent, medical facilities and potable water facilities were also found to have only 2% of facilities affected. Overall, the rest of the facility types are similarly impacted to each other across the state, ranging between 3 and 8% affected. Knowing which facility types are most at risk during a flood can allow decisionmakers to better prepare for those facilities being compromised.

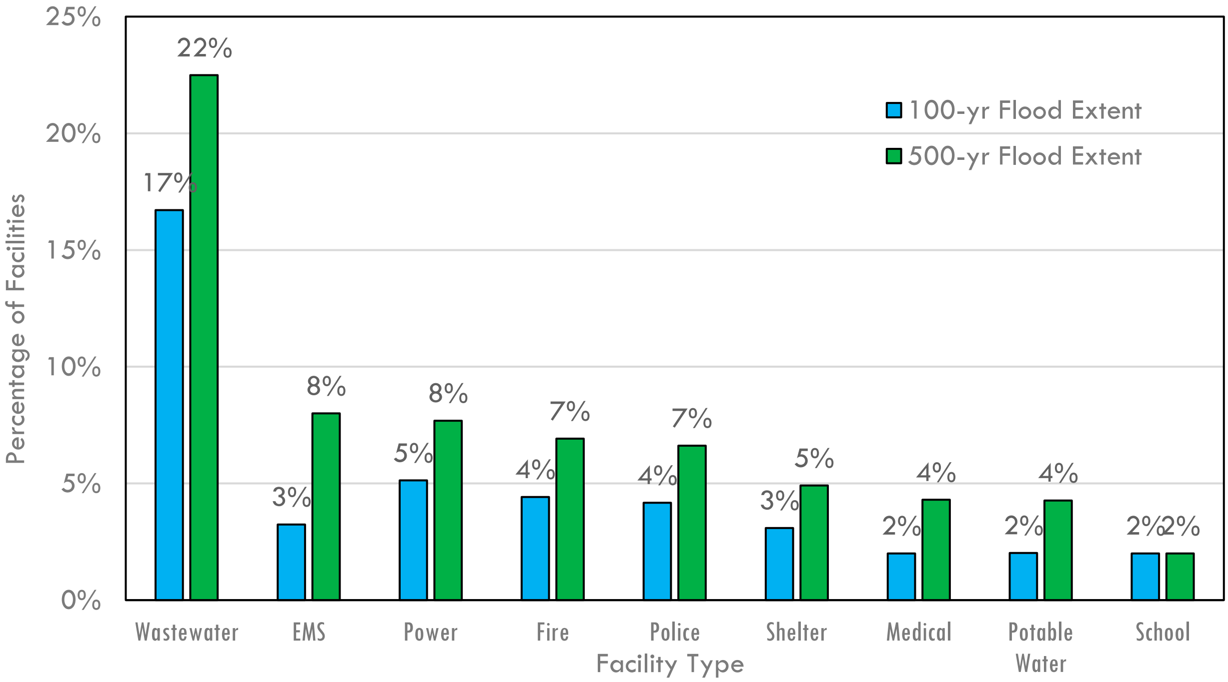

Figure 5. The percentage of essential facility types affected in the 100 y and 500 y flood extent across the state of Iowa.

3.2. County-Level Flood Vulnerability Analysis

Flood depth analysis is useful for informing other types of flood-related analyses, such as facility damage costs and facility functionality. Figure 6 shows the number of essential facilities at various flood depths in the 100 y and 500 y flood extents per county. This depth analysis was the first analysis conducted at the county level, which only covers the top six most affected counties in Iowa based on the 100 y flood extent. Results show that the vast majority of flood depths were between 1 and 4 feet. Pottawattamie County had the highest number of essential facilities within this depth range by far, with 40 facilities in the 100 y extent and 51 in the 500 y extent. The next highest in this range is Polk County, with 6 facilities in the 100 y extent and 20 in the 500 y extent. Pottawattamie also had the highest amount of facilities within the 4 to 8 feet flood depth range, with 11 in the 100 y extent and 41 in the 500 y extent. The county impacted the least by flood depth was Story County, with only four facilities within the 1 to 4 feet range in the 100 y extent and 10 in the 500 y extent.

