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Using GIS Network Modeling to Evaluate Access Disruption to Critical Health Facilities During Flood Events

by

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Under the Direction of Chetan Tiwari, PhD

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ABSTRACT

In recent decades, floods have been among the most devastating disaster events, resulting in significant losses of lives and properties. When flooding occurs and people could not access a particular hospital, they would need an alternative route which might increase their driving time. For disaster mitigation, it is important to understand how flood events impact accessibility in this respect. This research used GIS network modeling to determine potential disruptions of road connectivity between hospitals to census tracts in Atlanta. The obstructed-network map was used to determine the shortest path between each census tract to major hospitals in Atlanta.

This research aims to generate crucial insights on node disconnectedness and help to improve the accessibility of critical services such as emergency rooms during weather-related disaster events. Such information can be used to plan appropriate mitigation strategies by multiple stakeholders, including emergency management, public health, and hospital systems, among others.

INDEX WORDS: Flood risk, Hospital, Road, Urban, Disaster mitigation, Resilience, Network Analysis

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DEDICATION

To my parents, siblings, friends, and mentors whose shoulders I rode on during my graduate school journey. To Baba Ron and Mom Becky whose exemplary personalities exude compassion, warmth, and love.

ACKNOWLEDGEMENTS

I sincerely appreciate Georgia State University, particularly the Geosciences department for according to me the privilege to undertake my masters' program in this great citadel of learning. I am enormously grateful to my thesis supervisor, Dr Chetan Tiwari, for his immense support and guidance during my entire journey through graduate school. I would like to extend my heartfelt gratitude to my committee members, Dr Anu Bourgeois and Dr Flávia D.S. Moraes, for their unwavering support and encouragement.

To friends and family, my success story would not be possible without your relentless support. For this reason, I am truly grateful.

I am forever indebted to the Almighty God.

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LIST OF ABBREVIATIONS

FEMA – Federal Emergency Management Agency

GEMA – Georgia Emergency Management and Homeland Security Agency

GIS – Geographic Information System

ICU – Intensive Care Unit

NFHL – National Flood Hazard Layer

NOAA – National Oceanic and Atmosphere Administration

NSSL – National Severe Storms Laboratory

NWS – National Weather Service

USGS – United States Geological Survey

CHAPTER 1

1.1 INTRODUCTION

In the United States (U.S.), flooding is one of the most frequent natural hazards (Bousquin & Hychka, 2019; Doocy et al., 2013; Sepideh Khajehei et al., 2020; Li et al., 2021). They occur when water overflows onto dry land, and may result in serious harm to infrastructure, loss of life, and property (Geographic, 2023; N.O.A.A.). Floods can be brought on by a number of several events such as hurricanes, tropical storms, collapsed dams, and flash floods that happen shortly after a few minutes or hours of heavy rain (SAMHSA, 2023). Over the years, flooding has been one of the most expensive natural disasters in the U.S. (Tebor, 2021). Over 15 million homes are at risk of flooding (C.B.S, 2020), with an estimation to cost U.S. businesses about $49 billion by 2023 and about $84 billion projected cost of flood damage by 2052 (Forbes, 2022).

Likewise, it has been termed one of the most common natural disasters worldwide, with remarkable impacts on public health and economic welfare (Alderman et al., 2012). Climate change has resulted in flood damage amounting to billions of dollars in the U.S. over the past three decades (Stanford, 2021), and it is expected to increase the frequency and intensity of floods (Kuzniecow Bacchin et al., 2011). This is why adaptability to and resistance against the flood hazard is critical to retain functionality of cities (Abshirini et al., 2017).

Floods in previous years have caused great damage and resulted in significant losses. In the U.S., flooding has claimed the lives of close to 5,000 individuals during the past century (Ashley & Ashley, 2008). The U.S government estimates tens of billions of dollars in economic losses every ten years (G.A.O., 2004). According to the National Weather Service (NWS), flooding in the U.S. typically results in 100 fatalities and $8 billion in damages annually (N.W.S., 2013, 2022). Climate change, population increase, and urbanization will all contribute to an increase in the frequency and intensity of floods (Sadler et al., 2017; Zhang et al., 2011). Floods can happen anywhere and can range in size and duration; however, they are more likely to occur in coastal locations. During periods of intense rainfall, even seemingly safe small streams and creeks can become dangerous floods (SAMHSA, 2023).

In addition to causing immediate harm to homes and buildings, floods can also have an adverse effect on public health by impeding access to essential facilities (Ohl & Tapsell, 2000). Aside from the possibility of landslides, significant environmental issues like power, water, and gas shortages, disruptions to commercial supply, transit routes, and drinking water systems can all happen (Luo & Wang, 2003). Sadly, the inaccurate analysis of intense rainfall using outdated federal data has significantly downplayed the likelihood of flooding and would continue to impact infrastructure (Nilsen, 2023).

One of the key infrastructures for the operation of a society's economy is its transportation network (Guze, 2014). They are designed to facilitate movement in both urban and rural settings. These characteristics have a substantial impact on whether economic growth would be fostered or hindered (Arrighi et al., 2019). However, access to healthcare facilities might be hampered due to flood, emergency response can be slowed down, and the national economy can be negatively impacted by the road networks including highways, and bridges (Alabbad et al., 2021). To provide access to healthcare facilities during and after severe flood catastrophes, a robust transportation infrastructure should continue to be in use (Pregnolato et al., 2016).

Road transport network functionality and economic growth are significantly influenced by the connectivity and configuration of a network, also referred to as its topology. However, because of the additional strain that natural disasters like flooding place on transportation networks, healthcare facilities are less accessible, especially at the local and regional levels. During flood disasters, road networks and medical infrastructure can be disrupted, which can have both direct and indirect negative effects, including the loss of access to crucial services (Rodrigue, 2020b).

For flood risk mitigation, it is essential to evaluate the susceptibility of road networks and comprehend the demographics of impacted communities (Collins et al., 2019). Geographic information technologies can be used to evaluate transportation networks in real time under dynamic disaster conditions (Pregnolato et al., 2016). Utilizing network analysis approaches, vulnerable road networks can be found, and demographic data from disconnected nodes can be used to understand the population that is impacted (Nurwatik et al., 2022). Risks associated with flooding are higher for vulnerable populations, such as those who are socially and economically poor (Alderman et al., 2012; Bubeck et al., 2017), or racially marginalized people of color (Fothergill & Peek, 2004; Knighton et al., 2021; Zahran et al., 2008). In general, earlier research on the environmental justice implications of urban flooding sought to better understand the socio-economic differences in flood risk with the purpose of enhancing the resilience of the people who were most disproportionately affected. One of these studies revealed that lower social classes were more susceptible to floods in different regions (Mittan, 2020).

Therefore, the vulnerability of infrastructure, such as roadways, to flooding must be evaluated in order to provide sustainable flood risk management (Nasiri et al., 2016). Since accessibility is a crucial concept in health policy and health services research (Penchansky & Thomas, 1981), so, understanding and mitigating the effects of floods requires analysis and evaluation of the road system and the healthcare system (Klipper et al., 2021).

This study attempts to assess how flooding events affect the road infrastructure, with an emphasis on access issues to critical healthcare institutions such as hospitals that offer emergency services. The goal of this study is to improve flood risk management tactics by identifying susceptible road networks and understanding the demographic make-up of disconnected nodes. Atlanta, a city that is rapidly urbanizing and becoming more vulnerable to flooding threats (Paulikas & Ashley, 2011), will be the study area. It is hoped that this work will help put in place effective measures to lessen the disruption caused by floods and safeguard the population's health and well-being by better understanding the effects of flooding on road infrastructure and accessibility.

1.2. LITERATURE REVIEW

1.2.1 What is Flooding?

Flooding is a natural disaster and a hydrological phenomenon characterized by the overflow of water onto land. Flooding can typically occur when prolonged rain falls over several days, when intense rain falls over a short period of time, or when an ice jam causes a river to overflow onto the surrounding area. The two main types of flooding are flash flooding, and river flooding (U.S.G.S.). Flash flooding is the sudden rise and fall of floodwater and is primarily brought on by a large amount of rain that falls quickly, usually in less than six hours, in a specific area. River flooding occurs when a river overflows its natural banks, leading to potential damage or threats (NWS; U.S.G.S.). Other types of flooding are coastal flooding and inland flooding (NSSL). Flash floods are the most common cause of flood deaths. This kind of flooding can be triggered by thunderstorms that move slowly, move over the same area repeatedly, or bring heavy rain from hurricanes and tropical storms (N.O.A.A.). Floods are influenced not only by the amount and rate of rainfall but also by a number of factors such as topography, land use, soil type, and pre-existing moisture levels in the watershed (Ran et al., 2022).

Previous studies have looked at mortality caused by U.S. floods (Coates, 1999; Rappaport, 2000; Thomas & Mitchell, 2001). Between 1959 and 1991, an average of 119 flood-related deaths per year across the nation was revealed (Dittmann, 1994). A research analyzed during the period of 1969 to 1981 indicated that a majority of flash floods occurred in the warm season, specifically from July to September, with September being the month with the highest number of fatalities (French et al., 1983). The study also found out that drowning accounted for 93% of flash flood fatalities. Flash floods account for between 80% and 90% of all flood-related fatalities each year in the U.S., with about 40% of these deaths being related to pedestrians who were crossing streams (Zevin, 1994).

Geographic Information Systems (GIS) have been used as the foundation of a methodology to measure and map flood features. This innovative method entails the integration of several topological, meteorological, geological, and land-use data sets into a GIS setting (Dawod et al., 2012). Likewise, the impacts of various flood events on transportation disruption were analyzed by integrating high-resolution flood modeling with a transport network model. The framework designed was used to assess the advantages of flood risk management actions in terms of minimizing disruptions to transportation (Pregnolato et al., 2016).

