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Intelligent Transportation Network Decision Support with Real-time Routing and Data Analytics

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16. Abstract This project aims to develop a real-time data analytics framework for transportation network analysis during disasters, focusing on flooding. By integrating wayfinding techniques with dynamic data from DOT and federal agencies, it provides emergency services and residents with real-time routing options and information on shelters. Initially piloted in flood- prone Iowa cities, the framework will eventually include AI-driven decision-making and communication features. It will also accommodate factors like road conditions, traffic, and population changes to ensure its effectiveness during emergency situations.			
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List of Abbreviations

Mid-America Transportation Center (MATC) Nebraska Transportation Center (NTC)

Iowa Flood Center (IFC)

University of Iowa Hydroinformatics Lab (UIHILAB)

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Abstract

Transportation systems can be significantly affected by flooding, leading to physical damage and hindering accessibility. Despite flooding being a frequent occurrence, there are limited accessible online tools available for supporting routing and emergency planning decisions during flooding. Existing tools are generally based on complicated models and are not easily accessible to non-expert users, highlighting the need for efficient communication and decision-making 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.

Executive Summary

Flooding significantly impacts transportation systems, causing damage and reducing accessibility. Despite frequent occurrences, there are few accessible online tools to aid in routing and emergency planning during floods. Existing tools are complex and not user-friendly for non-experts, highlighting a need for effective decision-making resources for various stakeholders.

This project presents a user-friendly web application leveraging graph network methods and modern web technologies to analyze flood impacts on transportation networks. It enables non- expert users to easily access information on road status, the shortest paths to critical amenities, location-allocation, and service coverage. Field testing in Cedar Rapids and Charles City, Iowa, demonstrated the application's ability to address disruptions in bridge operations, routing to essential services, arbitrary routing, and emergency facility planning. The application simplifies complex flood-related tasks and clarifies transportation vulnerabilities, enhancing mitigation strategies. Thus, this web application is a valuable tool for stakeholders to make informed transportation decisions during flood events.

Chapter 1 Background and Problem Introduction

Flooding is a major global threat, causing displacement, infrastructure damage, and financial losses (Borowska-Stefańska et al., 2017; McDermott, 2022). From 1980 to 2022, the U.S. experienced 37 flood disasters, each causing over 50 fatalities and exceeding one billion dollars in damages (NOAA, 2022). Ongoing efforts to regulate flood risk (Yildirim et al., 2022) are challenged by factors like poor planning and climate change, which are expected to increase flood frequency and magnitude (Kundzewicz et al., 2014). Effective flood risk management necessitates urgent development of both long and short-term strategies (Rentschler & Salhab, 2020).

Flood risk assessment is critical for managing flood hazards and reducing damage by evaluating hazards, exposure, and vulnerability (Reisinger et al., 2020; Yildirim & Demir, 2022). It involves assessing flood hazards and identifying at-risk areas (Alabbad & Demir, 2022). Flood disaster management includes preemptive measures like flood prevention (Tingsanchali, 2012). Routing systems are essential for maintaining social and economic activities and are particularly vital during disasters like floods, which disrupt transportation networks (Yin, 2016).

Floods can impair roads, leading to issues such as bridge failures and access loss, highlighting the need for reliable routing systems (Haltas et al., 2021). Addressing human limits in understanding flooding's impact is crucial as flooded roads can cause economic losses and business closures (Winter et al., 2019) and have been significant in flood-related fatalities in the U.S. (FEMA, 2019). Efficient routing systems are necessary for managing transportation networks during disasters (Alabbad et al., 2022).

Various studies have explored road network behavior during floods, employing methods like spatial intersection analysis and graph theoretical approaches for emergency planning (Papilloud et al., 2020; Yin et al., 2017; Demirel et al., 2015; Alabbad et al., 2021). Vulnerability indices and accessibility measures assess network performance and critical link identification (Murray-Tuite et al., 2004; Chen et al., 2015). Other research extends to routing in natural and human-induced hazards, including earthquakes (Alipour & Shafei, 2016) and terrorist attacks (Lou & Zhang, 2011).

Advancements in information technology have enhanced data analysis and visualization for flood risk management (Xu et al., 2019; Demir et al., 2009). Decision support systems (DSS) help assess flood impacts on accessibility and manage emergencies, incorporating routing with flood hazard information (Mirfenderesk, 2009; Windhouwer et al., 2005; Kaviani et al., 2015). Existing applications like Google Maps and the 511 website have limitations in providing flood-specific routing and emergency features (Iowa DOT, 2022). A need exists for interactive web platforms to guide people and assist in planning during flooding, especially for facility allocation. Timely information access during floods is crucial as new research during events is impractical. It is vital to study road network vulnerability to build resilient transportation systems (Akhlaghi et al., 2023).

1.1 Project Objectives

This project presents a web-based routing decision support system that integrates flood scenarios into various analytical processes, focusing on enhancing flood response and recovery efforts. It is designed to assist various stakeholders (e.g., public and emergency responders) in navigating around flooded roads, exploring accessibility to critical amenities, and facilitating efficient response by accessing optimization functions (i.e., location-allocation and 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). Beyond its accessibility, the system serves as a significant resource for minimizing the risk of being caught in a flood, providing alternative routes, and relocating essential supplies to improve flood response. Our approach strategically integrates well-established techniques into the developed framework, contributing to the scientific domain by providing a comprehensive solution to flood-related decision-making.

