A Web-based Decision Support Framework for Optimizing Road Network Accessibility and Emergency Facility Allocation During Flooding

Yazeed Alabbad[1,2,3 *], Jerry Mount[1], Ann M. Campbell[4], Ibrahim Demir[1,2,5]

[1] IIHR Hydroscience and Engineering, University of Iowa, Iowa City, US
[2] Civil and Environmental Engineering, University of Iowa, Iowa City, US
[3] Civil Engineering, King Saud University, Riyadh, Saudi Arabia
[4] Department of Business Analytics, University of Iowa, Iowa City, US
[5] Electrical and Computer Engineering, University of Iowa, Iowa City, US

* Corresponding Author, Email: yazeed-alabbad@uiowa.edu

Abstract

Transportation systems can be significantly affected by flooding, leading to physical damage and subsequent adverse impacts such as increased travel distance to essential services. Even though flooding is a frequently recurring phenomenon that can affect thousands of people per event, there are limited accessible online tools available for analyzing and visualizing flood risk for supporting decisions on routing and emergency planning, and response. Existing tools are generally based on complicated models and are not easily accessible to non-expert users. Therefore, it is critical to have efficient real-time communication and decision tools for analyzing flood impacts on transportation networks for various stakeholders, including the public, to minimize the adverse impacts on those groups. This paper presents a web application that uses graph network methods and the latest web technologies and standards to assist in describing flood events in terms of operational constraints and provide analytical methods to support mobility and mitigation decisions during these events. The framework is designed to be user-friendly, enabling non-expert users to access information about road status, shortest paths to critical amenities, location-allocation, and service coverage. The study area includes the following two communities in the State of Iowa, Cedar Rapids and Charles City, which were used to test the application's functionality and explore the outcomes. Our research demonstrates that flooding can significantly affect bridge operation, routing from locations to critical amenities, arbitrary point-to-point routing, planning for emergency facility placement, and service area accessibility. The introduced framework can solve complex flood-related analytical decision tasks and provide an understandable representation of transportation vulnerability, enhancing mitigation strategies. Therefore, this web application provides a valuable tool for stakeholders to make informed decisions on transportation networks during flood events.

1. Introduction

Flooding as a natural disaster, poses the largest threat worldwide, killing or displacing people, destroying infrastructures, and causing significant financial losses (Borowska-Stefańska et al., 2017). Globally, flooding causes millions of people to become displaced each year and hundreds of billions of dollars in flood-related losses (McDermott, 2022). Between 1980 and 2022, the United States experienced 37 flood disasters, with each event resulting in 50 or more fatalities and more than one billion dollars in damages (NOAA, 2022). Although governments and agencies have made extensive efforts to regulate and minimize flood risk (Yildirim et al., 2022), flooding still occurs and is projected to occur more frequently with increasing magnitudes due to many factors such as poor planning, climate change, and increased population density (Kundzewicz et al., 2014). This evolving risk requires urgent actions to develop long and short-term plans and strategies for effective flood risk management (Rentschler & Salhab, 2020).

Routing systems are of paramount importance in enabling social and economic activities, disaster response, and emergency management. During disasters, such as flooding, routing systems become even more significant as they can help evacuate people, respond to emergency situations, and connect critical services. However, regarding infrastructure and capacity, transportation networks are among the first assets to be affected when a community experiences flooding (Yin, 2016). Floodwater can impair the operation of roadways and cause direct and indirect negative impacts such as bridge failure, road deterioration, loss of access to essential services, and unexpected changes in travel costs due to inundated roads. The unexpected flood behavior and damage can pose a challenge in accessing amenities during flood events, making it all the more important to have reliable and robust routing systems in place (Haltas et al., 2021).

Although humans can adapt to seasonal or annual flooding, climate change, unsustainable development, and increased urbanization can create unforeseen difficulties for people due to the changing flood impact on transportation networks. Humans operate on bounded rationality regarding flooding, so they may not comprehend how changes in accessibility can affect them. Additionally, flooded roads can result in economic losses and business closures (Winter et al., 2019). Moreover, inundated roadways have been found to be a significant contributor to flood-related fatalities in the United States (FEMA, 2019). To effectively manage and mitigate these risks, it is crucial to develop efficient routing systems that provide necessary information and resources for transportation networks during disasters (Alabbad et al., 2022).

Flood risk assessment is crucial for managing flood hazards and minimizing potential damage caused by flooding. It involves evaluating the hazards, exposure, and vulnerability (Reisinger et al., 2020; Yildirim & Demir, 2022). Flood hazard assessment is based on determining the likelihood and magnitude of potential flooding. Elements of exposure, such as people, buildings, and transportation networks, are assessed for their susceptibility to damage (vulnerability) at the flood hazard location (Alabbad & Demir, 2022). This process helps identify at-risk areas and the potential consequences of flooding. Flood disaster management comprises activities undertaken before a flood occurs, such as flood prevention or mitigation measures (Tingsanchali, 2012). During flooding, timely access to information becomes crucial.

Conducting new flood risk research during a flood event is often impractical due to the extensive processing, integration, and analysis of data required, which can be time-consuming and require significant effort. Therefore, it is essential to investigate the vulnerability of road networks during flood hazards in order to develop innovative plans and tools aimed at building resilient transportation systems (Akhlaghi et al., 2023).

Several studies have investigated the behavior of road networks during flood events, employing diverse methods to assess flood hazards and identify vulnerable components. Spatial intersection analysis of flood hazard and road segments have been used to identify exposed elements (Papilloud et al., 2020; Yin et al., 2017; Demirel et al., 2015), while graph theoretic methods, including betweenness centrality and shortest path, have been utilized for emergency planning (Alabbad et al., 2021; Mount et al., 2019; Green et al., 2017; Masuya et al., 2015). Vulnerability and disruption indices have also been applied to identify critical links and the overall level of network vulnerability (Murray-Tuite et al., 2004). In addition, accessibility measures have been utilized to evaluate network performance during flooding (Chen et al., 2015). An empirical function has been developed to estimate vehicle speed reduction during flooding events (Pregnolato et al., 2017). Research on routing has extended beyond flooding to other natural and human-induced hazards, including earthquakes (Alipour & Shafei, 2016) and terrorist attacks (Lou & Zhang, 2011).

In the last two decades, the advancements in information technology and systems, including web applications, have facilitated the analysis of complex data (Xu et al., 2019) and the delivery of valuable information through visualization (Demir et al., 2009) across various disciplines, including flood risk management (Alabbad et al., 2023). In the domain of transportation research, decision support systems (DSS) have allowed decision-makers, including the public, to assess the effects of floods on accessibility and manage emergency activities. Researchers have integrated routing with flood hazard information into DSS for several purposes, including emergency planning (Mirfenderesk, 2009), minimizing evacuation time and providing alternative routes for residents (Windhouwer et al., 2005), and estimating and visualizing transportation damage (Kaviani et al., 2015).

In terms of web applications, Google Maps is widely used as a navigation tool. However, it has limited functionality for routing during flooding and lacks emergency features such as evacuation routes. The 511 website (Iowa DOT, 2022) provides current road conditions in Iowa, but it does not incorporate accessibility analysis for critical services or the impacts of floods, such as the 100-year flood, on road networks. Thus, there is still a need for interactive web platforms that can guide people during flooding and assist in emergency activity planning, including tasks such as facility allocation.