1.2.2 Impact of Floods on Health Services

Flooding has the potential to either cause damage to hospital facilities or disrupt patient accessibility (Meusel & Kirch, 2005), and the damage could come in the form of outright costs like the destruction of infrastructure, medical equipment, hospital furniture, and medical supplies (Geroy & Pesigan, 2011). In respect to evaluating access disruption, many studies have been conducted. For instance, the shortest-path network model was applied to evaluate the interruption of road network flow pattern (Ye & Kim, 2021). In addition, a thorough research of the 2013 floods in the Lockyer Valley region of Australia was undertaken to improve the community's resilience during and after extreme exposure to flood events, notably with regard to road networks and crucial structures like bridges, and floodways. The study pinpointed the fundamental mechanisms of road bridge systems that fail when subjected to flood conditions (Setunge et al., 2014).

In addition, a flood routing strategy was included in the mathematical formulation of an optimization model (Tahiri et al., 2022). This integration allowed for an effective strategy to regulate and lessen the damaging consequences of flooding. Graph-theoretic techniques and single-source shortest path analyses were used in the State of Iowa to undertake an extensive study to assess the effects of floods on road network topology and accessibility to critical facilities like hospitals under 100- and 500-year flood scenarios (Alabbad et al., 2021).

Hospitals would face significant health risks as a result of the increased frequency of climate change-related extreme weather events, which were not initially considered in their design and infrastructure (Loosemore et al., 2014). The impact of catastrophic events like floods on people's lives, livelihoods, and communities can be significantly reduced by being prepared (Petrucci et al., 2017). Centrality metric has been used to investigate how the topological and graphical properties of road network patterns relate to one another (Zhang et al., 2011). To pinpoint key areas in need of flood risk management action, betweenness centrality, weighted by travel time, was used as a network metric (Pregnolato et al., 2016). The study suggested that preventing floods at the most important area could result in an 11% decrease in traffic jams. To determine the level of socio-economic differences in flood risk within the Atlanta region, race, ethnicity, and poverty data from the US Census Bureau was utilized to estimate demographic characteristics inside the 500-year flood zone. The dasymetric map generated suggest that environmental injustices were systemic, as vulnerable individuals were between 14% and 42% more likely to reside in areas at risk for flooding (Debbage, 2019).

1.2.3 Disruption to Transport Infrastructure

The transportation infrastructure plays an essential role in responding to and recovering from floods (Alabbad et al., 2021). Engineers, decision-makers, and planners are all very concerned about the disruption of critical infrastructure (Splichalova et al., 2020). A transportation system's resilience is measured by its ability to withstand the effects of extreme weather, continue operating under difficult conditions, and quickly recover from any negative effects (Rodrigue, 2020a; Splichalova et al., 2020). The consequences and functionality of transportation infrastructures during extreme weather events were examined, and not just the recovery period of the transportation network (Markolf et al., 2019).

In many regions, excessive rain combined with inadequate or neglected local drainage systems can result in abrupt surface water flooding, damaging surface infrastructure and disrupting traffic networks (Boilé, 2001). Considering the interdependence of the transportation system, it is essential to have a deeper knowledge of network behavior under hazard situations to improve our ability to mitigate the effects of disaster events, such as flooding (Jongman et al., 2015). Hence, to analyze options for lessening the impact of risks, it is necessary to enhance modeling methodology and techniques.

Using real-time and integrated information frameworks, considerable research on flood risk management and disaster mitigation has been conducted over the past few years (Alabbad et al., 2021). Similarly, scholars have investigated and evaluated the negative consequences of a flood occurrence on the vulnerability of transportation infrastructure, using centrality metrics are to determine the relative weights of nodes and edges in a network (Jia et al., 2012). These include graph theoretic methods that evaluate network connectivity using graph measures such as betweenness and centrality (Kermanshah & Derrible, 2017; Mount et al., 2019) and damage indices (Setunge et al., 2014). Graph-based methodology has also been used to capture the characteristics of flood control infrastructure and assist in identifying the elements that contribute to the systems' susceptibility (Ogie et al., 2020). However, this method can become computationally complex and slow as network grows, limiting its ability to analyze large-scale network efficiently (Tahiri et al., 2022). On the other hand, GIS based approaches have proven useful in estimating impacts of flood on road network at different scales (Dawod et al., 2012; Yin et al., 2016).

1.2.4. Network Analysis

Network complexity science, which seeks to understand the dynamics of failures in networked systems, has been applied to the study of critical infrastructure resilience (Wells et al., 2022). Prior efforts in this area, however, tended to rely primarily on metric-based methodologies to predict component failures (Chen et al., 2021; Dong et al., 2020). These strategies have proven successful, but they do not fully take into consideration the consequences of reduced performance over the entire network or in some specific areas, such as links that are becoming more challenging to travel (Gao et al., 2019). Alternately, strategies based on short-path and travel-time analysis that utilize publicly available information on road infrastructure may be used to evaluate which areas are likely to be cut-off from services during flooding events (Papilloud & Keiler, 2021).

Understanding flooding and its consequent disruption of access to critical facilities requires the development of new approaches that combine flood risk models with traditional network analysis designed to measure connectivity between services and demand points (Dong, Esmalian, et al., 2019). In particular, when evaluating the level of vulnerability in a network of connected infrastructure components, their interdependencies, vulnerability, and resilience, network analysis can be an incredible useful tool. This was done by representing individual infrastructure components as connections or nodes (Latora & Marchiori, 2005). Similarly, the investigation of vulnerability in a variety of infrastructures, including water, wastewater, road, and drainage networks, has been effectively done using network analysis (Dong, Wang, et al., 2019; F. Maltinti, 2012; Mattsson & Jenelius, 2015; Meng et al., 2018). In addition, network analysis has been used, for instance, to find subnetworks that can be separately maintained in the context of artificial drainage networks by exploiting network attributes like between-centrality (Poulter et al., 2008). Likewise, the shortest-path method was used to conduct a thorough investigation of how floods affect Iowa's road network topology and residents' access to facilities (Alabbad et al., 2021). During the study, to help decision-makers identify susceptible locations and lessen the effects of a failing road system during flooding, an integrated real-time decision support system was created under 100- and 500-year flood scenarios. Also, all origin-destination pairs in a network were subjected to a flow-based network under the shortest path model while taking passenger flows, nodal disruption, and the impact of r nodes' disruption of the network flow pattern into consideration (Ye & Kim, 2021). Based on the idea of shortest paths, how close a node is to every other node inside the network can be measured. The various pairs of starting points and destinations can be identified, each having at least one shortest path between them. In other words, the connection of a node to the overall network can be determined, with higher values denoting nodes that are comparably closer to the center (Golbeck, 2013; Marsden, 2005).

1.2.5. Vulnerability Analysis

Vulnerability analysis is a useful approach to analyze accessibility and find alternate pathways to facilities after a flood (Bader et al., 2011). Nodes are represented as points and edges are used to connect them. Identifying the vulnerable regions within the road infrastructure that might be subject to disruptions and understanding the impact of such disruptions on society are necessary for evaluating the vulnerability of transportation networks (Mattsson & Jenelius, 2015). When a node or edge is covered by water, it becomes impassable and presents a risk to travel since it is inaccessible (Wang et al., 2023). Utilizing an integrated system that employed hydrodynamic modeling, land use functions, and meteorological data, a thorough approach was taken to determine how vulnerable urban road infrastructure is to flood. With the use of this framework, two different rainfall scenarios were modeled: one with a return period of 1 in 10 years and the other with a return period of 1 in 100 years. A spatial risk assessment of the road network was then carried out using the obtained inundation mapping (Papilloud et al., 2020; Singh et al., 2018). Enhancing our understanding of vulnerability enables us to develop strategic approaches aimed at improving the effectiveness, dependability, and emergency preparedness of the road system (Fox-Rogers et al., 2016; Maidl & Buchecker, 2015).

1.3 STUDY AREA

The City of Atlanta, like other urban areas, faces risks to life and property from many natural and man-made hazards, including fire, tornadoes, toxic spills, wind, drought, wildfire, and flood. Of all these risks, flooding is arguably the greatest threat to the residents of Atlanta. The economic crisis associated with urban flooding in the southeastern United States, including the September 2004 and 2009 recorded flood events in Georgia, point to the need for better flood risk assessment capabilities (Wright et al., 2012). Atlanta city has been one of the most rapidly urbanizing population centers in the United States since the mid-20th century, with population increasing from less than one million in 1950 to over five million in 2010 (Ambrose, 2004; McDonald, 2013). This growth has increased regional vulnerability to thunderstorm-related hazards such as flash flooding, tornadoes and hail (Paulikas & Ashley, 2011).

Figure 1: Map of Georgia showing the city of Atlanta.

Urban areas are more susceptible to floods because of complex interaction of social and physical variables. The demands of urbanization have increased the number of people living in flood zones, especially among the most vulnerable (Houston, 2011). Atlanta, Georgia, saw catastrophic floods in late September 2009, providing a startling illustration of this city vulnerability to heavy rainfall (McCallum & Gotvald, 2010). The rainfall totals in several areas of

Atlanta were higher above the threshold for a 100-year flood, which happens once in every 100 years (Dobur & Noel, 2005). Between September 16 and September 22, 2009, there was an extended period of heavy precipitation, which led to the flood. The highest 24-hour rainfall total of 534.16 mm was recorded on September 21 in Douglas County, west of Atlanta. Georgia’s landscape, the Gulf of Mexico, and the Atlantic Ocean were great influences in causing the 2009 flood event (N.W.S., 2009). The flood was caused by several hydrometeorological processes, including moist pre-existing conditions, and sufficient atmospheric moisture. Georgia's flooding is mostly a result of its location in relation to mesoscale, extratropical, and tropical cyclone systems, as well as how these systems interact with the topography of the area and with seasonal vegetation characteristics (Debbage & Shepherd, 2019).