Chapter 2 Methodology

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 Python for the back-end server and 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.

2.1.1 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 and served as inputs for the system's methods. 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, and hosted at the University of Iowa Hydroinformatics Lab (UIHILAB) servers.

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.

2.1.2 Client-Side Components

The web interface is developed using HTML, CSS, and JavaScript, with Leaflet (Agafonkin, 2022) for interactive map display. The entry page provides access to the framework's main functions via an intuitive design, featuring an OpenStreetMap and Mapbox-compatible base with scale and zoom controls. Users can define their area and scenario (no flood or flood event) to examine. The system offers six main functions:

- Road Assessment: Visualizes open and closed roads and bridges under various flood conditions, providing a summary of affected segments.
- Road Conditions by Flood Stage: Displays closed and open routes based on river flood stages, showing flood inundation extents and current and 10-day flood levels, allowing advance planning to avoid affected areas.
- Accessibility Analysis: Shows the shortest paths from a defined location to critical amenities such as fire departments and hospitals pre- and post-flood. Users can view distance information for route planning.
- Point-to-Point Routing (Route Finder): Finds the shortest path between any two locations, dynamically updating routes and distances considering potential flooding effects.
- Facility Allocation: Identifies optimal locations for emergency sites, displaying locations, demand points, and mean distances to aid emergency planning.
- Service Coverage: Displays reachable routes from a defined location within a set travel distance, useful for emergency travel planning.

Figure 2.1. depicts the system's architecture and components, highlighting server and client-side features.

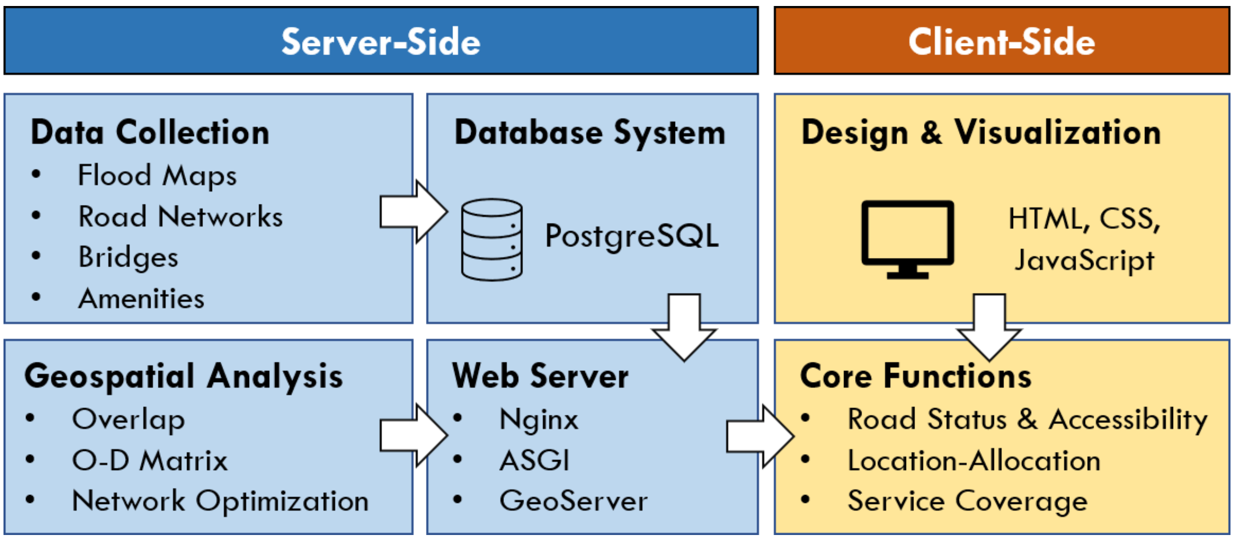

Figure 2.1 A flowchart illustrating web-based application development

2.2 Framework Functions

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

2.2.1 Road Network Topology Analysis

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.

2.2.2 Road Conditions Analysis (Flood Return Period)

Flooded routes were identified by overlaying 100- and 500-year flood maps on road networks using intersection techniques. Bridge conditions during floods were assessed using LiDAR for elevation data (Alabbad et al., 2021). Bridges were closed if flood depth plus DEM exceeded deck height, with a 2D approach applied where DEM surpassed LiDAR elevation.

2.2.3 Road Conditions Analysis (Flood Stage)

Advanced flood prediction systems allow preemptive flood stage identification using river gauges. We used QGIS to intersect flood extents with road networks, aided by USGS and National Weather Service data, to help users plan alternative routes.

2.2.4 Accessibility Analysis

The Dijkstra algorithm (Dijkstra, 1959) finds the shortest paths from nodes to critical amenities pre- and post-flood. Inundated roads are excluded in the analysis using QGIS and QNEAT3 (2018), optimizing emergency response by identifying efficient paths to amenities.

2.2.5 Point-to-Point Routing (Route Finder)

The Dijkstra algorithm was applied for shortest-path analysis before and after floods using ngraph.graph in JavaScript (Kashcha, 2022), constructing a graph to quickly identify routes between points.