This research presents a web-based routing decision support system during flooding to help various stakeholders (e.g., public, emergency responders) navigate around flooded roads, explore accessibility to critical amenities, and facilitate efficient response by accessing optimization functions (location-allocation, service area). The developed online application allows non-technical users, including the public, to access relevant information easily while avoiding requirements for advanced software or tools (e.g., GIS) that need technical expertise in data management and analysis (Demir & Beck, 2009). Also, it is a significant resource for minimizing the risk of being caught in a flood, providing alternative routes, and relocating essential supplies to improve flood response.

The rest of the paper follows the following structure. Section 2 focuses on the methodology for the framework development, including the web application components, analysis functions, data preparation, and case study. Section 3 presents and interprets the outcomes of the study. The last section demonstrates conclusions and further research.

2. Methods

2.1. Web-Based Routing Engine Development

The main objective of the proposed framework is to provide operational and analytical methods that can be used by experts and the public for routing during flooding, eliminating the need for complex software and skilled analysts. We understand that dealing with complicated data processing and analysis software can be time-consuming and frustrating for non-experts, which is why our system is designed to be user-friendly and straightforward. Our web application development involves integrating spatial and non-spatial data with programming languages, including (i.e., Python) for the back-end server and (i.e., JavaScript) for the client-side user interface. The following sections provide a detailed description of both server-side and client-side development, including each component's technical specifications and functionalities.

Server-Side Components

The back-end server is the system's backbone and is responsible for controlling and providing services to support the front-end users. It plays a crucial role in data processing and storage and handles various functions and tasks that are accessible by the client-side. Data for the framework was collected from multiple sources (see section 2.3) and served as inputs for the system's methods (see section 2.2). A relational database system, PostgreSQL with PostGIS spatial extensions, was used to store spatial and aspatial information, including pre-computed shortest paths and flood inundation boundaries. Methods supporting the framework functionality are handled by a custom application programming interface (API) enabled by an Asynchronous Server Gateway Interface (ASGI, 2018). We use the FastAPI framework with API services provided by ASGI. The NGINX web server (Reese, 2008) provides load-balancing and proxy services for front-end requests. To expedite the sharing of geographical data on the map, we linked the PostgreSQL database to GeoServer, an open-source server, that provides a platform to serve and publish geospatial data (geoserver.org, 2023). Using GeoServer allows the system to share geographic data quickly and efficiently with the front-end users.

Client-Side Components

The Hyper Text Markup Language (HTML), Cascading Style Sheets (CSS), and JavaScript are used to build the web interface. Leaflet (Agafonkin, 2022), a free open-source JavaScript library, is employed to display spatial data (e.g., vector) into interactive maps. The entry webpage for the framework provides access to the main functionality of the framework through an intuitive and user-friendly design. This features a map based on OpenStreetMap and Mapbox-compatible map tiles, with map scale and zoom controls to allow users to navigate and zoom in/out of the map easily. The system provides the user with the ability to define the geospatial area of interest and the scenario (no flood or flood event) they want to examine.

The system offers six main functions that the user can interact with. The first is road assessment under flood return period scenarios, which enables users to visualize open and closed roads under various flood conditions as well as bridges in the study area. The system provides a summary panel that lists the total length and quantity of the impacted segments for the user's convenience. This allows users to quickly assess which roads and bridges are affected by a flood event. In addition, the road conditions based on flood stage can be explored (second function). This function visualizes the closed and open routes based on river flood stages. The system provides users with information on the flood inundation extent linked with each flood stage. Additionally, the current and 10-day flood river levels within the study area are integrated into the map, enabling users to learn in advance about the condition of the road. This feature is important because it allows users to plan their travel routes and avoid flooded areas during a flood event.

The third function is accessibility analysis, which provides users with the shortest path length from a defined location to critical amenities, including fire departments, police stations, and hospitals, before and after a flooding event. The system generates the shortest paths and allows users to hover over each path to display relevant information such as distance. This feature is important because it lets users plan their travel routes and avoid flooded areas during an emergency. Also, we have created a point-to-point routing function that empowers users to effortlessly discover the shortest path between any two locations on the map within the communities under study. Our map interface displays two markers representing the origin and destination points. Users can manipulate these markers, allowing them to explore different locations and observe the corresponding outcomes. As they adjust the markers, the system dynamically updates the displayed route, along with the associated travel distance, considering the potential effects of flooding.

The fifth function is facility allocation, which helps users to identify the best locations for emergency sites (e.g., food and medical supplies) based on the input parameter (number of required facilities). The system displays the optimal locations, demand points belonging to each location, and mean distance on the map. This feature is useful for emergency response planning as it enables users to identify the most appropriate locations for emergency facilities while minimizing travel distance for demand points. The last function is the service coverage, which displays the routes that users can reach from a defined location within a certain travel distance. This feature is useful for users who need to travel within a specific area, such as first responders, during an emergency.

The system's main web interface offers a range of functions that enable users to visualize and analyze the impact of flooding on roads and bridges, plan travel routes, and identify the best locations for emergency facilities. Figure 1 illustrates the overall architecture and components of the system, including both server and client-side features.

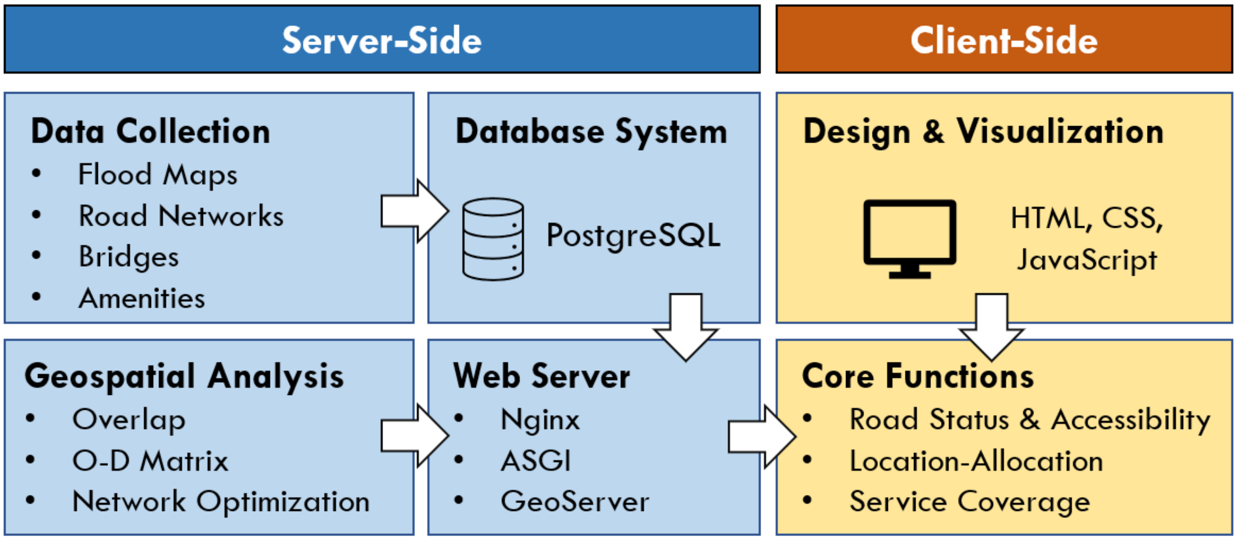


Figure 1. A flowchart illustrating web-based application development.