Inadequate flood mitigation allows water to accumulate on the road, which either causes traffic to sluggishly move or, if it becomes deep enough, to stop completely. The damage-based flood severity index classified the 2009 flood as "catastrophic" in terms of its effects on society (Schroeder et al., 2016). This historic urban flooding left severe damage; the popular Six Flags theme park was flooded, major school systems were shut down, important transit routes in the Atlanta area were closed (Shepherd et al., 2011). Sadly, there were about 10 recorded fatalities, and flood damage claims are close to $500 million. Some 20,000 homes, businesses, and other structures sustained significant damage, and 23 counties received Federal Disaster Declarations (GEMA).

Prior research on flooding has been constrained by concentrating only on a particular flood type, especially flash flood (S. Khajehei et al., 2020; Li et al., 2022; Martins et al., 2023; Merz et al., 2021). Therefore, the main goal of this study is to investigate flooding in general, using the 100-year floodplain data to assess road network vulnerability. Specifically, this study is aimed to assess how flooding affect hospital accessibility and to raise awareness of this issue among all relevant stakeholders.

1.4 RESEARCH OBJECTIVES

This study attempts to provide a framework for evaluating how flooding incidents can cause access disruptions to vital services like hospitals. The 100-year National Flood Hazard Layer (NFHL) from the Federal Emergency Management Agency (FEMA) will be used to identify segments of road network that are susceptible to flood events. Subsequently, network analysis techniques will be used to identify the most vulnerable healthcare facilities that are at risk of access disruptions due to damage to roads due to flooding.

The results of this thesis will enable decision-makers to evaluate vulnerable components of the road infrastructure and ensure that people have safe access to essential utilities. This will help build a more resilient community in Atlanta.

CHAPTER 2

2.1 DATA AND METHOLOGY

2.1.1 Flood Zone Data

FEMA’s NFHL was used to locate Atlanta's flood-prone zones. The NFHL is a digital repository that classifies flood risk into various zones based on the likelihood that flooding may occur. To narrow down the analysis, the flood data was filtered, and Zone AE and Zone A were selected from the NFHL in accordance with FEMA's classifications of flood risk zones.

According to FEMA’s classification of flood zones, Zone AE denotes areas with 1% annual chance of flooding and a 26% chance over the life of a 30-year mortgage. For Zone A, it represents areas subject to inundation by the 1% annual chance flood event. While there are other flood zones, such as AO, AH, and VE, with unique characteristics and requirements, our analysis focused exclusively on Zone A and Zone AE because both zones signify a 1% probability of a flood of that magnitude occurring in any given year. In other words, they represent areas that have high risk of flooding over time.

The primary difference between Zone AE and Zone A is the availability of detailed base flood elevation (BFE) information. Zone AE typically has more precise BFEs identified through extensive engineering assessment, while Zone A might have less detailed information. Both zones, however, signify locations susceptible to flooding, emphasizing the need for property owners and communities to adopt suitable strategies for mitigating the associated risks.

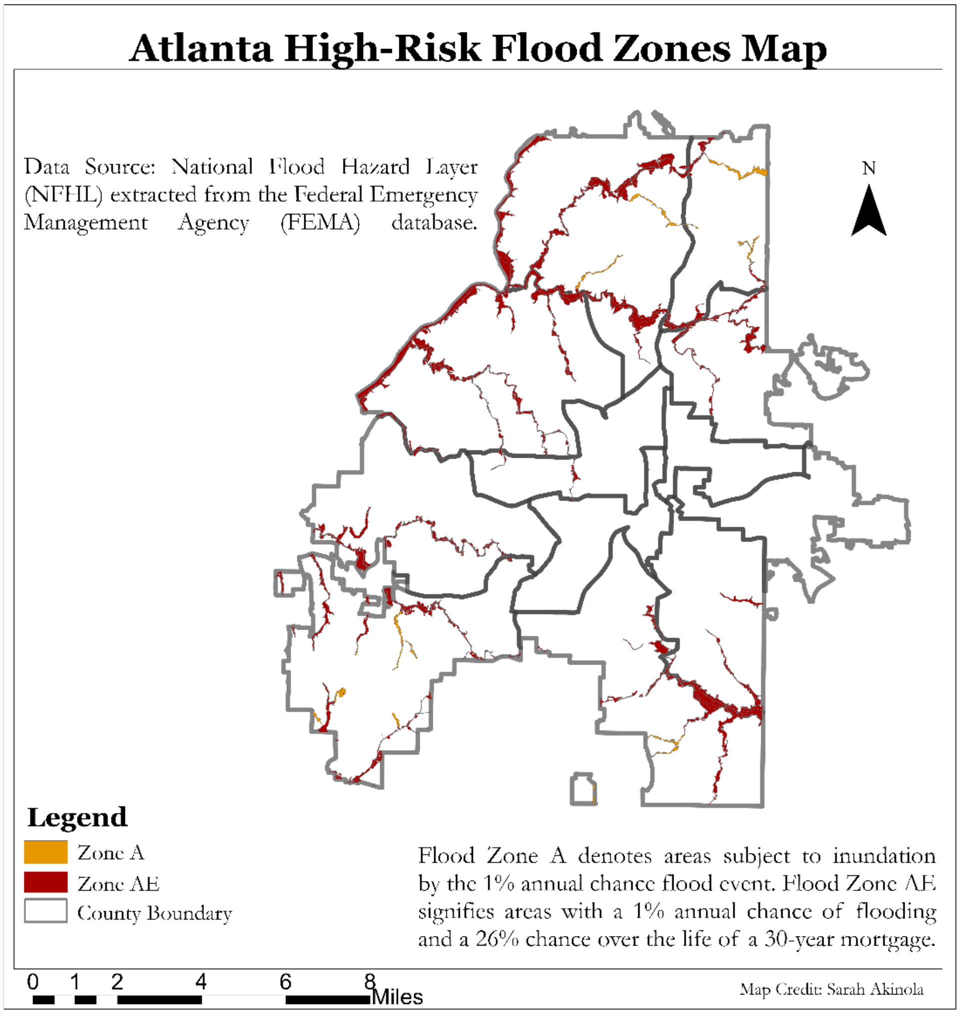


Figure 2: Map of Atlanta showing high-risk flood zones.

2.1.2 Hospital Location Data

For data collection on hospital locations, the ArcGIS Business Analyst Online (BAO) was utilized. This portal offers a vast selection of resources and datasets for gaining access to and exploring geographic information. Data for the contiguous United States was specifically gathered, and Atlanta hospital locations were then extracted by filtering the data by location. For all Atlanta hospitals, the collection contained information such street names and zip codes.

2.1.3 Road Data

The census tract records were used to extract the TIGER/Line Road dataset for Atlanta. Census tracts are geographic divisions that were created by the U.S. Census Bureau for the purposes of gathering and organizing statistical data. Tracts are intended to represent regions of generally homogenous population characteristics. The TIGER/Line Road data contains important information on Atlanta's transportation system. It includes the network of streets, roads, and highways that facilitate the movement of vehicles and pedestrians throughout the city. This dataset enables a thorough investigation of the road network, including its connection, density, and distribution across various communities and neighborhoods.

Figure 3 shows Atlanta major hospital locations, census tracts and random points. The points represent simulated location of residences. The random tool point in ArcGIS was used to create five locations within each census tract in the Atlanta area. The points were snapped to the closest road segment when computing the shortest-path distances.