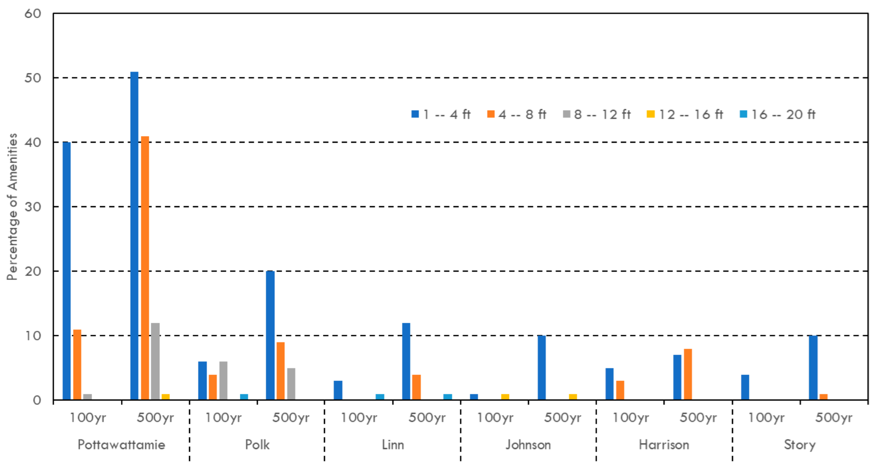

Figure 6. Number of essential facilities at various flood depths in feet for 100 y and 500 y flood extents, showing the top 6 most affected counties in Iowa.

Table 4 shows the amount of impacted, but functional, essential facilities on the county level for 100 y and 500 y flood extents. Results from the functionality analysis showed that Story County was the only county to have any functional facilities in the 100 y extent. In the 500 y extent, Pottawattamie County was found to have the highest number of functional facilities when compared to the others. However, for both the 100 y and 500 y extents, Pottawattamie County also had the highest amount of nonfunctionality. All 52 of its impacted facilities in the 100 y extent were considered nonfunctional, and 102 out of 105 of its impacted facilities in the 500 y extent were considered nonfunctional. Story and Johnson counties tied for the lowest number of nonfunctioning facilities in the 500 y extent, both having only nine. It can be seen in the chart that, overall, the 500 y extent had more functional essential facilities than the 100 y extent. This is because of a discrepancy between the flood raster maps to determine the flood depth at each essential facility and the statewide flood extent maps used to determine the location of affected facilities.

Table 4. Functionality of impacted essential facilities within 100 y and 500 y flood extents, showing the top 6 most affected counties in Iowa.

County Name	Impacted Facilities		Yes		No	
	100 y	500 y	100 y	500 y	100 y	500 y
Pottawattamie	52	105	0	3	52	102
Polk	17	34	0	2	17	32
Johnson	2	11	0	2	2	9
Linn	4	17	0	1	4	16
Story	4	11	3	2	1	9
Harrison	8	15	0	1	8	14
Total	87	193	3	11	84	182

Some of the essential facilities were within the extents of the statewide flood extent maps but were not in the flood extent used by the flood raster maps, and, therefore, returned a flood depth of 0. The functionality analysis only considered essential facilities that were flooded. If an facility was found to have a flood depth of 0, it was not considered to be flooded, and, therefore, not included in this analysis. It is also caused by the fact that the 500 y extent has a wider range than the 100 y extent and, therefore, can reach more facilities. However, the flood depths at those facilities are often shallow, as they are often on the outskirts of the 500 y extent, or they are facilities that have higher thresholds for functionality, such as medical facilities. It is important to understand not just which essential facilities are being impacted by flood events, but also to what extent. Functionality analysis informs decisionmakers which impacted facilities may still be accessed and used during an emergency.

Figure 7 shows the number of days estimated for the restoration time of flooded essential facilities based on the type of facility impacted for both 100 y and 500 y flood extents per county. Results from the restoration time analysis show that the majority of flooded facilities take approximately 480 days to be restored. Pottawattamie County is the most affected, with 40 facilities requiring 480 days to recover in the 100 y extent and 35 facilities requiring 480 days to recover in the 500 y extent. While the number of facilities requiring 480 days decreases from the 100 y to 500 y extent in this case, the number of facilities requiring 630 days of recovery time in the 500 y extent increases from only 7 in the 100 y extent to 46 in the 500 y extent for Pottawattamie County. Pottawattamie and Polk counties are the only ones with any essential facilities requiring 900 days of restoration time.