2.2. Framework Functions

This section describes the implements platform functionalities and underlying methods used in the analytical components.

Road Network Topology

The study utilized graph theory for analyzing the road network topology. Graph theory provides a useful framework to represent and analyze the relationships between network elements in studying the topology of road networks. Specifically, a graph theory equation of the form $G = (V, E)$ can be employed to capture the topology of a road network, where G represents the graph, V denotes the set of vertices or nodes, and E represents the set of edges that connect the vertices (Thomson & Richardson, 1995). The edges of the graph can be directed or undirected, signifying the direction of the route, and can also be assigned a weight or cost, such as the distance between nodes, to reflect the attributes of the network.

Road Conditions Analysis (based on flood return period)

Flooded routes are extracted by overlaying 100 and 500-yr flood return period maps on road networks using two-dimensional geometric object intersection techniques. When the flood inundation extent intersects with a road, the road is closed to traffic. However, the assessment of bridge conditions during flooding requires a three-dimensional set intersection approach (Alabbad et al., 2021), as evaluating the functionality of bridges involves calculating bridge elevation, which is not included in bridge data. In this study, bridge deck elevations were extracted from LiDAR (Light Detection and Ranging) representation, and it is assumed that a bridge is overtopped and closed once the flood depth plus bare earth digital elevation model (DEM) exceeds the height of the bridge deck. In some cases, the DEM was found to be higher than LiDAR elevation, which was related to culvert locations. In these cases, a two-dimensional intersection approach was utilized to assess the condition of the bridge.

Road Conditions Analysis (based on flood stage)

Considering advanced flood prediction systems incorporating stream gauges, it is possible to anticipate flood stages with several days' notice before they occur. This analytical approach enables users to identify closed edges based on flood stages at river gauges, providing more time for individuals to prepare for and respond to potential flooding events. We used QGIS software to perform an intersection algorithm between the flood inundation extent and the road network. The U.S Geological Survey (USGS) is the source of real-time river gauge stage data, while the Hydrologic Ensemble Forecast Service Model Simulations (National Weather Service, 2020) provide the 10-day river level probabilities. With this information, users can proactively prepare for potential flooding events, such as by identifying alternative routes.

Accessibility Analysis

The Dijkstra algorithm (Dijkstra, 1959) has been employed in this study to identify the path with the minimum travel distance from a source node to all nodes within a directed graph. In this study, the algorithm calculates the shortest distance from all nodes to critical amenities (hospitals, police stations, and fire departments) both before and after flooding occurs. QGIS software with the QNEAT3 plugin (2018) is used to implement the algorithm. Following the application of the algorithm, the shortest distance from each node to the closest amenity is obtained. On the map, users can visualize all routes with their distances from a node to the critical amenity. This information can be used to optimize the emergency response during flood events by identifying the most efficient paths from a source location to critical amenities. People can also watch how flooding affects their accessibility and discover alternate safe routes.

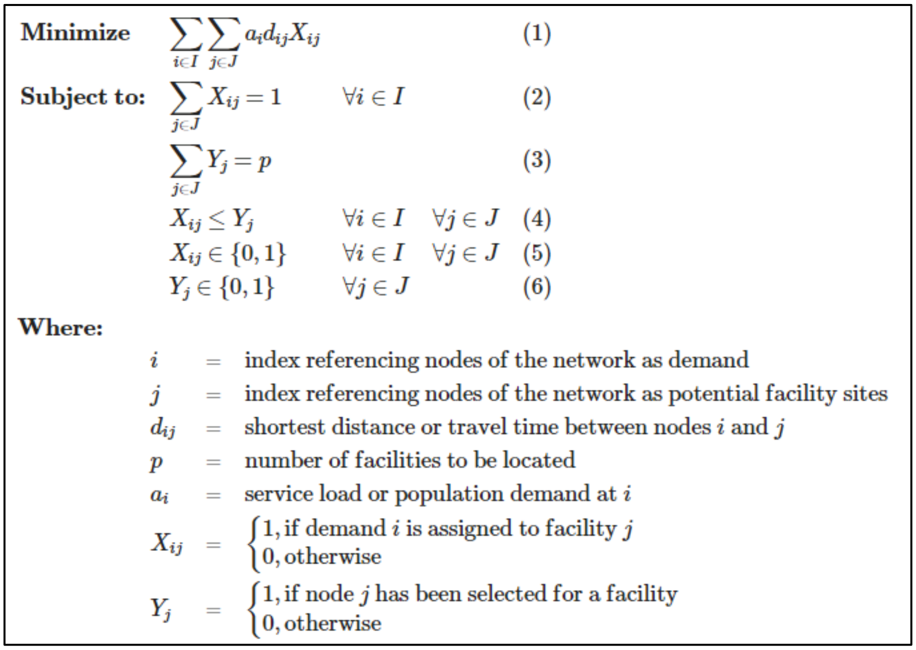
Route Finder

In our study, we employed the Dijkstra algorithm to conduct shortest-path analyses before and after the occurrence of flooding events on a node-to-node basis. We built the routing engine using the ngraph.graph library (Kashcha, 2022), graph data structure in JavaScript, to speed up the process of returning the shortest routes on the map. The library facilitates the construction of a navigable graph using a JSON file that comprises node-to-node features representing a given road network. The constructed graph provides an efficient means to perform rapid searches for the shortest routes connecting two arbitrary points on the graph before and after flooding. This approach enables users to investigate the impact of flooding on the routes in a timely and accurate manner.

Facility Allocation

Critical locations such as ambulance services may face challenges in responding effectively during flooding. This is due to the fact that flooded routes can cause changes in distance and time required to reach the destination, making emergency activity management challenging. Additionally, the baseline emergency locations can be affected due to flooding, resulting in limited accessibility or an unexpected increase in travel costs. To address this issue, our web application integrates the P-median model (Church & Murray, 2018) into the system (Figure 2), allowing users to determine the optimal locations for required facilities. The P-median model involves placing a set number of facilities to minimize the total trip distance and ensure that each demand point is covered by a facility.

In this study, we generated an origin-destination matrix using ArcMap software, with the 2020 census block-based population serving as the demand points (origin) and graph nodes serving as candidates for placing facilities (destination). However, the network used in this study had a large number of nodes, which caused issues when solving the model within our framework. To address this issue, we utilized the betweenness centrality algorithm (Mount et al., 2019) to identify the most important nodes by indicating the number of shortest paths that crossed a node in a graph. This analysis was performed using the PySAL Python library (pysal.org, 2020) and Gurobi optimizer (Gurobi Optimization, 2022). The model can help emergency management teams optimize emergency response and evacuation routes during flood events, ensuring that critical facilities are optimally placed to minimize the total travel distance and cover all demand points.