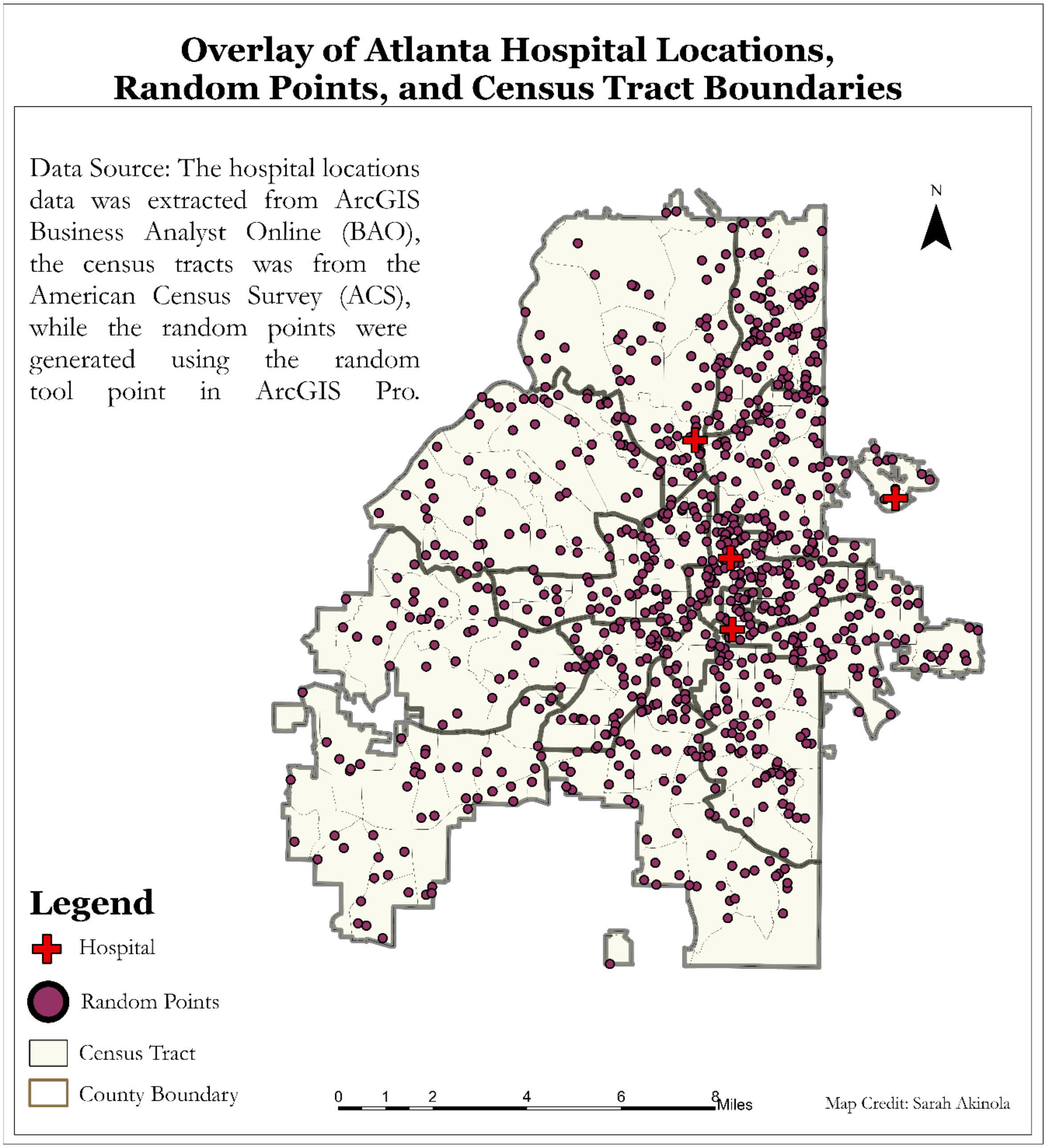


Figure 3: The map shows major Atlanta hospital locations, census tracts and random points.

Additionally, the TIGER/Line Road dataset is a crucial tool for researching the connection between socioeconomic characteristics and transportation. It enables researchers to investigate the effects of road accessibility on various towns, neighborhoods, and demographic groups. This information can be used to identify disparities in the transportation system and potential obstacles to mobility faced by certain populations.

The TIGER/Line Road data extracted from selected census tracts can be used by scholars to learn more about several facets of Atlanta's urban planning and transportation administration. It makes it possible to locate important transit routes, traffic patterns, and potential areas of congestion. Making insightful decisions about infrastructure construction, traffic control measures, and enhancing accessibility and mobility around the city may all depend on this information.

Table 1: Data Sources of Flood-Related Events, BAO Hospital Locations, and Road Network.

Dataset & Source	**Events of Interest**	**Variables**	**Spatial and Temporal Resolution**	**Records**
100-year floodplain boundary Source: FEMA	Flood Zones	CSLF ID, Pre Zone, New Zone, Shape Length, Shape Area	Spatial Resolution: Point & Line. Temporal Resolution: flood data: 100-year floodplain	22, 980

Road Network Source: U.S Tiger/Line	Nodes connectivity	Road Name, Road from Add, Road to Add, Shape Length	Spatial Resolution: Polygons Temporal Resolution: 2022	110, 469
Hospital Locations Source: ArcGIS BAO	Point locations	Street, City, State Name, Location Name		4

2.1.4 Random Point Data

Random points were generated to simulate households requiring emergency services (hereafter referred to as the “random point dataset”). Although parcel data may be used to create a more accurate representation, it would require consolidating multiple datasets from different county appraisal district data repositories. Given the high density of housing in the Atlanta area, the simulated point dataset will closely approximate the distribution of households in the region. Further, the simulated dataset may also be used in future studies to perform a Monte Carlo simulation to account for random chance in identifying and quantifying access disruptions.

2.1.4 Overview of the Research Methodology

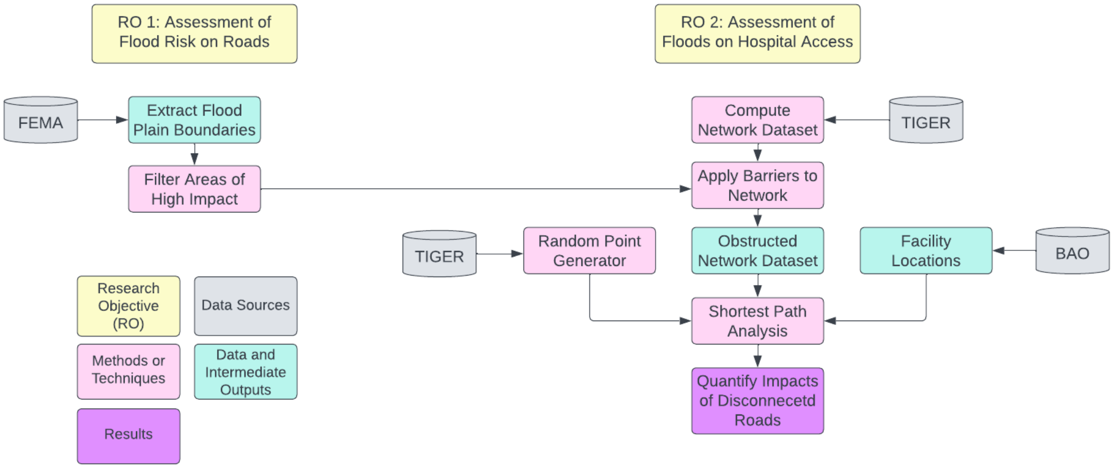


Figure 4: Overview of the general workflow.

Figure 4 provides a general perspective of the research methodology and table 2 summarizes the main processes involved in our data analysis.

Table 2: Overview of the key processes involved.

Steps	**Processes**
1	Atlanta TIGER/Line Road data and city boundaries were extracted from census tract.
2	The road dataset was used to construct a network dataset to define connectivity and restriction of the road network.

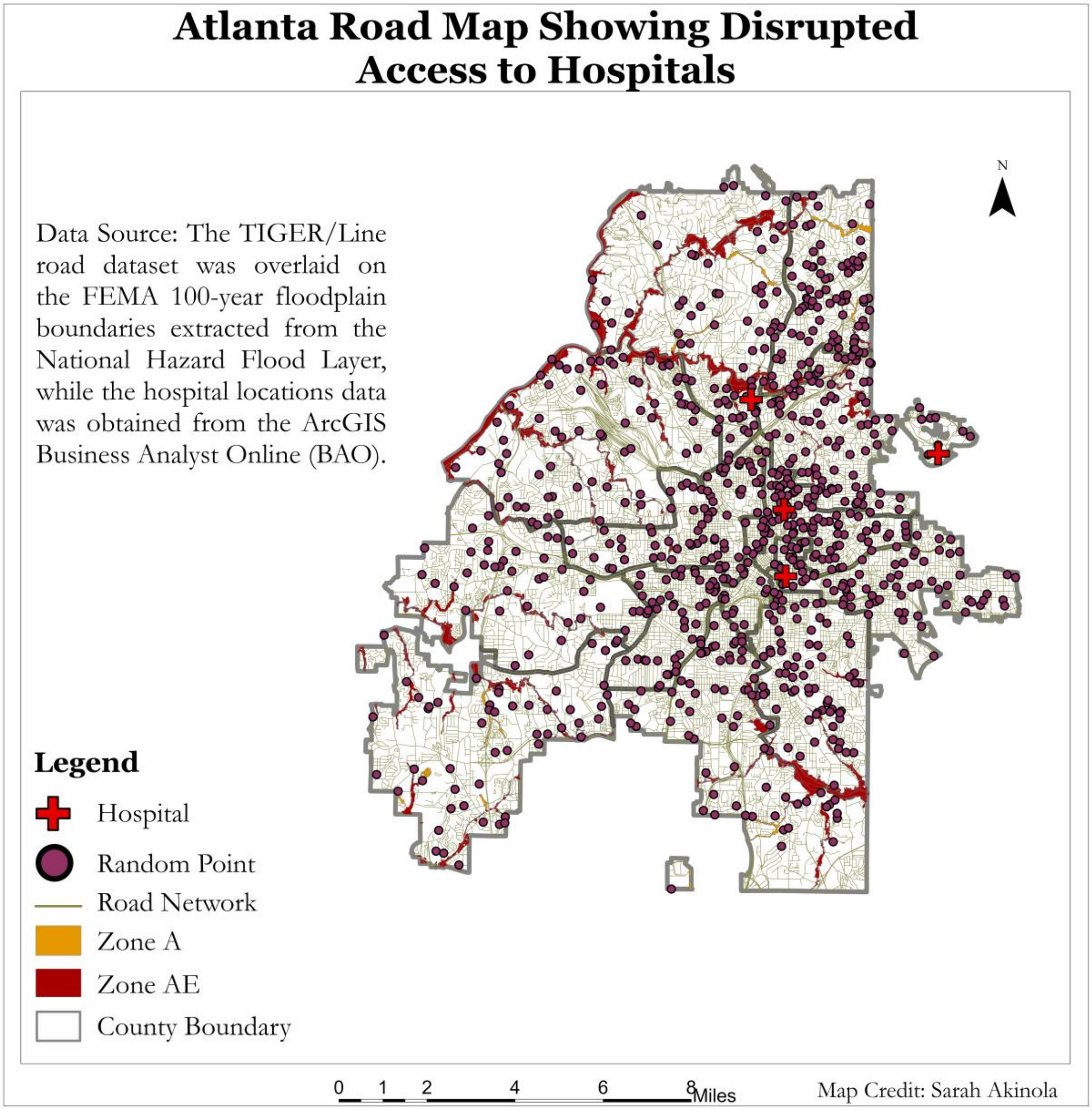
3	5 random points were generated within each census tract in Atlanta to simulate the location of residences.
4	The shortest path analysis was performed to compute the most efficient route from a generated point to the closest hospital.
5	Atlanta flood boundaries were obtained from FEMA and were filtered using FEMA high risk flood zones criteria.
6	The flood zones obtained in step 5 were included as polygon barriers to re-compute shortest paths from a generated point to the closest hospital using disrupted networks.
7	The two distance datasets were joined based on simulated ID and their differences in driving distance were calculated. The geographic patterns of drive-time differences were visualized using a spatially continuous map

	produced using the Inverse Distance Weighting (IDW) technique in ArcGIS Pro.
8	Statistical analysis was conducted on distances and closest hospital locations.
9	The results generated were validated by performing statistical analysis using Statistical Package for the Social Sciences (SPSS) to ensure accuracy of the analysis.
10	Final outputs were presented as maps and statistical tables.