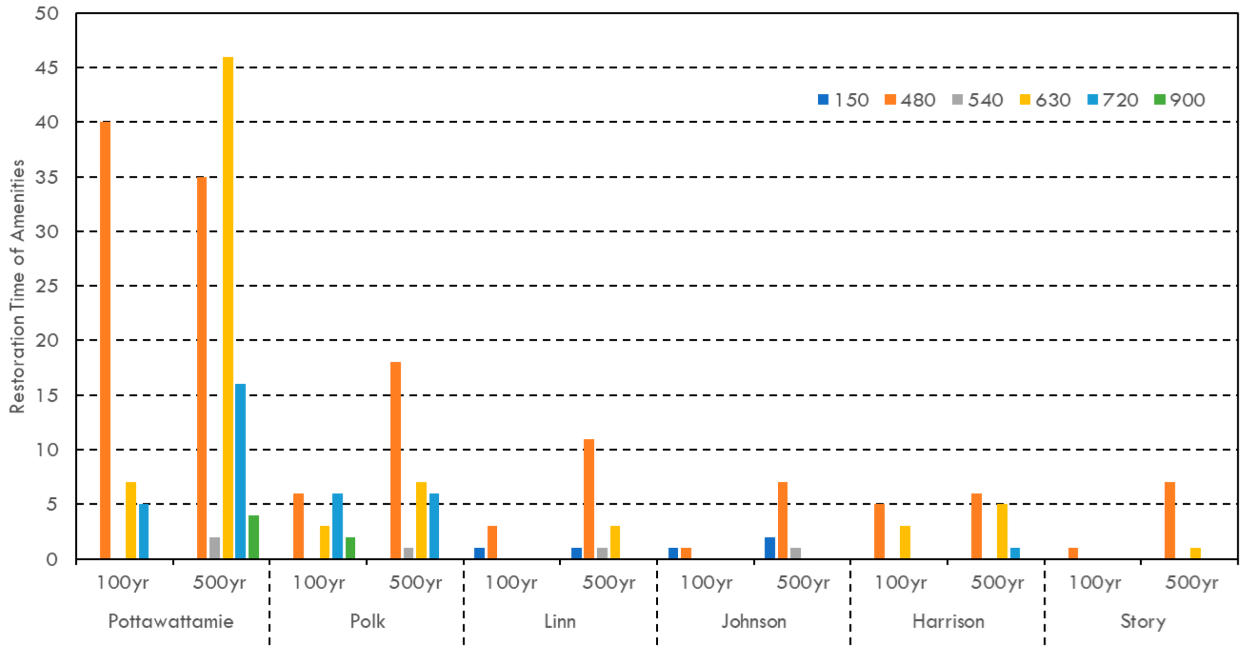

Figure 7. Restoration time of impacted essential facilities measured in days for 100 y and 500 y flood extents, showing the top 6 most affected counties in Iowa.

The county that appears to be the least affected is Story County, with only one facility requiring 480 days in the 100 y extent and seven in the 500 y extent. Providing insight to restoration times can allow for more thorough preparation, ensuring timely service delivery, thus enhancing overall disaster response effectiveness. It is important for decisionmakers to understand the economic impact that flooding events may cause to essential buildings in their communities so that proper funding may be allocated ahead of time to ensure that restoration can begin swiftly and effectively. Table 5 shows the structural damage cost estimations of impacted essential facilities in the 100 y and 500 y flood extents per county.

Table 5. Structural damage in USD for impacted facilities in 100 y and 500 y flood extents, rounded to the nearest 100,000.