Minimize

$$\sum_{i \in I} \sum_{j \in J} a_i d_{ij} X_{ij} \qquad (1)$$

Subject to:

$$\sum_{j \in J} X_{ij} = 1 \qquad \forall i \in I \qquad (2)$$

$$\sum_{j \in J} Y_j = p \qquad (3)$$

$$X_{ij} \leq Y_j \qquad \forall i \in I \quad \forall j \in J \qquad (4)$$

$$X_{ij} \in \{0,1\} \qquad \forall i \in I \quad \forall j \in J \qquad (5)$$

$$Y_j \in \{0,1\} \qquad \forall j \in J \qquad (6)$$

Where:

i = index referencing nodes of the network as demand
j = index referencing nodes of the network as potential facility sites
d_{ij} = shortest distance or travel time between nodes i and j
p = number of facilities to be located
a_i = service load or population demand at i
$X_{ij} = \begin{cases} 1, \text{if demand } i \text{ is assigned to facility } j \\ 0, \text{otherwise} \end{cases}$
$Y_j = \begin{cases} 1, \text{if node } j \text{ has been selected for a facility} \\ 0, \text{otherwise} \end{cases}$

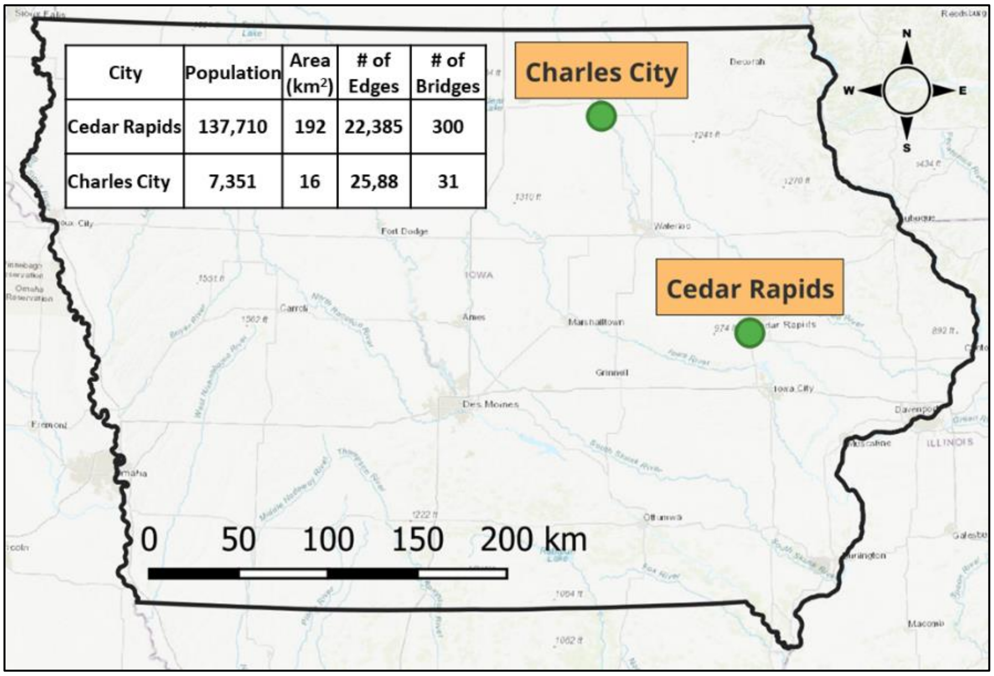
Figure 2. The P-Median Equation used in the analysis (Church & Murray, 2018)

Service Coverage

This analysis aims to identify the geographical areas that are accessible within a given distance from a defined location. The resulting analysis can be visualized as isochrone maps, illustrating the inundation extent to which one can travel from the starting point. In order to construct these maps, we employed the OSMnx and Networkx python libraries (Boeing, 2022), which allowed us to build ego-graphs before and after a flooding event. Ego-graphs enable us to identify all nodes and edges that fall within a specific distance from a designated point. Within the context of this research, the starting point is represented by a graph node, and the edges correspond to the service area covered by the user-defined distance. This approach provides a valuable tool for understanding the spatial distribution of accessibility and can help inform decision-making processes related to urban planning, emergency response, and other relevant domains.

2.3. Case Study

The State of Iowa is recognized as one of the areas in the United States that is highly susceptible to riverine flooding, primarily because it is home to significant rivers, such as the Cedar River, which can potentially inundate nearby communities. Iowa has experienced several major flood events in the past, with the most significant recorded in 2008 (USGS, 2010). During this event, the Cedar River experienced its second-highest crest on record, which resulted in severe flood damage in nearby communities, including Cedar Rapids and Charles City. The introduced framework is tested on two Iowa communities, namely Cedar Rapids and Charles City (Figure 3). The analysis is carried out using the city boundary buffered 3 miles to avoid the effect of the city boundary.



City	Population	Area (km^2)	# of Edges	# of Bridges
Cedar Rapids	137,710	192	22,385	300
Charles City	7,351	16	25,88	31

Figure 3. Cities in current framework.

In order to accomplish the research objective, data has been acquired from multiple sources (refer to Table 1). The Iowa Flood Center has generated 2-dimensional flood maps for different flood return periods (e.g., 10, 50, 100, and 500-yr), which are used to determine road closures. The 100-year and 500-year floods represent flood events with a 1% and 0.2% chance of occurring in any given year, respectively. The road network topology has been extracted from OpenStreetMap (OSM) by utilizing the OSMnx Python library. OSMnx allows for the downloading of edges and nodes for any areas where OSM data is available. Additionally, OSMnx can be used to analyze road networks and provide basic statistical data such as the number of nodes. To identify bridge edges, point geometry information about bridge locations was obtained from Iowa DOT.

Furthermore, Lidar data was utilized to estimate bridge deck heights. To evaluate bridge operation during various flood scenarios, we compared the elevation of each bridge with DEM heights with added flood depths. The bridge is considered closed if the bare earth elevation plus flood depth exceeds the bridge elevation. We have used critical amenities dataset obtained from ArcGIS Business Analyst to assess accessibility before and after flooding. It provides valuable information about essential services and facilities in the studied areas. Also, we employed census block-based population centroids as the demand points for conducting location-allocation analysis. These centroids represent the geographic centers of the population residing in each census block as well as the number of households within each block.

Table 1. Data description and sources.

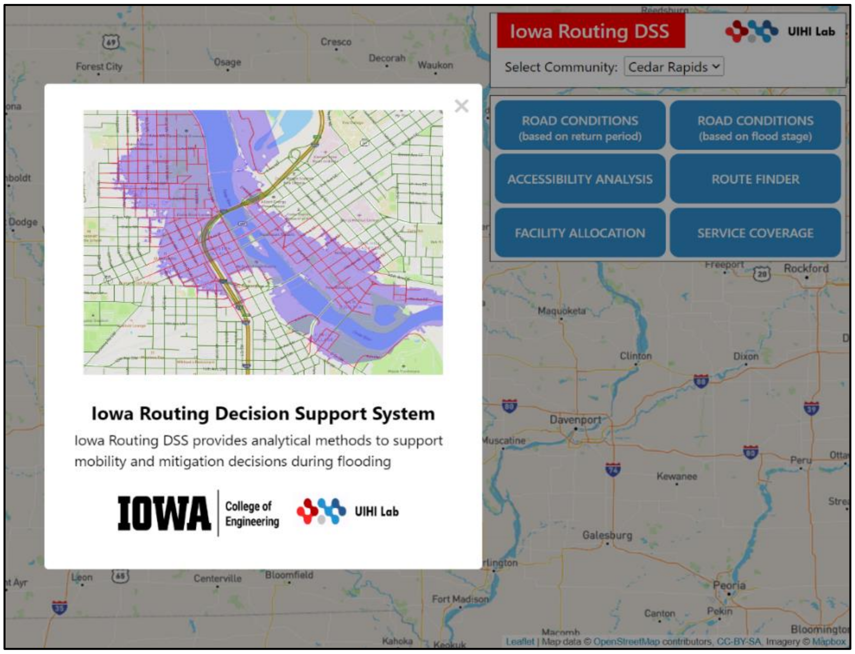
Layers	**Description**	**Source**
Flood maps	High resolution flood inundation maps	(Gilles, 2012)
Road Network	Edges & nodes	OpenStreetMap (Boeing, 2017)
Bridges	Bridge locations	(Iowa DOT, 2019)
Light detection and ranging (LiDAR)	3D positions of objects on the surface	(GeoTREE, 2009)
Digital Elevation Model (DEM)	3-m resolution bare earth elevation	(Iowa Geodata, 2020)
Demographic	Population & households	2020 US Census Bureau
Amenities	Locations of critical infrastructure	(ArcGIS Business Analyst, 2019)