2.1.6 Network Analysis and Shortest Path Analysis

During flood event, the original topology of the road network graph may alter as a result of the removal of flooded nodes and areas. Both individuals and emergency service providers may suffer serious consequences because of this disturbance to the road network. These impacts may include increased travel times and distances for specific areas within the study region.

The methodology adopted in this study uses a combination of overlay and network analysis to identify road segments that are most likely to disrupt connectivity between neighborhoods and critical hospital facilities. It aims to assess the network's connectivity by identifying critical road segments or intersections that may become inaccessible or impassable during flooding. This analysis helps to identify potential bottlenecks and areas of concern for emergency response. This was achieved by performing a shortest path analysis utilizing the Atlanta flood data and road network data to assess how access disruption to hospitals is affected by flooding events. In order to gain important insights into potential access issues and vulnerabilities in emergency scenarios, this analysis sought to evaluate the impact of flood occurrences on the shortest paths from various random points to hospitals. From the flood data obtained, the zones that can potentially obstruct access to hospitals during flood occurrences were identified and overlaid on the road network data, which contains details about road segments, intersections, and connectivity between various points. With the use of this network, the most effective paths between various sources and hospital destinations were determined, which formed the basis for the shortest path analysis conducted in this research.



Atlanta Road Map Showing Disrupted Access to Hospitals

Data Source: The TIGER/Line road dataset was overlaid on the FEMA 100-year floodplain boundaries extracted from the National Hazard Flood Layer, while the hospital locations data was obtained from the ArcGIS Business Analyst Online (BAO).

Map Credit: Sarah Akinola

Figure 5: Map of Atlanta showing hospital locations in relation to high-risk flood zones and all major and minor roads to show access disruption to hospitals.

Furthermore, a network topology from the road network data was built. This involves defining connectivity between road segments and establishing the relationships between intersections and road segments. The network topology allows for efficient routing and analysis of the road network, which was later used to identify other routes and evaluate potential access disruptions. The research gave useful information regarding the extra distance or time needed to go to hospitals when specific road segments were inundated.

The analysis performed allows for the creation of informative maps that illustrate access disruptions, critical areas, and alternative routes for hospitals during flooding events. The first research objective of this project led to creating a flood-risk map to identify areas that are most likely to experience high impact of flooding. Risk is defined as the inability of populations to access emergency services at major regional hospital systems due to the disruption of road networks because of flooding. This component uses the historical records of flood events from FEMA to identify those areas that are likely to face access disruptions during a flooding event. First, a database of flood boundaries and events was constructed by extracting and integrating data from various repositories (Table 1). Second, the floodplain data extracted from the constructed database was filtered by FEMA flood severity scale.

The second research objective determines potential disruptions of road connectivity between hospitals to a set of randomly generated points across Atlanta. For this, we use the Topologically Integrated Geographic Encoding and Referencing (TIGER)/LINE road network data from the U.S Census Bureau to construct a network dataset for use in the ArcGIS Pro network analysis. Flood-risk polygons obtained from the first research objective will be used to identify network barriers in the TIGER/Line derived network dataset. The obstructed-network map will be used to determine the shortest path between each random point to major hospitals in the region. To ensure adequate coverage, five random points were generated for each census tract in the study area. The shortest path obtained represents the driving distance. Location information about regional hospitals will be obtained from ArcGIS Business Analyst Online (BAO). Final output includes a statistical analysis of excess time /distance burdens as well as a visual representation of disconnected road segments. The output can also be used to evaluate the extent to which hospital facilities remain accessible under flood-induced disruptions. The premise of this interpretation is that, if a node remains connected, then such neighborhood can reach the hospital facilities. On the other hand, people in the disconnected nodes would be hindered from accessing health care services during this period.

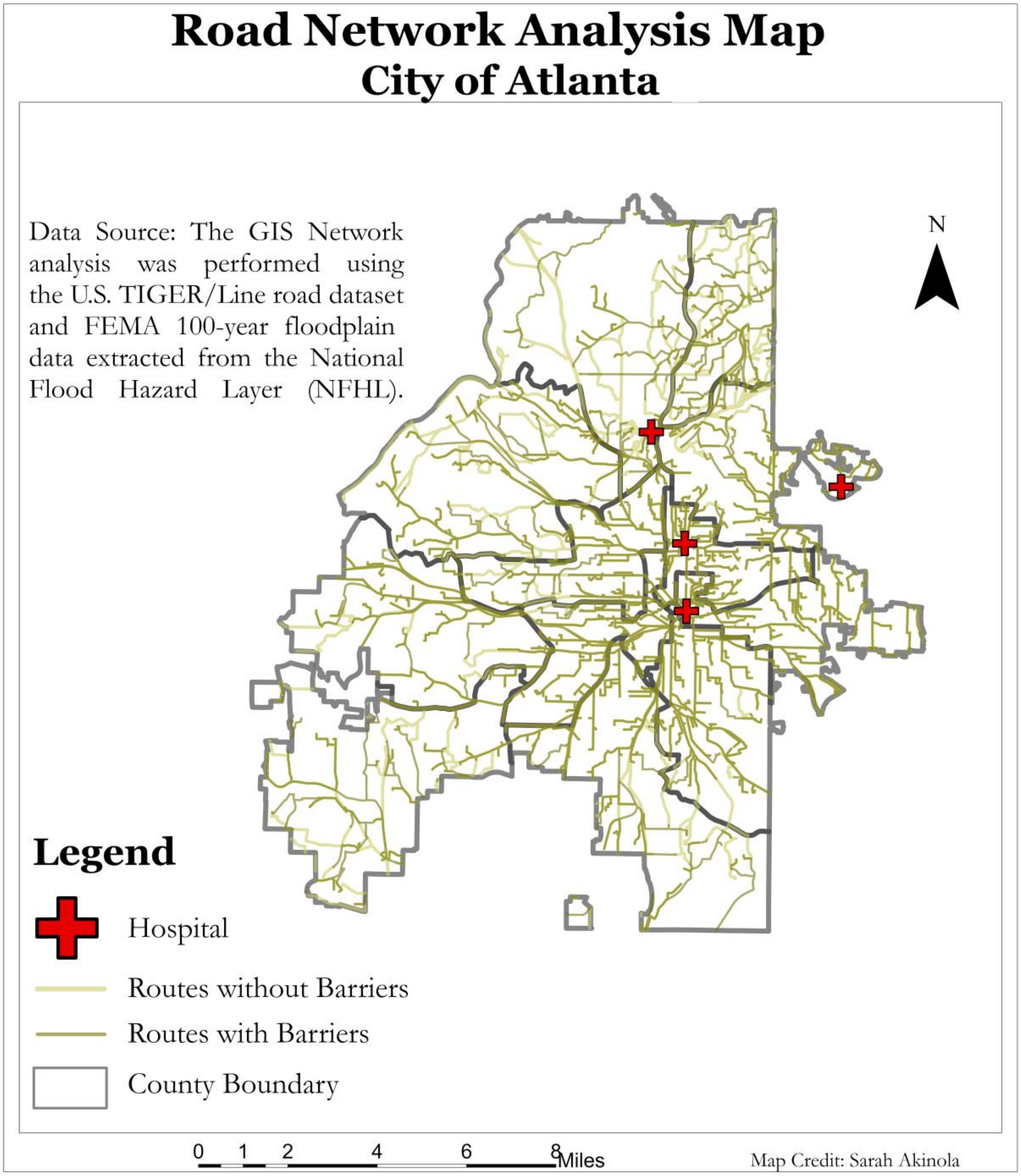
2.1.7. Mapping the Impact of Network Disruption using Inverse Distance Weighting (IDW) Interpolation

A spatially continuous surface representing the geographic patterns of increased travel distances was constructed using the Inverse Distance Weighting (IDW) interpolation algorithm applied to the generated random points. The resulting maps provide an overview of additional driving distance in Atlanta during flood events. The IDW interpolation was a neighborhood size of 8 and power value of 2. These values were selected to avoid over smoothing the data. The surface constructed was then clipped to the city boundary and reclassified using the natural breaks method with 5 classes.

CHAPTER 3

3.1 RESULTS AND DISCUSSION

In this study, an assessment was performed to look at how disruptions in the transportation network affect the accessibility of hospitals, under 100-year flood scenario. Figure 6 shows an overlay map with all the data layers used in the analyses. The hospital locations, indicated by the red cross symbols, only represent major hospitals with emergency departments. Note that only those locations that were completely within the study area were selected. Although no other hospitals were situated just outside the study area boundary in this research, it is possible that the allocation of points to the closest hospital may be incorrect if hospitals that are outside, but close to the study area boundary are excluded. Roads disrupted due to flooding (i.e., roads with barriers) are represented using the dark colored lines while the non-disrupted road segments are represented using the lighter colored lines. Areas of discontinuity in the road network, represented by alternating patterns of light and dark lines, show parts of the road network that are most likely to experience flooding disruptions.