	Pottawattamie		**Polk**		**Linn**		**Harrison**		**Story**		**Johnson**		**Total**	
Flood Extent	**100 y**	**500 y**	**100 y**	**500 y**	**100 y**	**500 y**	**100 y**	**500 y**	**100 y**	**500 y**	**100 y**	**500 y**	**100 y**	**500 y**
Medical	USD 677 k	USD 3.5 M	-	USD 2.1 M	-	USD 360 k	-	-	-	USD 96 k	-	USD 47 k	USD 677 k	USD 6.2 M
EMS	-	-	-	USD 136 k	-	-	-	-	-	-	-	-	-	USD 136 k
Fire	USD 278 k	USD 976 k	USD 1.6 M	USD 1.1 M	-	-	USD 470 k	USD 494 k	-	-	-	-	USD 2.4 M	USD 2.5 M
Police	USD 371 k	USD 1.5 M	-	-	-	USD 642 k	USD 61 k	USD 195 k	-	-	-	-	USD 433 k	USD 2.4 M
School	USD 6.9 M	USD 25.1 M	USD 1.3 M	USD 2.2 M	USD 1.2 M	USD 6.1 M	-	-	-	-	-	USD 946 k	USD 9.4 M	USD 34.4 M
Shelter	USD 19.4 M	USD 44.3 M	USD 5.5 M	USD 9.8 M	USD 397 k	USD 2.4 M	USD 866 k	USD 2 M	USD 42 k	USD 1 M	USD 48 k	USD 2.7 M	USD 26.3 M	USD 62.2 M
Wastewater	-	USD 24 k	-	-	-	USD 24 k	-	USD 48 k	USD 80 k	USD 104 k	-	-	USD 80 k	USD 200 k
Potable Water	-	-	-	USD 194 k	-	-	-	-	-	-	-	-	-	USD 194 k
Power	-	-	-	-	USD 15 k	USD 15 k	-	-	-	-	USD 75 k	USD 110 k	USD 90 k	USD 125 k
Total	**USD 27.7 M**	**USD 75.5 M**	**USD 8.4 M**	**USD 15.6 M**	**USD 1.6 M**	**USD 9.5 M**	**USD 1.4 M**	**USD 2.7 M**	**USD 122 k**	**USD 1.2 M**	**USD 123 k**	**USD 3.8 M**	**USD 39.3 M**	**USD 108.3 M**

Shelters were found to be the facility type with the highest damage costs in both the 100 y and 500 y extent across all six counties, with approximately USD 26.3 million and USD 62.2 million worth of damages, respectively. Generally, shelters were also found to sustain the highest damage costs in each individual county. However, Linn County is an exception to this, with schools being the highest costing facility instead, at approximately USD 1.2 million and USD 6.1 million in the 100 y and 500 y extents, respectively. Story County also saw a higher damage cost in wastewater facilities than shelters in the 100 y extent scenario specifically. Pottawattamie County was found to have the highest overall structural damage costs in both the 100 y and 500 y flood extents, at approximately USD 27.7 million and USD 75.5 million worth of damage, respectively.

Structural damage costs were found to consistently increase from the 100 y to the 500 y extents, except for fire stations in Polk County. Overall, the total damage to essential facilities across all six chosen counties amounted to approximately USD 39.3 million and USD 108.3 million for the 100 y and 500 y extents, respectively. Table 6 shows the content damage cost estimations of impacted essential facilities in the 100 y and 500 y flood extents per county. Shelters were again found to be the facility type with the highest damage costs in both the 100 y and 500 y extent across all six counties, with approximately USD 81.2 million and USD 195.8 million worth of damage, respectively.

Table 6. Content damage in USD (USD) for impacted facilities in 100 y and 500 y flood extents, rounded to the nearest 100,000.