3. Results and Discussions

The developed framework is designed to provide easily accessible routing information during flooding and functions to help the public and emergency responders (e.g., firefighter teams, ambulance) react timely and efficiently. The platform is called Iowa Routing Decision Support System. The main interface of the web application allows the user to select the geographical extent and type of the analysis (see Figure 4).

The analysis of road conditions is conducted based on flood maps corresponding to flood return periods and river gage stages. The flood return period map represents the likelihood of a flood of a certain magnitude occurring within a specific timeframe, while the flood stage-based map provides information about the inundation extent of flooding at various water levels in a river. When selecting the flood return periods-road condition function, the user can choose between different scenarios such as No-flood, 100-yr flood, and 500-yr flood.

The application provides information on open and closed road segments and bridges, as well as an overview of the affected area and total length (see Figure 5). Communities can roughly estimate the costs of mitigating solutions such as road elevation by specifying the complete length of impact. When clicking on a specific road segment, a popup window appears, displaying relevant information such as the segment name, classification (e.g., residential, motorways), and length. Based on the methodology used in this research, we found that the west and east sides of the Charles City network are split by the 500-year flood scenario (Figure 6), which may lead to constraining the mobility of people and emergency providers. The split is the result of flooded roadways surrounding the open bridge.

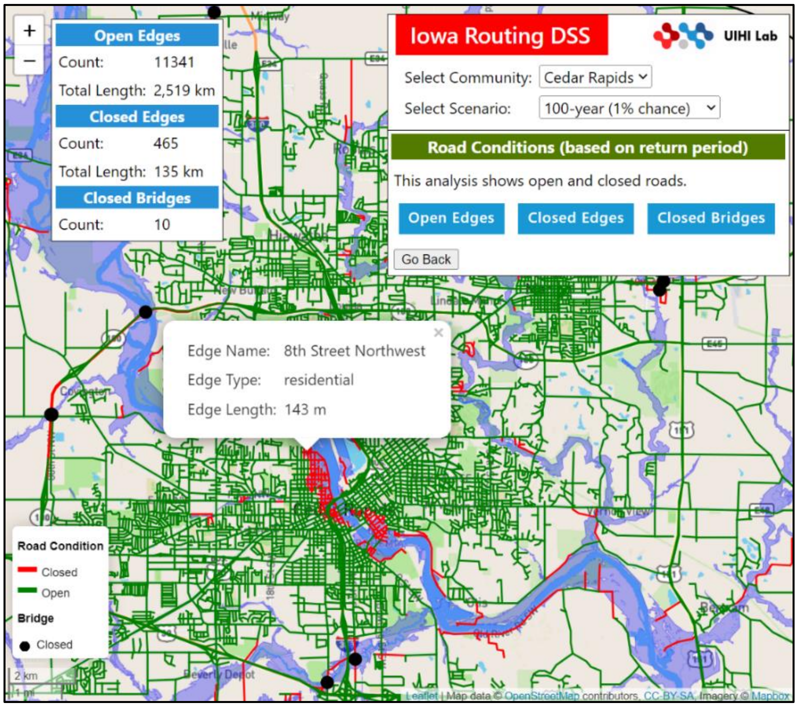


Select Community: Cedar Rapids

Iowa Routing DSS provides analytical methods to support mobility and mitigation decisions during flooding

Figure 4. The main page of the web application.

In this study, we have incorporated 60 and 46 flood inundation extents for Cedar Rapids and Charles City, respectively, into the flood stage-based road condition function. This function allows users to visualize the open and closed edges of the road network based on hypothetical flood scenarios represented by different flood stages (as shown in Figure 7). Closed edges are highlighted in red, indicating inaccessible routes, while green edges indicate accessible routes. Additionally, the most recent river gauge stage from USGS is displayed on the map. Moreover, the map is linked with the prediction of possible flood stages over the next 10 days, allowing users to anticipate future flood conditions and plan accordingly. For instance, critical services can be relocated, or warnings can be issued to the public. This feature provides a valuable tool for emergency responders and local authorities in managing flood events and reducing the damage caused by floods.



Open Edges
Count: 11341
Total Length: 2,519 km
Closed Edges
Count: 465
Total Length: 135 km
Closed Bridges
Count: 10

Iowa Routing DSS

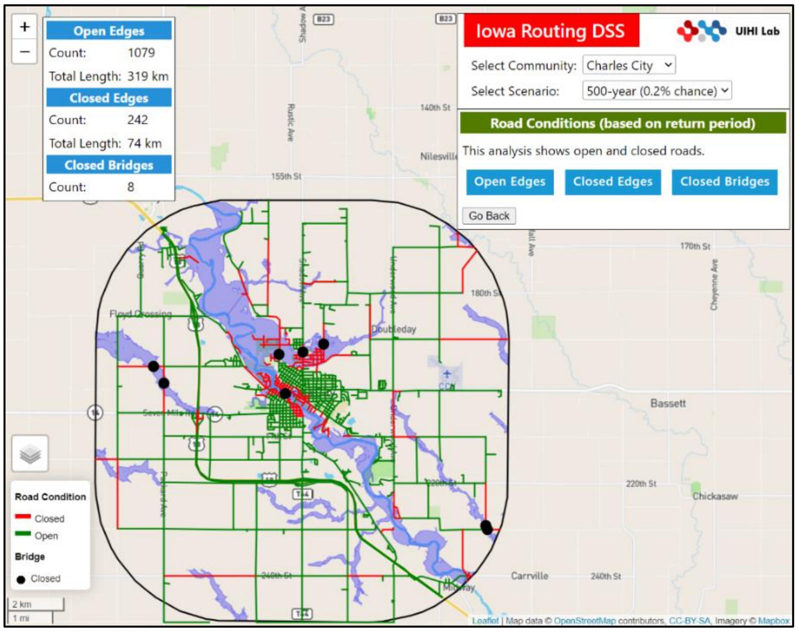
Select Community: Cedar Rapids
Select Scenario: 100-year (1% chance)

Road Conditions (based on return period)

This analysis shows open and closed roads.

Edge Name: 8th Street Northwest
Edge Type: residential
Edge Length: 143 m

Figure 5. Representation of open and closed edges and bridges for Cedar Rapid during 100-yr flood event.