Data Source: The GIS Network analysis was performed using the U.S. TIGER/Line road dataset and FEMA 100-year floodplain data extracted from the National Flood Hazard Layer (NFHL).

Figure 6: The map shows the input data used in the network analysis. The road network consists of all major and minor roads in Atlanta, simulated with and without flood barriers.

To validate the results gotten from our network analysis, we performed the statistical analysis of our simulated point data. Table 3 shows that out of 1101 random points generated to simulate location of residences and calls for emergency services, 77.5 percent (n=853) were assigned to the same “closest” hospital before and after network disruption (Valid = 0). The remaining 22.5% (n=248) were allocated to a different hospital as a result of road network disruption (Valid = 1). This indicates that roughly 22% of households in our simulated dataset would have been assigned to a different hospital than the one that is geographically closest to them. In addition to adding increased distances, such reallocation of hospitals may also create additional burdens such as not being able to access previous medical records, not having access to routine care provided by existing set of providers, among others.

Table 3: Assessment of Connectivity to Hospitals (0 = Same Hospital Allocated | 1 = Different Hospital Allocated).

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	0	853	77.5	77.5	77.5
	1	248	22.5	22.5	100.0
	Total	1101	100.0	100.0	

Furthermore, table 4 presents the central tendency measures for driving distances with and without flood barriers, highlighting differences in distances. Results show that the average driving distance is ~19 km without flood barriers and ~22 km due to flooding disruptions. The worst-case driving distances increase by ~20 km from 65 km (without barriers) to ~85 km (with barriers). Note that the standard deviation, i.e., the variability in time taken to get to hospitals, increases from ~12 km (without barriers) to ~15 km (with barriers). This may suggest that not all areas in Atlanta are equally impacted by flood-related road network disruptions. Another significant finding of this study is that 56 random point locations were completely disconnected i.e., they lost access to hospitals due to flooding.

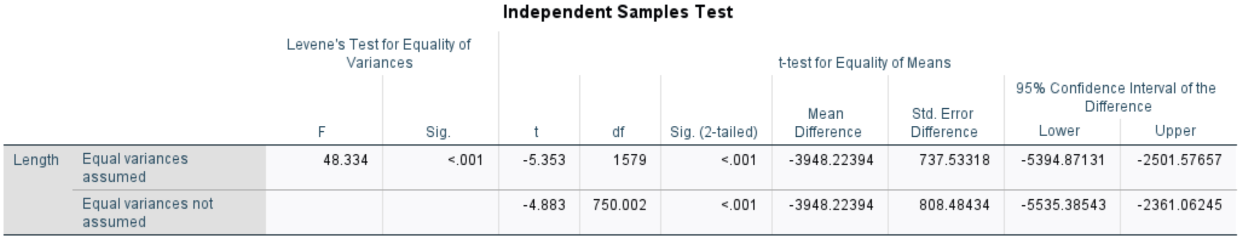
Table 4: Central Tendency Measures of Additional Distance Added due to Road Network Disruption.

	N	Minimum (km)	Maximum (km)	Sum (km)	Mean (km)	Std. Dev. (km)
Driving Distance without Flood Barriers	1101	0.038	65.2	20722. 608	18. 821	12.390
Driving Distance with Flood Barriers	1045	0.038	84.4	23173.614	22.175	15.273
Differences in Driving Distances	56	0	19.2			
Average Differences in Driving Distance with and without Barriers	1045	0	5.2	-4360. 531	-4.172	8.174

Our findings from table 4 demonstrate varied implications in terms of edge and node losses. The results show that floods can have an impact on both state highways and city roads, causing marginal losses of up to 5% (56 random points out of 1045), underscoring a serious flooding vulnerability. In addition, the result demonstrates that the shortest path length to the nearest hospital, under typical circumstances, can change to second paths under flooding. This proves that critical infrastructure in the city is vulnerable to floods, underscoring the necessity of taking preventative action to ensure their accessibility.

Table 5 shows the results of the Independent Samples t-test, comparing the means of length of road without barriers and with barriers, to ensure accuracy of our results. Given a significant result for the Levene's test for equality of variances, we use the results associated with unequal variances. The p-value associated with the t-test is less than 0.001 which indicates that there is a statistically significant difference between the two means – i.e., the average driving distance with barriers is greater than the average driving distance without barriers.

Table 5: T Test Showing Differences in Driving Distances with and without Barriers.



Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Length	Equal variances assumed	48.334	<.001	-5.353	1579	<.001	-3948.22394	737.53318	-5394.87131	-2501.57657
	Equal variances not assumed			-4.883	750.002	<.001	-3948.22394	808.48434	-5535.38543	-2361.06245

The histogram shown in Figure 7 shows the distribution of driving times using non-impacted roads. The results suggest that most driving distances are less than ~45 km. A large proportion of that subset lies between 0 and ~30 km. The tail end of the distribution suggests that some points have much larger driving distances. In comparison, Figure 8 shows the histogram for driving distances after network disruption. This histogram is flatter than the one in Figure 7 and shows an extended tail suggesting that driving distances generally saw an overall increase due to possible flooding-related disruptions. The longer tail indicates that many more points had significant increases in overall driving distance.

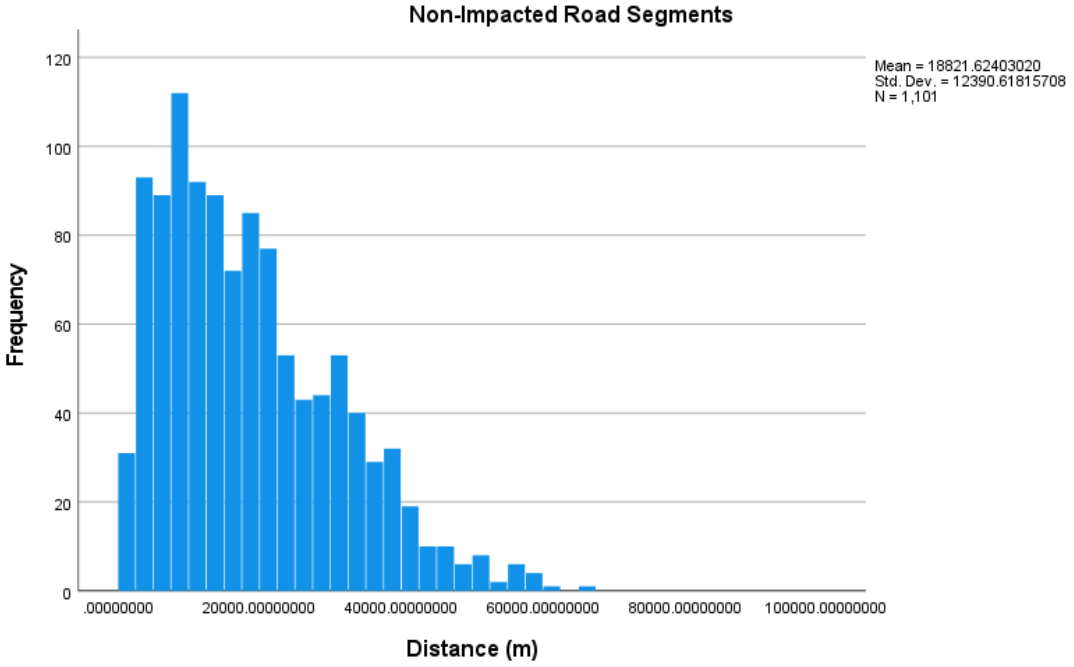


Figure 7: Histogram showing the distribution of non-impacted road network.

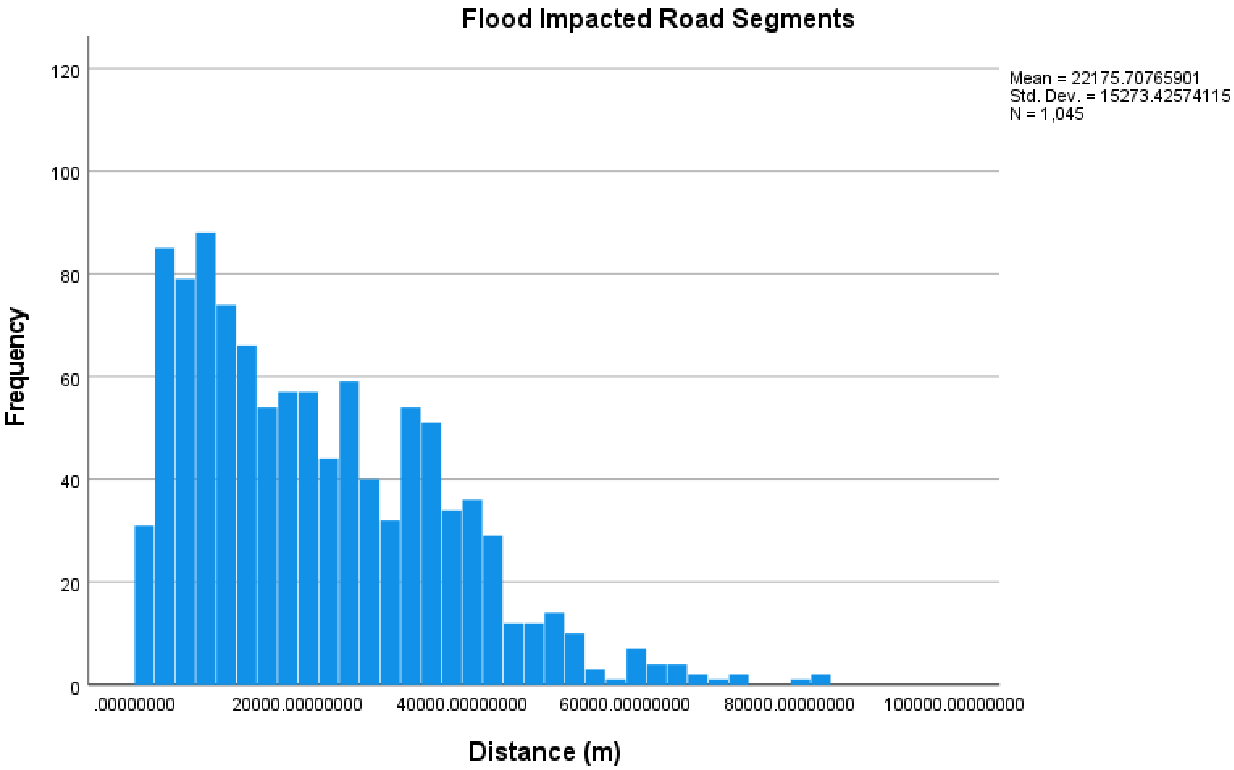


Figure 8: Histogram showing distribution of impacted roads.