	Pottawattamie		**Polk**		**Linn**		**Harrison**		**Story**		**Johnson**		**Total**	
Flood Extent	**100 y**	**500 y**	**100 y**	**500 y**	**100 y**	**500 y**	**100 y**	**500 y**	**100 y**	**500 y**	**100 y**	**500 y**	**100 y**	**500 y**
Medical	USD 2.6 M	USD 15.1 M	-	USD 12.4 M	-	USD 589 k	-	-	-	USD 369 k	-	USD 178 k	USD 2.6 M	USD 28.6 M
EMS	-	-	-	USD 1 M	-	-	-	-	-	-	-	-	-	USD 1 M
Fire	USD 1.4 M	USD 2.7 M	USD 3.5 M	USD 3.7 M	-	-	USD 646 k	USD 2.2 M	-	-	-	-	USD 5.5 M	USD 8.6 M
Police	USD 1.9 M	USD 10.1 M	-	-	-	USD 4.4 M	USD 100 k	USD 273 k	-	-	-	-	USD 2 M	USD 14.9 M
School	USD 36.5 M	USD 110.5 M	USD 8 M	USD 9.6 M	USD 1.9 M	USD 29.3 M	-	-	-	-	-	USD 7.2 M	USD 46.5 M	USD 156.6 M
Shelter	USD 58.3 M	USD 132.6 M	USD 19 M	USD 30.9 M	USD 2 M	USD 16.1 M	USD 1.6 M	USD 2.2 M	USD 160 k	USD 3.6 M	USD 30 k	USD 10.4 M	USD 81.2 M	USD 195.8 M
Wastewater	-	USD 24 k	-	-	-	USD 24 k	-	USD 48 k	USD 80 k	USD 104 k	-	-	USD 80 k	USD 200 k
Potable water	-	-	-	USD 194 k	-	-	-	-	-	-	-	-	-	USD 194 k
Power	-	-	-	-	USD 15 k	USD 15 k	-	-	-	-	USD 75 k	USD 110 k	USD 90 k	USD 125 k
Total	**USD 100.7 M**	**USD 271 M**	**USD 30.6 M**	**USD 57.7 M**	**USD 4 M**	**USD 50.5 M**	**USD 2.4 M**	**USD 4.7 M**	**USD 240 k**	**USD 4.1 M**	**USD 105 k**	**USD 17.9 M**	**USD 138 M**	**USD 406 M**

Generally, shelters were found to sustain the highest damage costs in each individual county as well. However, Linn County is an exception to this in the 500 y extent, with schools being the highest costing facility, at approximately USD 29.3 million. Johnson County also saw a higher damage cost in power facilities than shelter in the 100 y extent. Pottawattamie County was, again, found to have the highest overall content damage costs in both the 100 y and 500 y flood extents, at approximately USD 100.7 million and USD 271 million worth of damages, respectively. Content damage costs were found to consistently increase from the 100 y to the 500 y extents.

Overall, the total damage to essential facilities across all six chosen counties amounted to approximately USD 138 million and USD 406 million for the 100 y and 500 y extents, respectively. The loss of an essential facility's equipment and other items necessary for its function can be just as financially impactful as flood damage caused to its exterior. The cost of restoring content damage should also be considered when implementing flood disaster prevention. Table 7 shows the structural damage percentage of impacted essential facilities in the 100 y and 500 y flood extents per county. Each county was broken up into relevant damage percent ranges, and a count was taken of the number of essential facilities within those ranges per flood extent. Shelters were generally found to be the most impacted facility type.

Table 7. The percentage of structural damage to essential facilities in 100 y and 500 y flood.

	Damage	Shelter		School		Medical		Fire		Police		Potable Water		EMS		Waste-Water		Power	
		100	500	100	500	100	500	100	500	100	500	100	500	100	500	100	500	100	500
Pottawattamie	1–20%	32	58	9	14	1	3	2	1	1	1	-	-	-	-	-	-	-	-
Pottawattamie	21–40%	5	10	-	4	-	1	-	2	-	1	-	-	-	-	-	-	-	-
Pottawattamie	41–60%	2	8	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Polk	1–20%	9	19	3	4	-	2	-	1	-	-	-	1	-	1	-	-	-	-
Polk	21–40%	4	3	-	1	-	-	-	1	-	-	-	1	-	-	-	-	-	-
Polk	41–60%	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-
Harrison	1–20%	4	2	-	-	-	-	2	2	1	-	-	-	-	-	-	-	-	-
Harrison	21–40%	2	5	-	-	-	-	-	1	-	1	-	-	-	-	-	2	-	-
Harrison	41–60%	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Harrison	81–90%	-	-	-	-	-	-	1	1	-	-	-	-	-	-	-	-	-	-
Linn	1–20%	2	8	-	3	-	1	-	-	-	1	-	-	-	-	-	-	1	1
Linn	21–40%	-	-	1	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-
Linn	41–60%	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Johnson	1–20%	1	5	-	1	-	1	-	-	-	-	-	-	-	-	-	-	1	2
Johnson	21–40%	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Story	1–20%	1	7	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Story	21–40%	-	-	-	-	1	-	-	-	-	-	-	-	-	-	1	2	-	-