Open Edges
Count: 1079
Total Length: 319 km
Closed Edges
Count: 242
Total Length: 74 km
Closed Bridges
Count: 8

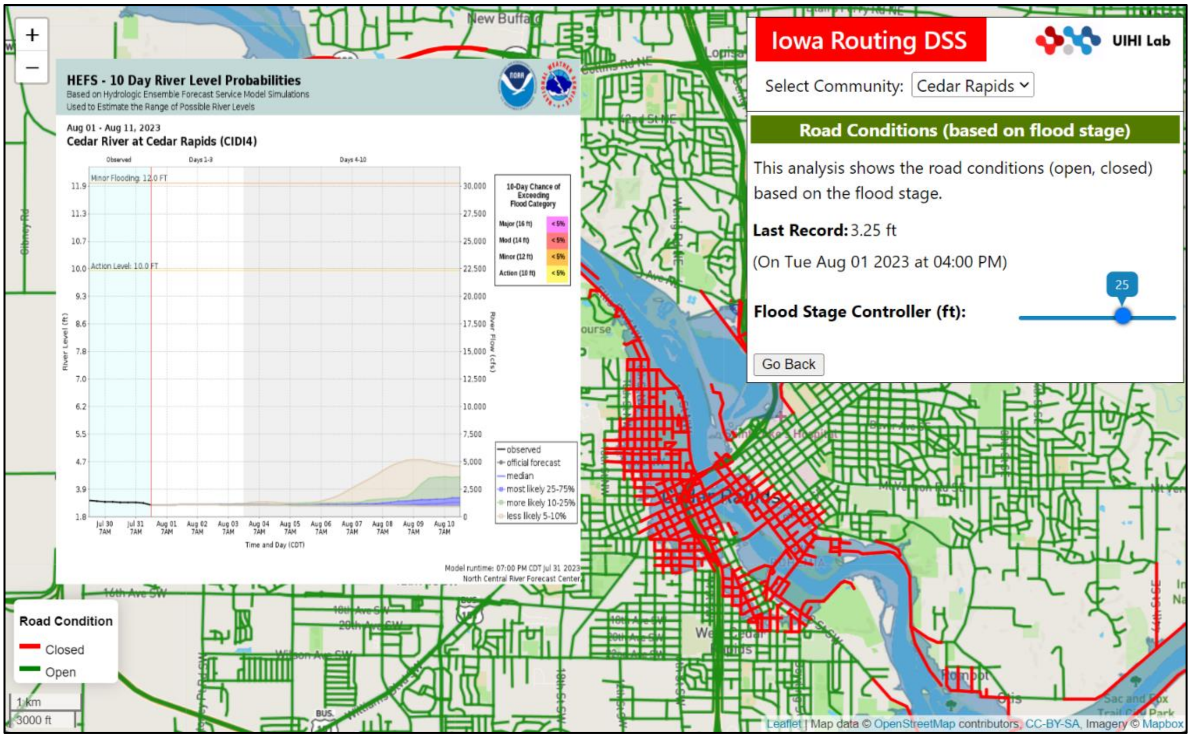
Iowa Routing DSS

Select Community: Charles City
Select Scenario: 500-year (0.2% chance)

Road Conditions (based on return period)

This analysis shows open and closed roads.

Figure 6. Charles City’s Road network under the 500-yr flood event.



Select Community: Cedar Rapids

This analysis shows the road conditions (open, closed) based on the flood stage.

Last Record: 3.25 ft

(On Tue Aug 01 2023 at 04:00 PM)

Flood Stage Controller (ft): 25

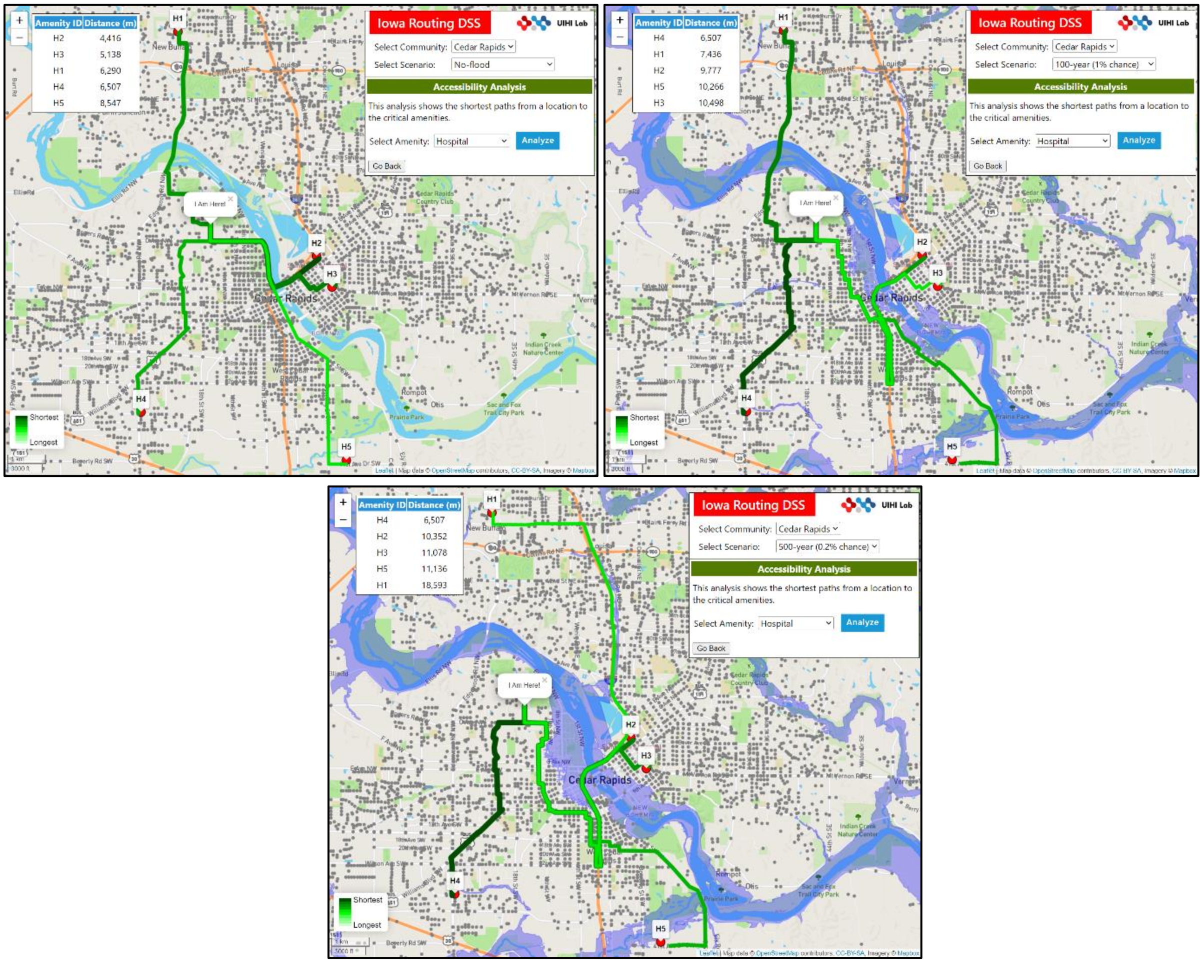
Figure 7. Road conditions based on the flood stage for the city center of Cedar Rapids.