2.2.6 Facility Allocation

The P-median model (Church & Murray, 2018) was integrated to optimize facility placement, minimizing trip distance from demand points (census blocks) to graph nodes. Betweenness centrality analysis (Mount et al., 2019) using PySAL and Gurobi (2022) identified key nodes to enhance emergency response.

2.2.7 Service Coverage

Service coverage was analyzed using OSMnx and Networkx (Boeing, 2022) to create isochrone maps, showing accessible areas from a point under given conditions. This informs urban planning and emergency response decisions.

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 2.2). The analysis is carried out using the city boundary buffered with an additional three miles to avoid the effect of the city boundary.

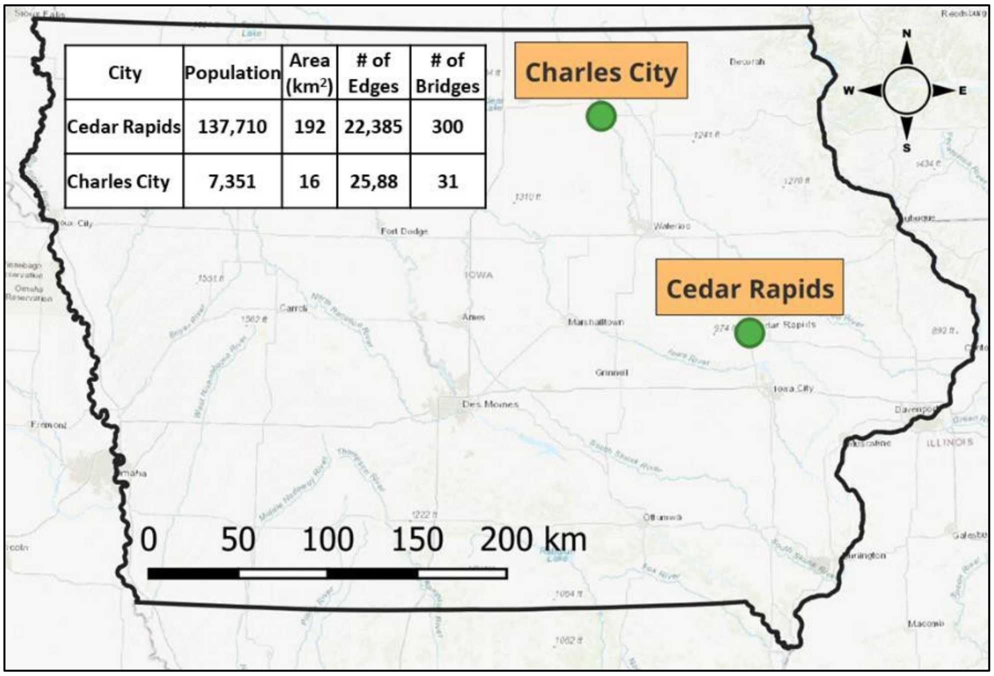

Figure 2.2 Cities in the case study for the decision framework

2.3.1 Data Preparation

To achieve the research objective, data was sourced from various origins (see Table 2.1). The Iowa Flood Center (IFC) provided 2D flood maps for different return periods (10, 50, 100, and 500 years) to determine road closures. The 100-year and 500-year events represent 1% and 0.2% annual probability floods. IFC also supplied flood stage-based inundation maps for assessing road conditions by stage. Road network topology was extracted from OpenStreetMap (OSM) using the OSMnx Python library, which downloads and analyzes network data and statistical information like node count.

Table 2.1 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)