EMS stations proved to be the least impacted, with only one facility affected in Polk County in the 500 y flood extent. Pottawattamie County was found to be the most affected county in both the 100 y and 500 y flood extents, with 32 and 58 facilities, respectively, within the 1 to 20% damage percent range alone. Johnson County was found to be the least affected county, with only two essential facilities impacted in the 100 y extent and 10 in the 500 y extent, and most falling within the 1 to 20% damage percent range. Understanding which essential facilities have higher percentages of structural damage can provide perspective for decisionmakers that may be useful in determining where best to focus recovery efforts.

Just like with the structural damage percentage, each county was broken up into relevant content damage percent ranges (Table 8), and a count was taken of the number of essential facilities within those ranges per flood extent. Shelters, again, were generally found to be the most impacted facility type. Also, just as in the previous results, EMS stations proved to be the least impacted, with only one facility affected in Polk County in the 500 y flood extent.

Table 8. Content damage percentage of impacted essential facilities in the 100 y and 500 y flood extents per county.

	Damage	**Shelter**		**School**		**Medical**		**Fire**		**Police**		**Potable Water**		**EMS**		**Waste-Water**		**Power**	
		100	**500**	**100**	**500**	**100**	**500**	**100**	**500**	**100**	**500**	**100**	**500**	**100**	**500**	**100**	**500**	**100**	**500**
Pottawattamie	1–20%	5	2	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	21–40%	8	12	4	4	-	-	1	-	1	-	-	-	-	-	-	1	-	-
	41–60%	14	19	1	3	-	2	-	1	-	-	-	-	-	-	-	-	-	-
	61–80%	5	7	3	8	1	1	-	1	-	1	-	-	-	-	-	-	-	-
	81–100%	7	36	-	3	-	1	1	1	-	1	-	-	-	-	-	-	-	-
Polk	1–20%	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	21–40%	1	2	-	1	-	-	-	-	-	-	-	2	-	-	-	-	-	-
	41–60%	3	2	1	2	-	1	-	1	-	-	-	-	-	1	-	-	-	-
	61–80%	1	4	2	2	-	1	1	1	-	-	-	-	-	-	-	-	-	-
	81–100%	8	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Harrison	1–20%	3	-	-	-	-	-	2	-	1	-	-	-	-	-	-	-	-	-
	21–40%	-	1	-	-	-	-	-	2	-	-	-	-	-	-	-	2	-	-
	41–60%	2	3	-	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-
	61–80%		2																
	81–100%	2	2	-	-	-	-	1	1	-	-	-	-	-	-	-	-	-	-
Linn	1–20%	-	1	-	1	-	1	-	-	-	-	-	-	-	-	-	-	1	1
	21–40%	1	-	1	1	-	-	-	-	-	-	-	-	-	-	-	1	-	-
	41–60%	1	3	-	1	-	-	-	-	-	1	-	-	-	-	-	-	-	-
	61–80%	-	2	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	81–100%	-	2	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Johnson	1–20%	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	2
	21–40%	-	4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	41–60%	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
	81–100%	-	1	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Story	1–20%	-	5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	21–40%	1	-	-	-	-	-	-	-	-	-	-	-	-	-	1	2	-	-
	41–60%	-	1	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
	81–100%	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Pottawattamie County was, again, found to be the most affected county in both the 100 y and 500 y flood extents, having 36 essential facilities within the 81 to 100% damage range of the 500 y extent. However, its distribution of essential facilities across the damage ranges was more evenly spread than that of the structural damage. Johnson County was also, again, found to be the least affected county, with only two essential facilities impacted in the 100 y extent and 10 in the 500 y extent, although two did land within the 81 to 100% damage range. Like Pottawattamie's case, its distribution of facilities across Johnson County's damage ranges is also more even than the previous analysis. Similarly to the case of structural damage, essential facilities with higher percentages of content damage may take precedent in restoration efforts over those less impacted.