The third function of the framework provides an analysis of accessibility from all nodes in the network to the nearest amenities before and after the 100-year and 500-year flood events. An example of this analysis applied to the Cedar Rapids area for the nearest hospitals is illustrated in Figure 8. The shortest traversable paths to the closest hospitals can change during flooding, and the darker green paths represent the shortest distances. The fourth-closest hospital (H4) in the baseline scenario becomes the nearest reachable hospital during the 100-year and 500-year flood events. This indicates that flooding can significantly affect the accessibility to critical facilities such as hospitals, which can impact emergency response and recovery efforts.

The pathfinder module's analysis indicates that flooding can considerably affect the shortest routes. The framework allows the users to explore the shortest paths under varying flood conditions by dragging markers on the map (A or B). Figure 8 provides an example of generating the route from the same starting point to the same endpoint in Charles City. The green route represents the shortest path under normal conditions, while the yellow and red routes depict the shortest paths during 100- and 500-year flood events, respectively. The figure clearly shows that the distance required to reach the endpoint increased from the no-flood scenario by 6.7 km under the 100-yr flood scenario and nearly 13 km under the 500-yr flood. Such analysis can prove highly useful for emergency providers and the general public, as it enables them to quickly identify the shortest and safest paths during flooding, thereby avoiding flooded routes and saving both time and fuel.

The Facility Allocation function enables the user to allocate a series of facilities such that the total distance from all demand points (i.e., census blocks) to all candidate locations is minimized.

Candidate nodes are those included in the 90th percentile on betweenness centrality analyses. These are the locations where a facility could be located. We use centrality measures to bias results towards nodes that are topologically robust from an accessibility perspective. The available facility numbers range from 1 to 8, and upon selection, the location and demand are automatically populated.



Amenity ID	Distance (m)
H2	4,416
H3	5,138
H1	6,290
H4	6,507
H5	8,547

Select Community: Cedar Rapids
Select Scenario: No-flood
This analysis shows the shortest paths from a location to the critical amenities.
Select Amenity: Hospital

Amenity ID	Distance (m)
H4	6,507
H1	7,436
H2	9,777
H5	10,266
H3	10,498

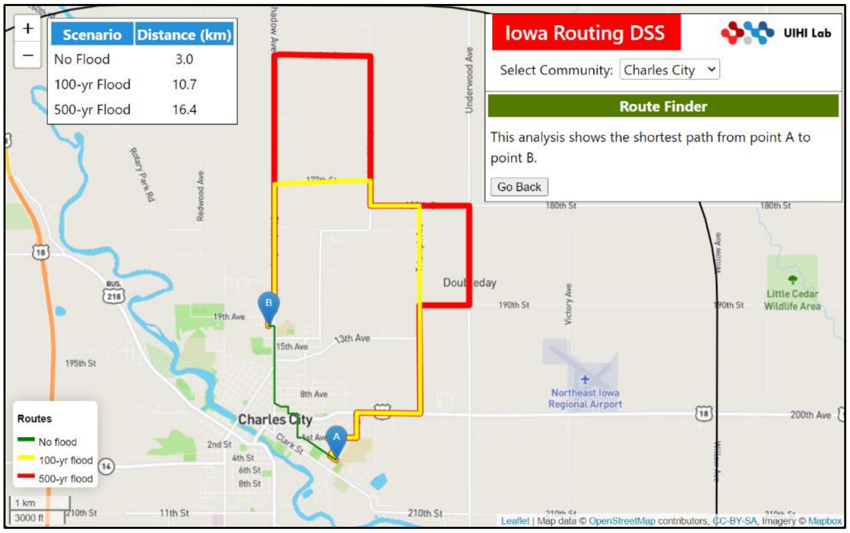
Select Community: Cedar Rapids
Select Scenario: 100-year (1% chance)
This analysis shows the shortest paths from a location to the critical amenities.
Select Amenity: Hospital

Amenity ID	Distance (m)
H4	6,507
H2	10,352
H3	11,078
H5	11,136
H1	18,593

Select Community: Cedar Rapids
Select Scenario: 500-year (0.2% chance)
This analysis shows the shortest paths from a location to the critical amenities.
Select Amenity: Hospital

Figure 8: An example of the shortest path analysis from a point to hospitals before (no flood scenario) and after flooding (100yr, 500yr scenarios).

Additionally, the mean distance, total population, and households associated with each proposed facility are displayed. However, it is important to note that inundated edges can influence the potential facility locations and demand points. As depicted in Figure 10, some of the blue demand points, especially those located in the city center, have been reassigned to the red facility (ID:160368586) under the 500-yr flood scenario. This analysis aids in determining optimal locations for accommodating demand points, particularly in areas prone to flooding.



Scenario	Distance (km)
No Flood	3.0
100-yr Flood	10.7
500-yr Flood	16.4

Iowa Routing DSS

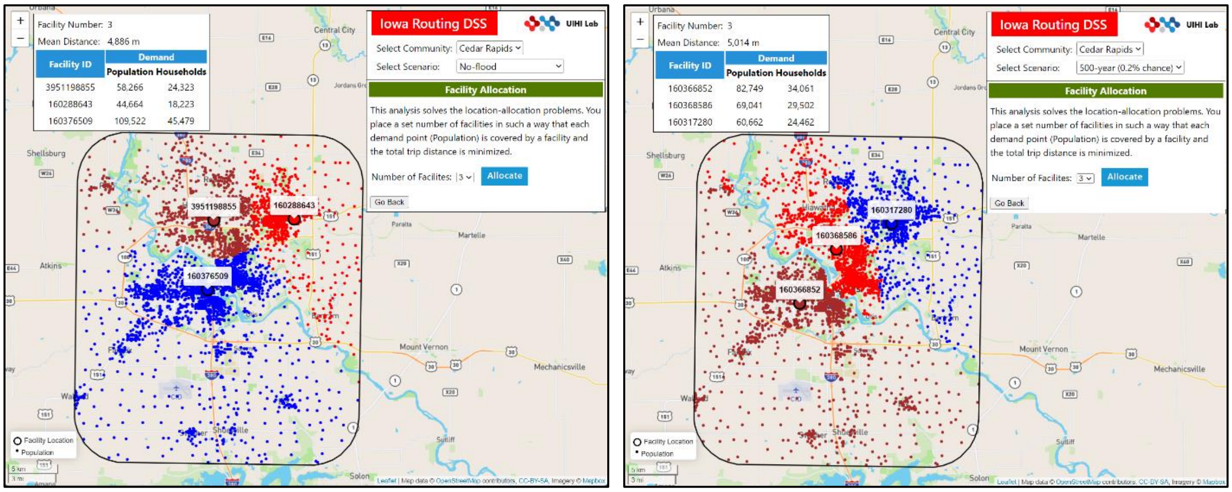
Select Community: Charles City

Route Finder

This analysis shows the shortest path from point A to point B.

Figure 9. Shortest paths representation from point A to point B before and after flooding.