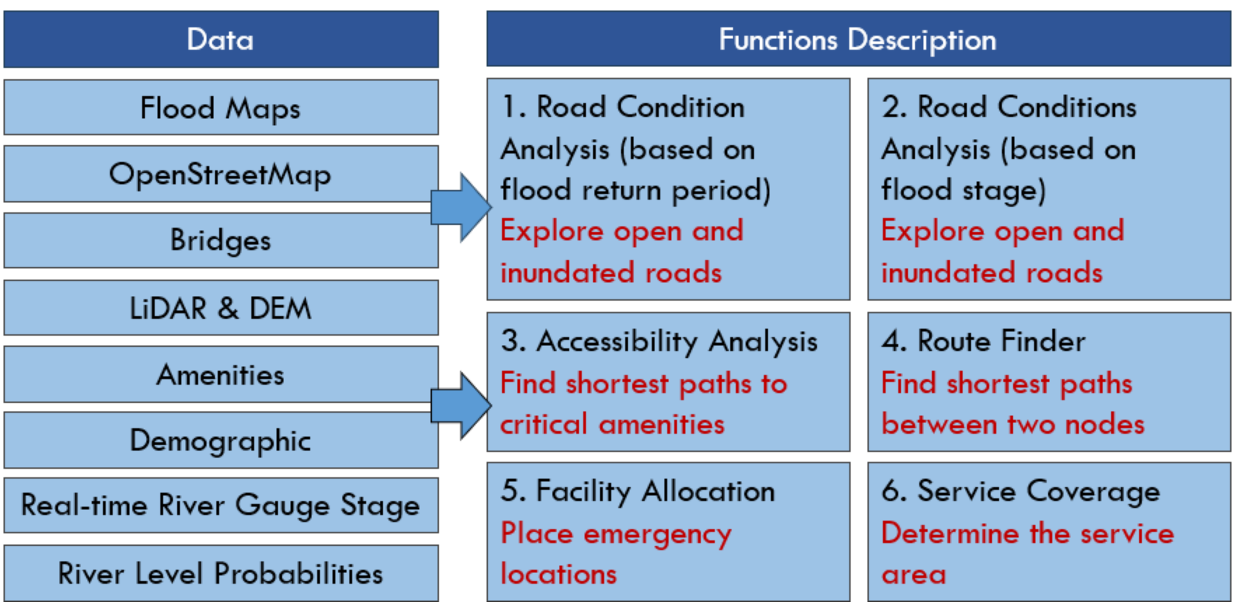

Figure 2.3 Cities in the case study for the decision framework

Iowa DOT provided bridge location data, and LiDAR was used to estimate bridge deck heights. Bridge operation was evaluated by comparing deck elevations with DEM heights plus flood depths; bridges are closed if flood depth plus elevation exceeds deck height. The ArcGIS

Business Analyst's critical amenities dataset assessed accessibility pre- and post-flood, detailing essential services in study areas. Census block population centroids were used as demand points for location-allocation analysis, representing geographic centers and household counts. Figure 2.3 visualizes data and framework functions.

Chapter 3 Results

The Iowa Routing Decision Support System provides accessible routing information during floods, aiding public and emergency responders like fire and ambulance teams. The main web interface allows users to select their analysis type and area (see Figure 3.1).

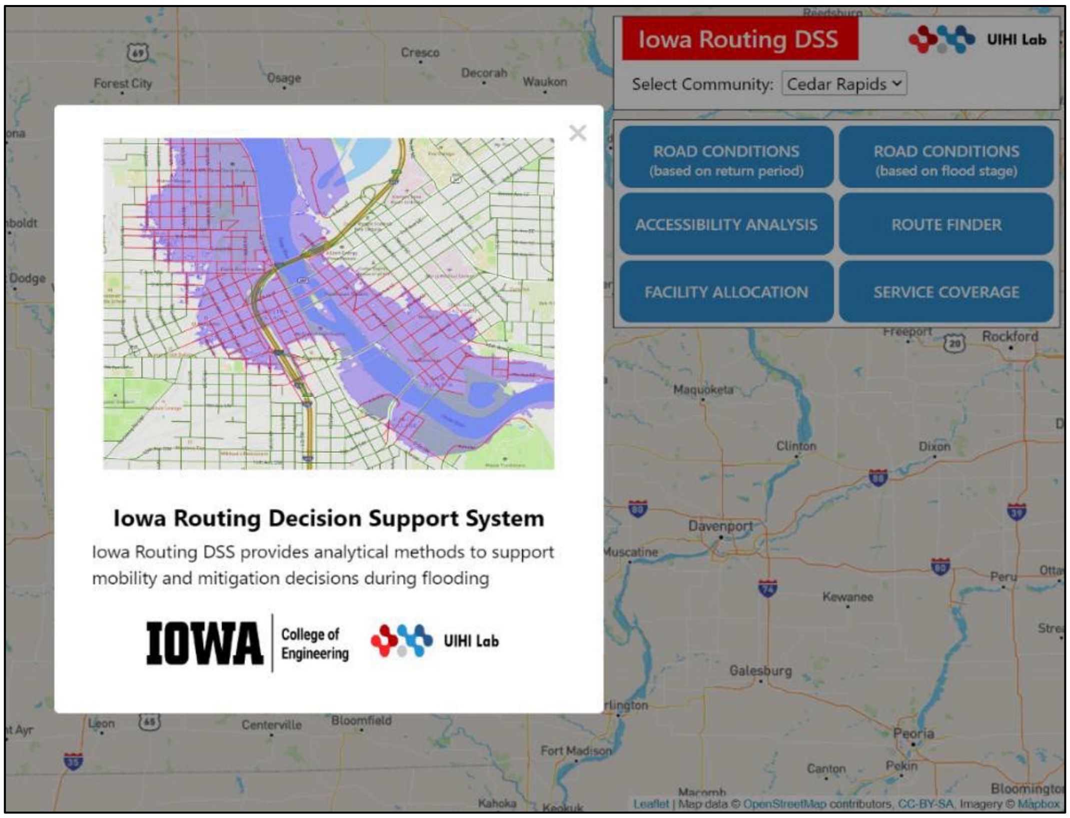

Figure 3.1 The main page of the web application

Road conditions are analyzed using flood maps for return periods and river stages. The tool identifies open and closed road segments and bridges (Figure 3.2), helping communities estimate road elevation mitigation costs. Users can access detailed segment information through pop-ups. Notably, the 500-year flood scenario splits Charles City's network, affecting mobility (Figure 3.3).