Figure 9 shows the histogram for the differences in driving distances between roads with flood barriers and without flood barriers. The trend shows an additional distance of about 40 km in a worst-case scenario.

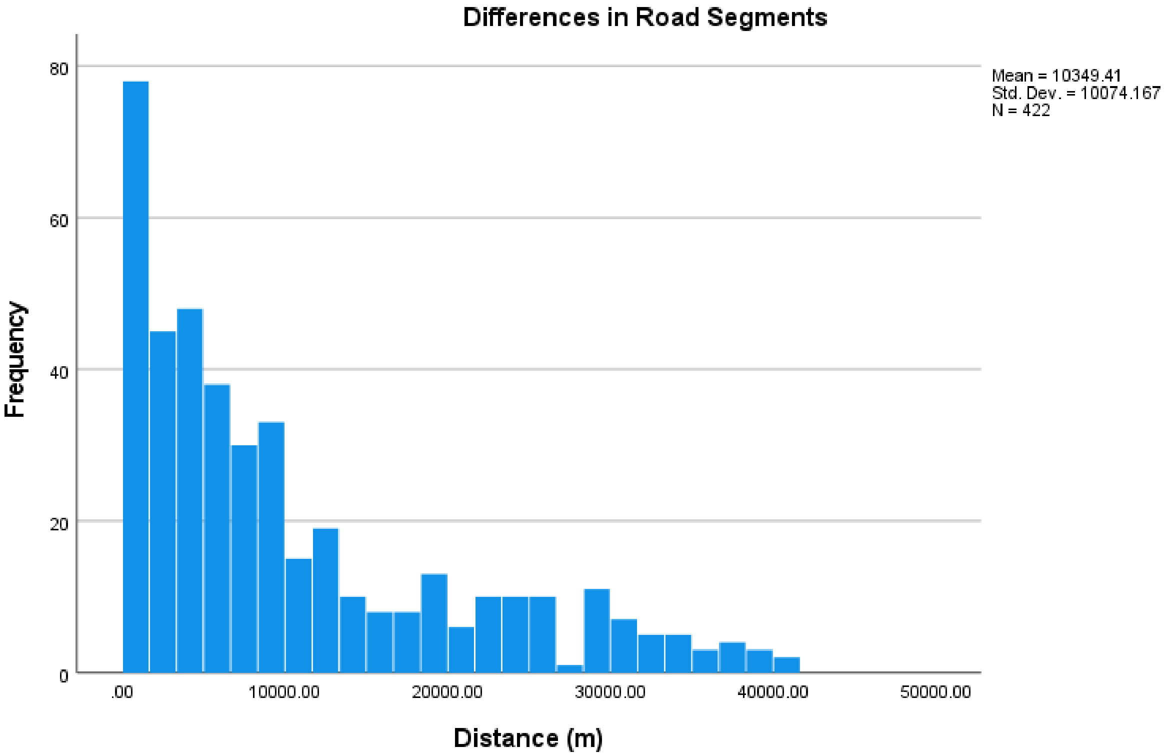
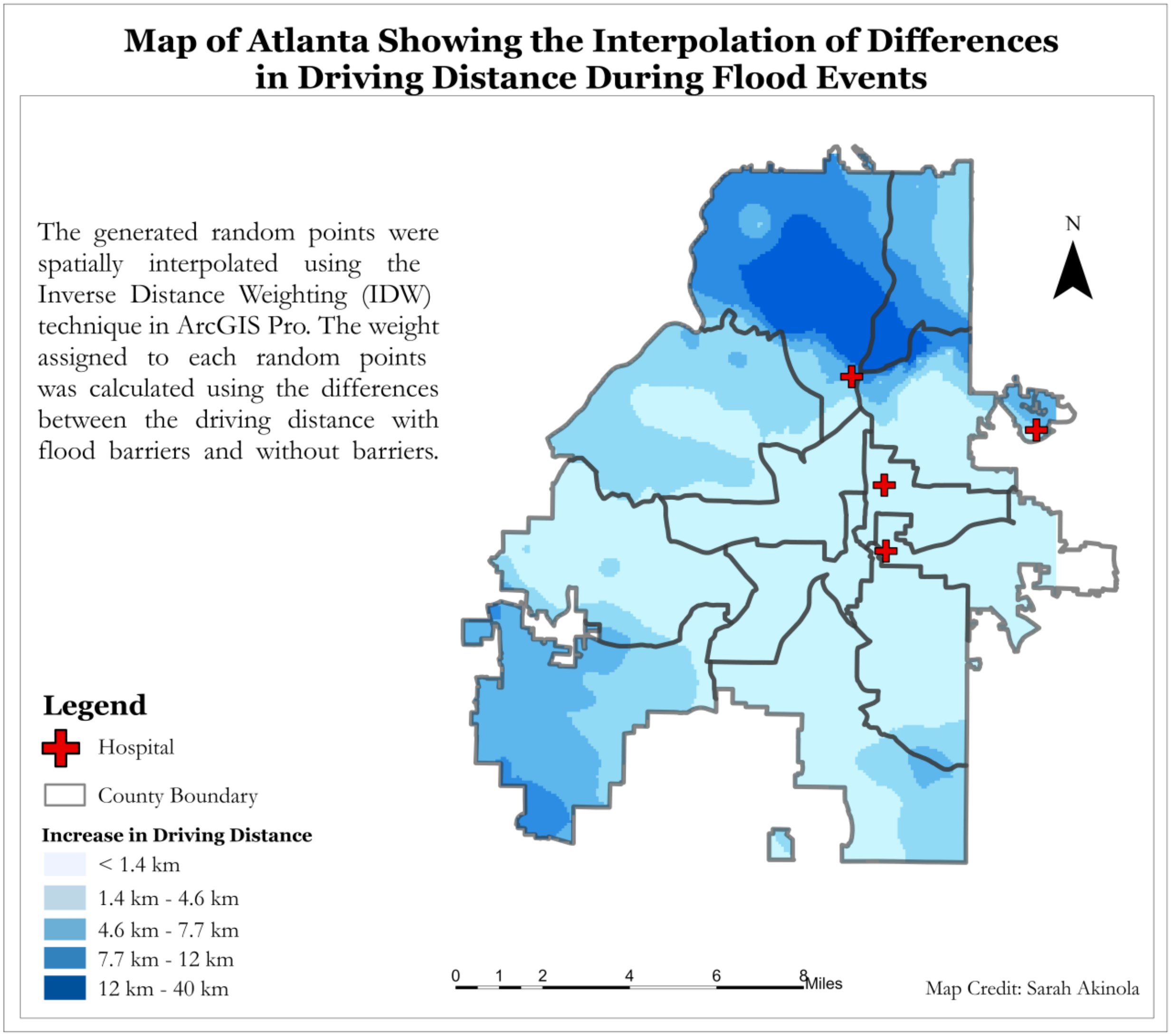


Figure 9: Histogram showing the distribution of differences in road network.

Figure 10 uses data on increased travel distances to create an interpolated surface of access disruption across the Atlanta area. The map reveals that the eastern part (light-colored) of Atlanta is less likely to experience increased travel distance during flood event, while the northern and southwestern areas (darker shade) in Atlanta have the greatest risk for access disruption due to flooded roads. This pattern is expected given the concentration of hospitals in the east-central part of the Atlanta metroplex and the relatively sparse road network in the northern and south-western suburbs. The lowest category of additional driving distance was less than 1.4 km. However, in a worst-case scenario, the additional distance will be between 11 km – 40 km. On the map, darker colors indicate areas where the amount of time added due to network disruptions was greater than those areas represented by lighter colors.



Map of Atlanta Showing the Interpolation of Differences in Driving Distance During Flood Events

The generated random points were spatially interpolated using the Inverse Distance Weighting (IDW) technique in ArcGIS Pro. The weight assigned to each random points was calculated using the differences between the driving distance with flood barriers and without barriers.

Figure 10: Map shows the interpolation of weighted differences between distance with flood barriers and without barriers.

Certain places became inaccessible due to the closure of road segments, increasing travel time, distance, and congestion on alternate routes. The alternate roads saw an increase in traffic because the regular, previously used routes were no longer the fastest links. This emphasizes the danger that flooding brings to residential areas and how it could affect people's movement.

Therefore, emergency organizations must determine suitable mitigation methods and response plans to properly handle these difficulties.

The ability of the main roads to facilitate effective supply would be hampered in several locations because they became inaccessible. However, because there were many alternative routes connecting the outside districts with the city center, it could still perform the necessary supply functions for the entire city.