The service coverage analysis function of the framework enables the user to input a specific travel distance and select any node within the graph to determine the corresponding edges covered within the specified range. This function is particularly useful in locating emergency activities, such as ambulances, during and prior to flooding events. The obtained information helps the user to understand how far they can travel from a particular point. The accompanying Figure 11 provides an instance of a service area analysis result from a graph node in Cedar Rapids. This figure indicates that during the 500-year flood, most baseline edges on the western side remain uncovered. Thus, the service area analysis function can provide valuable insights to emergency responders and aid in developing more effective disaster response plans.



Facility Number: 3

Mean Distance: 4,886 m

Facility ID	Demand	
	Population	Households
3951198855	58,266	24,323
160288643	44,664	18,223
160376509	109,522	45,479

Iowa Routing DSS

Select Community: Cedar Rapids

Select Scenario: No-flood

Facility Allocation

This analysis solves the location-allocation problems. You place a set number of facilities in such a way that each demand point (Population) is covered by a facility and the total trip distance is minimized.

Number of Facilites: 3

Facility Number: 3

Mean Distance: 5,014 m

Facility ID	Demand	
	Population	Households
160366852	82,749	34,061
160368586	69,041	29,502
160317280	60,662	24,462

Iowa Routing DSS

Select Community: Cedar Rapids

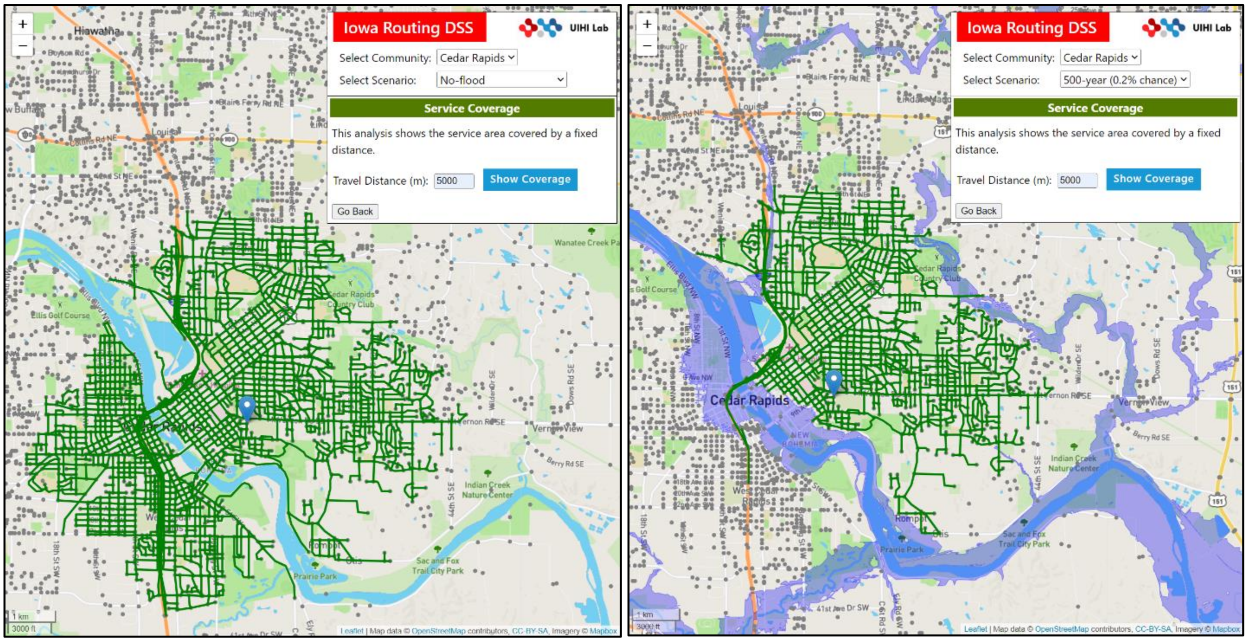
Select Scenario: 500-year (0.2% chance)

Facility Allocation

This analysis solves the location-allocation problems. You place a set number of facilities in such a way that each demand point (Population) is covered by a facility and the total trip distance is minimized.

Number of Facilites: 3

Figure 10. An example of allocating three emergency facilities in Cedar Rapids under no flood (left) and 500-yr (right) flood scenarios.


Iowa Routing DSS

Select Community: Cedar Rapids

Select Scenario: No-flood

Service Coverage

This analysis shows the service area covered by a fixed distance.

Travel Distance (m): 5000

Iowa Routing DSS

Select Community: Cedar Rapids

Select Scenario: 500-year (0.2% chance)

Service Coverage

This analysis shows the service area covered by a fixed distance.

Travel Distance (m): 5000

Figure 11. Service area from a defined location during the baseline scenario and the 500-yr flood event.

4. Conclusions and Future Work

This research presents a web-based framework for routing and allocating emergency facilities during flood scenarios. The framework employs various geospatial analytics and optimization methods, including graph theory and facility location optimization. We have implemented these methods to the road networks of two Iowa communities, namely Cedar Rapids and Charles City, to thoroughly evaluate the system's functions before and after flood events and visualize the outcomes on an interactive map. The system enables users to examine flooded routes and shortest paths to critical amenities, point-to-point routing, and perform location-allocation and service area analysis.

The findings indicate that inundated routes significantly impact accessibility to critical amenities, as well as the location-allocation and service areas. The developed web application facilitates access to information for decision-makers, including citizens and emergency responders, enabling them to respond appropriately to flooding irrespective of their technical knowledge. Furthermore, the system visualizes the results on the map in near-real-time without the need for expensive back-end systems, which may impede non-technical users and communities with limited resources. The framework's functionalities can help communities increase awareness of flood impacts on road networks, navigate around flooded routes, determine optimal locations for emergency services, and identify evacuation routes.

During this research, some challenges were encountered. Flood stage maps depict the floodplain for the gauged river, so the road conditions (based on flood stage) function may not support location without stage monitoring stations. The route finder function is designed with the assumption that each edge (road segment) has a two-way direction. This may not be constrained for emergency providers (e.g., police) as they can reverse the direction during an emergency. While it is vital to assess all network nodes when allocating emergency facilities, our research used the betweenness centrality measure to decrease the number of locations (nodes) due to solver memory limitations. Also, the extent and scale of the geographic area can complicate the process when analyzing road networks. Our study is applied within the city boundary area plus 3 miles to lessen the influence of the city boundary. This assumption, however, can limit some analyses (e.g., no shortest paths found), as in Charles City, where the west and east side of the network are separated under the 500-yr flood scenario.

To enhance the system's capabilities, future research could extend the framework to provide interactive routing analysis across different transportation modes (e.g., walking, bicycle, bus) during flooding as cities are reengineered as forces for good in the environment (Beck et al., 2010). Also, real-time flood inundation maps (Li & Demir, 2022), such as those generated using the Height Above Nearest Drainage (HAND) method, could be coupled with routing tools to enhance navigation and infrastructure management during flood events (Li et al., 2022). Traffic management during flood events is crucial, and traffic density should be taken into account in future investigations. Additionally, it is important to assess the resilience of critical amenities during flooding at various spatial scales to understand the impacts and take necessary actions, such as relocating facilities, to ensure an effective response. Social vulnerability analysis (Cikmaz et al., 2023) should also be integrated into the framework's facility allocation function to consider the requirements of susceptible groups, including individuals with disabilities and elderly people. The information generated by the system can be used to support affected people using social media.

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