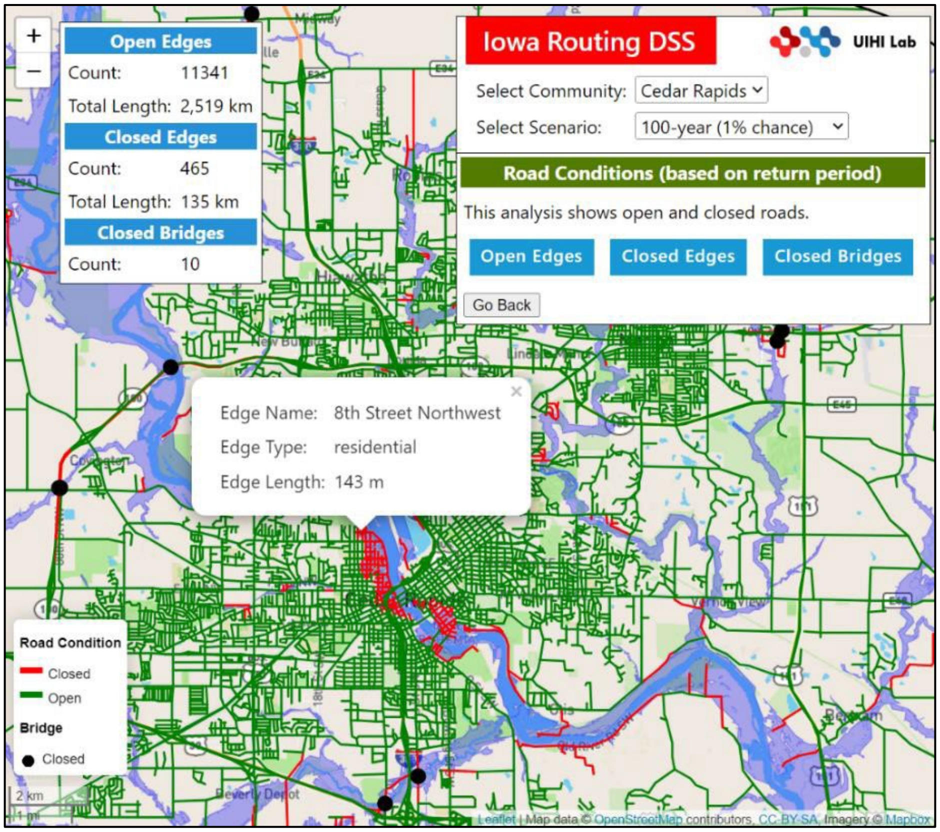

Figure 3.2 Representation of open and closed edges and bridges for Cedar Rapid during 100-yr flood event

For Cedar Rapids and Charles City, 60 and 46 inundation extents, respectively, are integrated into the flood stage-based road condition function. This visualizes open and closed road network edges under various hypothetical scenarios, aiding planning for potential future floods (Figure 3.4).

The framework's accessibility analysis examines network paths to nearest amenities pre- and post-flood. For instance, in Cedar Rapids, flooding alters the shortest paths to hospitals, affecting emergency response efforts (Figure 3.5).

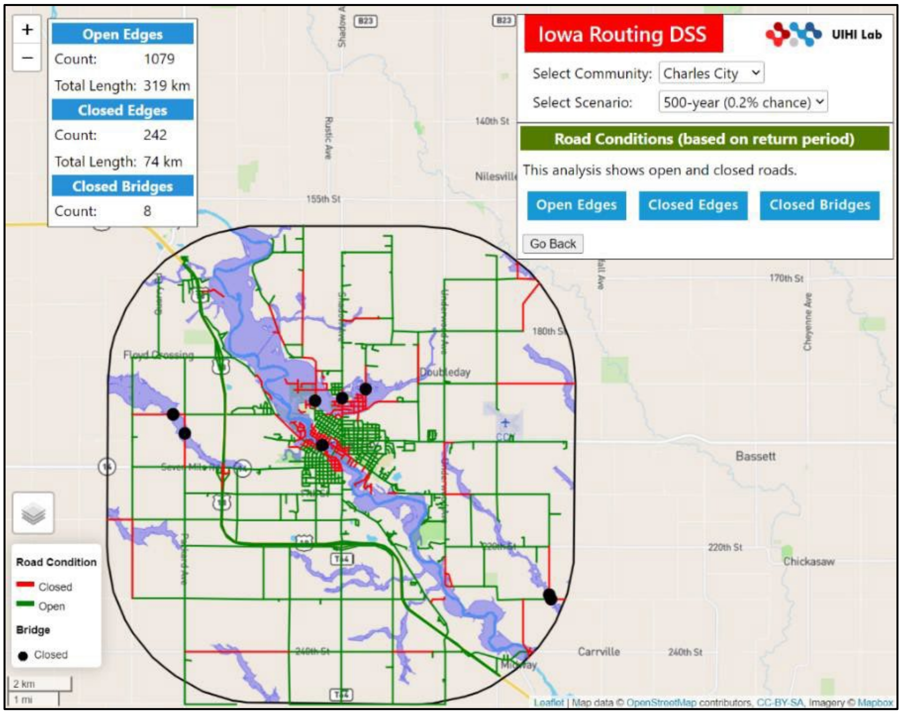

Figure 3.3 Charles City's Road network under the 500-yr flood event.