4. Conclusions

Over the course of this study, essential facilities of six counties within the state of Iowa were analyzed during the 100 y and 500 y annual flood extents in terms of flood depth, functionality, restoration time, and damage, in addition to an overall location analysis that was conducted on the statewide level. Findings show that for both the county and statewide levels, Pottawattamie County was, by far, the most impacted county overall, with over 35% of its facilities impacted in both flood extents and loss of functionality of 100% and 97% of its essential facilities in the 100 y and 500 y extents, respectively. Wastewater facilities were identified as the most affected facility type, with 17% impacted in the 100 y extent and 22% in the 500 y extent. Analysis showed that most affected facilities will require substantial time to restore functionality, with many taking up to 480 days and some requiring as long as 900 days for complete restoration. Results from the damage cost analyses showed that total costs across all six counties chosen for the secondary analysis typically exceeded USD 100 million and reached up to USD 406 million in the case of the content damage in the 500 y extent. Shelters incurred the highest damage costs in both 100-year and 500-year flood extents, with structural damages totaling approximately USD 26.3 million and USD 62.2 million, respectively, in the 100-year and 500-year flood extents, and content damages amounting to approximately USD 81.2 million and USD 195.8 million. These findings can be used to shed light on potential losses and the risk to affected communities in terms of essential facility availability during and after a flood.

It should be stated that there were some roadblocks throughout the course of this study that were not previously mentioned. The largest of these were the discrepancies of essential facility location data provided by the ArcGIS Business Analyst dataset. There were several data points that were found to have incorrect addresses, and these data points had to be relocated within ArcMap to their correct locations before an accurate depth analysis could be conducted. These locations were verified with Google Maps. Another issue came with the identification of occupancy types for the damage analyses. Some essential facilities were not listed in the NSI dataset as traditional occupancy types for their respective type of facility. For example, some churches were given residential (RES) occupancy types when they would typically be classified as religious institutions (REL1). Other times, an essential facility would have more than one occupancy type given and none of them would be the traditional code used. In these cases, the best judgment was used to pick the occupancy type closest to the facility of the occupancy types provided for the facility by the NSI dataset.

There are also some limitations associated with the flood maps themselves. The 500 y flood extent map layer had portions missing from it for Johnson, Harrison, and Pottawattamie counties. This had no impact on the analysis for Johnson County, as there were no essential facilities in that portion of the map, while Harrison County was only lightly affected. Pottawattamie County was largely affected by this as the portion missing from the 500 y flood extent was the area with a large concentration of essential facilities within Pottawattamie County. Fortunately, for both Pottawattamie and Harrison counties, all essential facilities that could have reasonably been within the missing pieces of the 500 y extent map were within the 100 y extent map and were, therefore, automatically considered to be within the 500 y extent as well. This discrepancy only impacted the location analysis, as all other analyses conducted were based on the depth analysis, and the flood depth analysis used different flood extent maps. The other limitation of the flood maps is that they were produced using an HEC-RAS model, which is typically more useful for fluvial flood events rather than flash flood events. This is an important limitation because it is all manner of floods that are increasing in frequency and intensity. Lastly, it should be noted that the percentages calculated in this study are a raw metric and may not be entirely actionable on their own. This study was simply meant to give a broad sense of where essential facilities may be most affected by future flood events. Furthermore, this study did not consider basement levels for any analysis. Some essential facilities (i.e., hospitals) might keep their power supply in their basements. Therefore, it might be reasonable to deem a facility nonfunctional even at minimal flood depth due to potential loss of power.

For future study, researchers might consider conducting a population impact analysis to better understand the value of essential facilities within an area to its respective population. It might very well be the case that two out of four hospitals are nonfunctional, but the two that are functional serve 90% of the population in that area, so, really, the impact is minimal. Another area of this study that might be improved would be the process in which functionality of an essential facility is determined. For this study, an essential facility's functionality was determined based on flood depth alone and was considered strictly either functional or not functional based on that depth. This was performed for simplicity and consistency across facility types, but a more in-depth analysis might be conducted to determine the functionality of essential facilities more accurately.

On a broader note, this study could be expanded to look beyond the selected counties in Iowa and instead perform the secondary set of analyses on every county in the state, or even to other parts of the United States lacking such a study. Moreover, the methods used in this study should be replicable in other countries as long as relevant building data and flood maps are accessible for them.

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