A road is regarded as inaccessible when water rises above its height. In reaction to the flood data examined in this study, some proportion of nodes and edges were flooded, although the susceptibility of road network topologies varies as expected. Some areas experienced significant losses to the road network, while some areas experienced little or no impact.

3.2 IMPLICATIONS OF THE STUDY

This study emphasizes the critical implications that road disconnections have on the healthcare system and the population's well-being. The consequences of impassable roads during flood events are far-reaching and diverse, significantly impacting various aspects of public health and emergency response. Public health and flood mitigation may be impacted in a significant way, making it more difficult to access medical care and respond to emergencies effectively.

Delayed emergency response is one of the most pressing implications. In this study, we use a simulated dataset to show that roads that are disconnected due to flooding will result in routes with statistically significant increases in driving distances. These increased distances may delay the dispatch of emergency services and medical professionals to hospitals, thereby causing patients to suffer catastrophic consequences. Also, disruptions in road networks between hospitals (figure 6) can make it difficult to transfer patients between different healthcare facilities.

Accessibility of healthcare services emerges as a major concern in addition to potential delays caused due to flooded roads. During floods, residents in locations with disconnected roads may have challenges reaching hospitals. Our study found that several simulated locations were completely cut off from access to hospitals (Table 4) while several others were reassigned to different hospitals as their closest accessible facility (Table 3). This implies that individuals may lose access altogether or may have to use services at hospitals where their primary care providers may not be available. People who depend on regular medical treatment and have chronic health issues may be faced with additional stresses and hospitals may be burdened due to the influx of patients that are not routinely treated there.

Restricted road access affects the transportation of medical equipment and supplies to hospitals. Floods can impede the flow of supplies, which could lead to a shortage of crucial medical supplies. Likewise, the accessibility of hospital workers may also be impacted by road closures during flooding. Healthcare workers may have trouble getting to work, which could lead to staffing shortages that can impact the quality of patient care. In extreme situations, hospital operations, including administrative, logistical, and maintenance tasks, may be disrupted, making it difficult to maintain the expected levels of service.

Road closures during emergencies can make it more difficult to safely evacuate patients from regions at risk of flooding. This presents difficulties in situations including emergency response and evacuation, increasing risk to vulnerable populations. Communities that are already susceptible may be disproportionately affected by disconnected roads during floods. The elderly, people with poor mobility, and people who live in poor neighborhoods that are more likely to see flooding would face greater barriers to receiving healthcare services, a factor that would worsen already-existing health disparities.

In conclusion, understanding the effects of disconnected roadways during flooding occurrences is crucial for healthcare and emergency preparation. A proactive approach to disaster planning, infrastructural improvements, and well-coordinated response efforts are required to address these problems.

CHAPTER 4

4.1 CONCLUSION

An evaluation of the susceptibility, connectedness, and accessibility of Atlanta Road network is required to prioritize access to healthcare infrastructure and resolve discrepancies in flooding's impact on roadway networks. This evaluation provided information that may be used to strengthen community resilience and lessen the negative effects of floods on healthcare facilities.

In this study, valuable insights were gained into potential disruptions to healthcare services during flood disasters by examining the road network and considering the 100-year flood data. The analysis's main findings include the identification of vital flood-prone road segments that may prevent hospital access, the identification of affected hospital areas with reduced accessibility, the identification of alternate routes to ensure continued hospital access during floods, and the estimation of an increased travel time to hospitals during flood events. During disasters brought on by extreme weather occurrences, mitigation plans can be devised by identifying the paths of node disconnection. This will increase the accessibility and functionality of essential services, like emergency rooms.

Based on the data analyzed, findings indicate that the northern and southwestern part of Atlanta is particularly susceptible to significant access disruption to hospitals due to flooding. Such disruption is brought upon due to closure of vital road networks, leading to extended travel distance and time for people in need of medical help. Consequently, patients in need of emergency care during flood event might face considerable challenges due to this access limitation. This knowledge is essential for emergency management organizations, healthcare organizations, and urban planners to create focused efforts that will mitigate the adverse impacts of flooding on hospital facilities.

In addition, this study emphasizes the value of preventative actions to improve the resilience of Atlanta healthcare system. The continuing provision of medical services during flood occurrences can be ensured by putting early warning systems into place, enhancing road infrastructure in flood-prone locations, and creating alternate transit routes.

The outcomes of this study provide valuable insights and data-driven evidence which can guide future decisions about resource allocation for healthcare, disaster management, and urban development. For instance, the research findings about the northern and southwestern part of Atlanta's vulnerability to flooding will allow for infrastructure improvement and increased emergency response capabilities in these vulnerable regions. This targeted approach would ensure that resources are used efficiently, thereby strengthening community resilience, and safeguarding public health. Considering the potential effects of flood on hospital accessibility, this study can motivate policymakers to create stronger and more effective measures to mitigate flood impacts. By leveraging GIS for road network analysis, this approach can also be adopted statewide and nationwide, thereby providing researchers and emergency planners valuable insights into the vulnerabilities and potential access disruptions hospitals may face during flooding. This information aids in developing effective emergency response plans and mitigating the impact of flooding on healthcare services.

Overall, this research offers insightful information on how Atlanta hospital network is vulnerable to flood occurrences. By understanding the issues and figuring out where improvements can be made, a more adaptable healthcare system that can quickly react to and recover from flooding-related disruptions can be made possible.

4.2 LIMITATIONS OF THE STUDY

Data issues relating to the Atlanta flood, the road network, and hospital locations came up while considering access disruptions to hospitals during Atlanta flooding. These difficulties may affect the analysis's precision and dependability.

Comprehensive Atlanta's flood data was difficult to find. Also, Atlanta Road network data must be accurate to determine the shortest routes because wrong computations and unreliable results may arise from using incomplete or inaccurate road network data. However, for some of the previous road network data gotten, some networks were not connected. The roads might have either undergone alterations, or closures. To accurately reflect the current state of the road infrastructure and assure the validity of the analysis, the most recent data on the road network was obtained. By acknowledging and addressing these data issues, it became possible to more accurately assess how Atlanta's flooding occurrences affected hospital access, giving emergency planners and decision-makers useful information for reducing the effects of floods on healthcare accessible.

In addition, it is crucial to note that traffic congestion in a city like Atlanta might also contribute to influencing travel time of patients who are trying to visit the hospital, and this was not considered in our analysis. In light of variables like the hour of the day and the day of the week, it is plausible to believe that accessibility might be lower or higher than what our findings suggest. Also, since traffic patterns may change during significant flood occurrences, the usage of traffic simulation models might be necessary.

Furthermore, our assessment has a notable limitation by not using real-time flood data. In contrast to the historical flood data that was used, real-time flood data would provide up-to-the-minute, accurate information about ongoing flooding events, which is essential for making timely decisions, assessing the actual impact on road networks and hospital accessibility, and enabling swift and effective response measures. Since flood situations can change rapidly, relying solely on the 100-year floodplain data might not reflect the current extent or severity of flood. This disparity can cause a big compromise in the flood warning system and lead to inaccurate flood mapping.

Another drawback of this analysis is that vehicle transportation was largely the focus when estimating connectedness and accessibility, omitting the considerable importance of public and semi-public transportation, such as minibuses, or trains, in a city like Atlanta. This probably led to inflated accessibility estimates gotten from the results. It is possible that the closest hospital from some residences might allow the use of Marta train, although more research is needed to fully understand these aspects, considering the waiting time of train or bus schedule on some days which could be approximately 25 minutes. Future research should investigate whether vehicle transportation would be sufficient or whether it is necessary to account for other transportation modes impacting journey speed in accessibility assessments.

Furthermore, the hospital locations used were clipped to the Atlanta boundaries. It is possible that other hospitals with emergency departments are just outside our study area. This may impact the shortest path analysis for simulated service points located at the peripheral edges of the study region and close to hospitals not included in our dataset. However, given the small number of hospitals with emergency service facilities in the region, overall, we do not expect this assumption to have a significant impact on our results.

4.3 RECOMMENDATIONS

The following recommendations and ideas are provided for future research based on this study.

Firstly, this study assumes that individuals are aware of delays and are well-informed enough to choose the shortest route. This might not be true in most cases, which is why increased flood forecasting and early warning systems can greatly enhance preparedness and response efforts. Authorities would be able to promptly inform hospitals and emergency responders of potential access impediments and enable them to take the necessary actions to maintain the continuity of medical services by combining real-time data on weather patterns, river levels, and flood projections.

In addition, increased investment in infrastructure can improve the resilience of hospital access during flood occurrences. This involves actions like elevating the level of roads in flood-prone areas, building flood barriers, and enhancing drainage systems. To properly prioritize and implement these infrastructure improvements, collaboration among city planners, transportation organizations, and healthcare institutions is required.

Furthermore, if dynamic traffic simulation is included in future studies, more accurate evaluations of hospital accessibility can be produced by combining real-time traffic data and considering congestion patterns during flood occurrences. By doing so, it will be possible to create more manageable and successful tactics to minimize access disruptions and better understand how traffic flow varies during flooding.

Lastly, the possible influence of climate change should be considered in future studies due to the growing frequency and severity of extreme weather events, particularly flooding. For long-term planning and resilience-building initiatives, evaluating how anticipated changes in rainfall patterns, sea level rise, and urban expansion may influence hospital access during floods would be extremely helpful.

By tackling these areas of future work and helping to provide practical solutions to lessen the effects of similar occurrences, more knowledge on hospital access disruptions during the Atlanta flooding can be expanded. In order to create a more resilient healthcare system that can successfully adapt to future flood occurrences, interdisciplinary research, data-driven methodologies, and stakeholder collaboration must all be integrated.

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