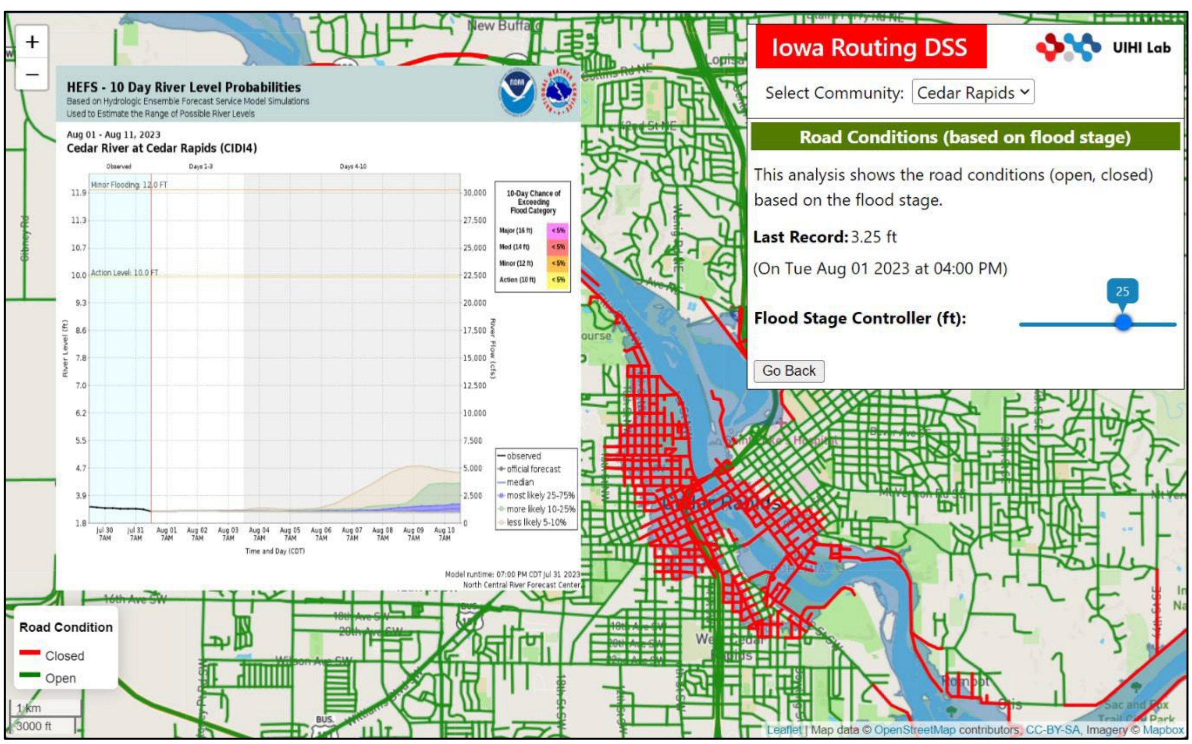

Figure 3.4 Road conditions based on the flood stage for the city center of Cedar Rapids.

Pathfinder analysis shows flooding affects shortest routes. Users can explore paths for different conditions by adjusting map markers; for example, the distance from start to endpoint in Charles City increases under flood scenarios (Figure 3.6).

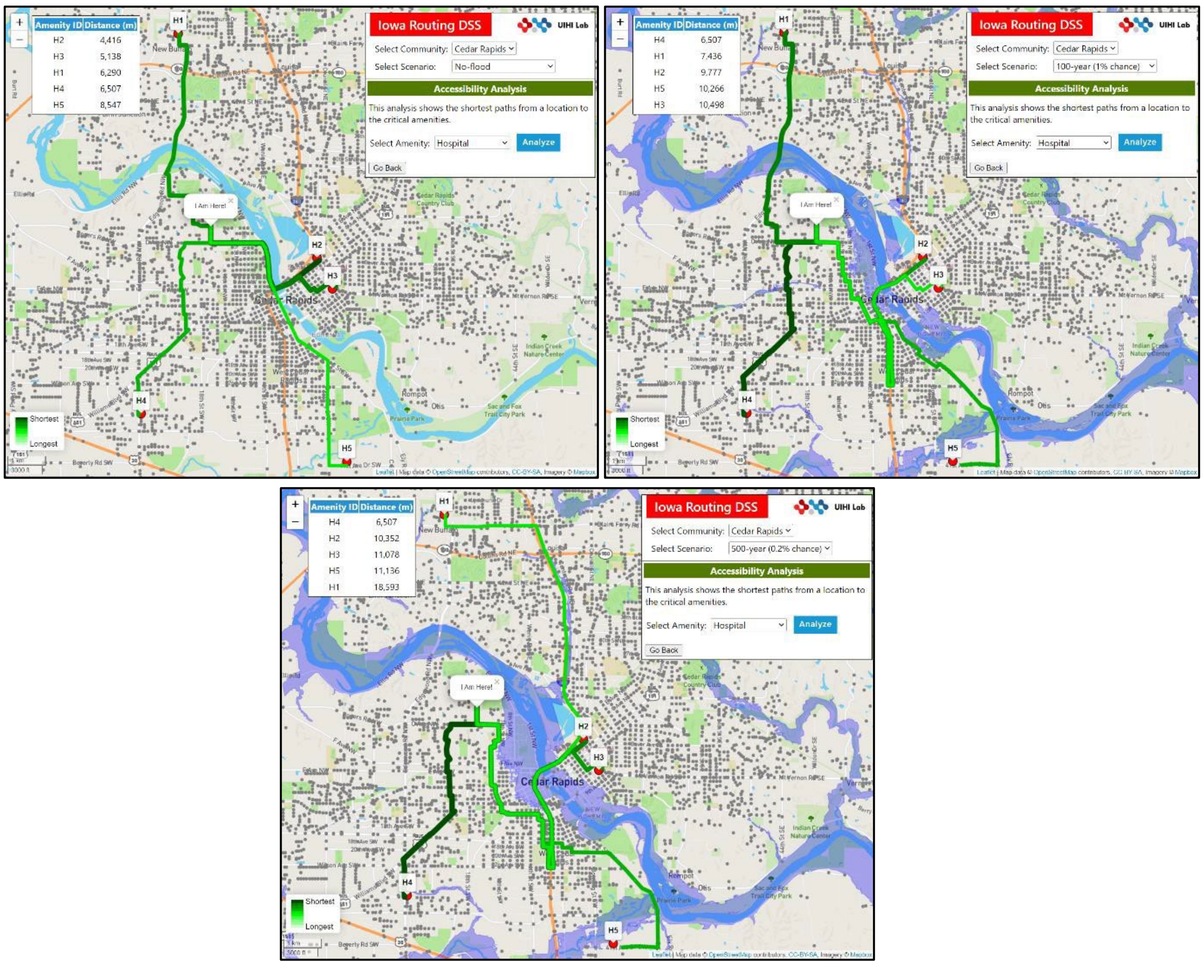

Figure 3.5 An example of the shortest path analysis from a point to hospitals before (no flood scenario) and after flooding (100yr, 500yr scenarios).

Facility allocation minimizes distances from demand points to facilities, focusing on nodes robust in accessibility. In flooded scenarios, demand shifts to alternate facilities (Figure 3.7), helping optimize locations for flood-prone areas.

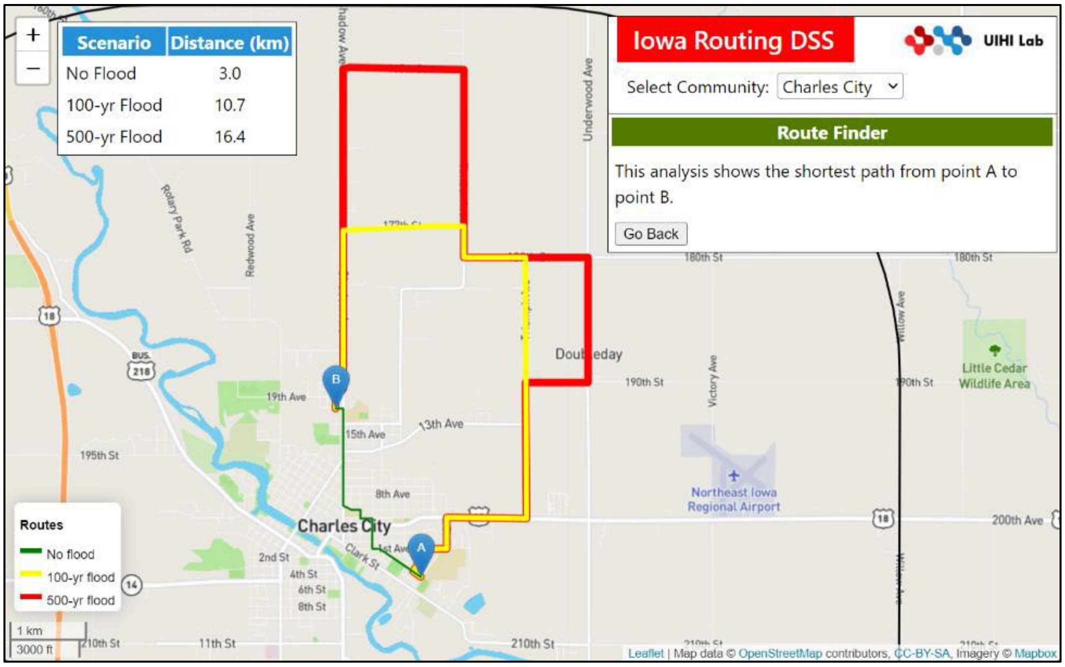

Figure 3.6 Shortest paths representation from point A to point B before and after flooding.

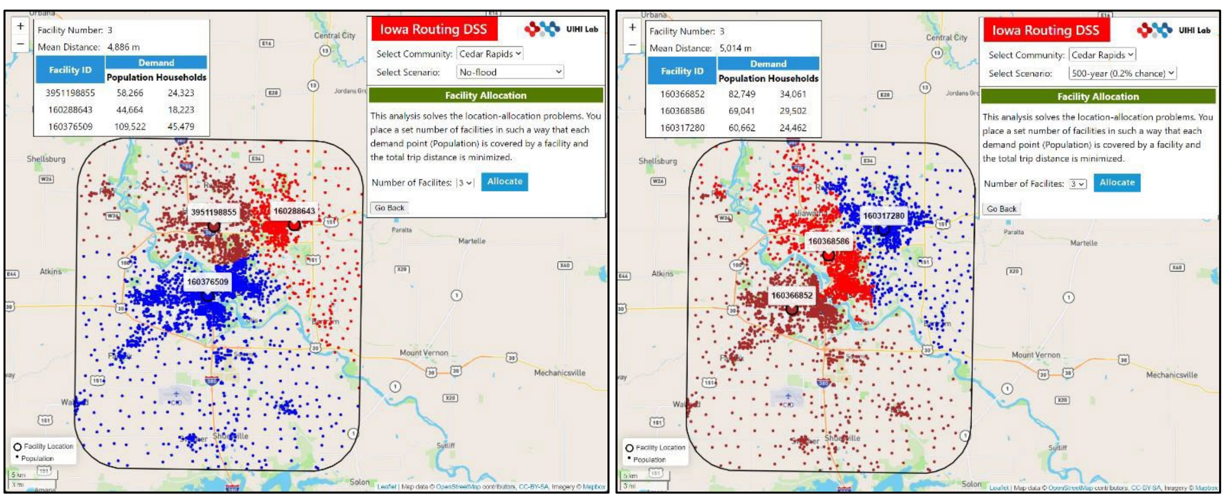

Figure 3.7 An example of allocating three emergency facilities in Cedar Rapids under no flood (left) and 500-yr (right) flood scenarios.

The accompanying Figure 3.8 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.

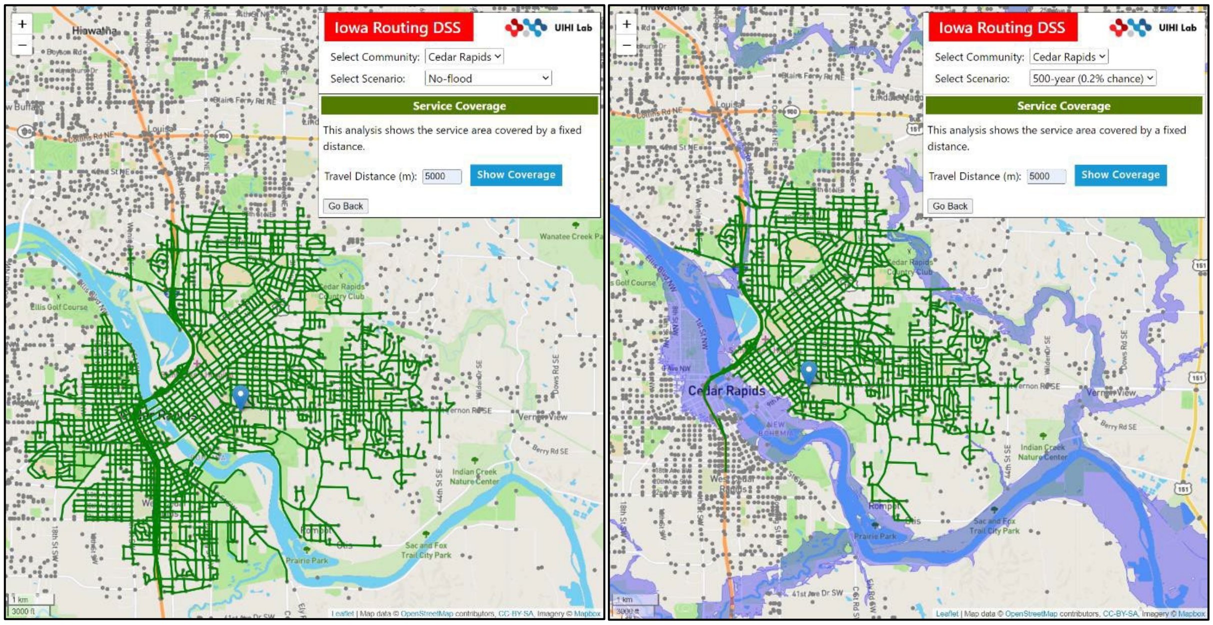

Figure 3.8 Service area from a defined location during the baseline scenario and the 500-yr flood event.

Chapter 4 Conclusion

This research introduces a web-based framework for routing and emergency facility allocation during floods, utilizing geospatial analytics and optimization methods like graph theory. Applied to Cedar Rapids and Charles City in Iowa, the system evaluates road networks pre- and post-flood, supporting users with interactive map visualizations of flooded routes, shortest paths, and facility location-allocation analyses. Findings show that floods significantly impact accessibility, and the application assists decision-makers, regardless of technical expertise, in navigating these challenges. It offers near-real-time data without costly back-end requirements, assisting communities in understanding road network impacts, navigating floods, selecting optimal emergency service locations, and identifying evacuation routes.

Some challenges include dependency on flood stage maps for gauged rivers and assumptions of bidirectional road segments, which may not suit all emergency scenarios. The use of betweenness centrality was necessary to manage computational limitations in facility allocation. Geographic boundaries also posed constraints, affecting analyses like shortest paths, particularly in flood-separated areas of Charles City. Future directions could expand the framework for multi-modal routing during floods, integrate real-time mapping (Li & Demir, 2022), incorporate traffic dynamics, and evaluate amenity resilience. Additionally, integrating social vulnerability analysis (Cikmaz et al., 2023) would enhance consideration for vulnerable groups, with system outputs potentially aiding affected populations via social media.

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