Dynamics of Link Importance Across Flood Disaster Phases And Flood Impacts on Operation of an Industry

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DYNAMICS OF LINK IMPORTANCE ACROSS FLOOD DISASTER PHASES AND FLOOD IMPACTS ON OPERATION OF AN INDUSTRY

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

by
Navin Bhatta
May 2024

Accepted by:
Pamela Murray-Tuite, Committee Chair
Abdul A. Khan
Shakhawat H. Tanim
ABSTRACT

Transportation damage and disruptions will become increasingly common as the frequency of floods increases due to climate change. Given the size and cost of the transportation network construction, communities' mitigation measures should be supported by evaluations that cover both normal and disaster management phases. This thesis examines the criticality of road segments in the normal, flood response, and recovery phases, considering the effects on emergency services, healthcare, industry, education, recreation, and transit and analyses that whether a flood disrupts the operational trips of a company in Anderson County, South Carolina. A 100-year event and a 500-year flood event provides context for analyzing flood impacts to the time-based shortest paths, determined using ArcGIS Pro 3.1.3. Local and secondary roads were especially affected, with rerouting concentrating around the Anderson City area. Blocked road sections identified potentially vulnerable roads, and normalized betweenness centrality metrics identified community dependence on road segments for daily and emergency operations. While the quantity and dispersion of parks and grocery stores mitigated rerouting distance, other purposes faced challenges from impassable routes. Southeastern and southern regions as most impacted across purposes as per the analysis, suggesting targeted mitigation. The most critical routes before, during and after the flood were I-85, State Routes 28 and 81, and Federal Routes 29, 76, and 178. Also, the analysis for flood impacts on accessibility of a company in Anderson County was done using Boolean value assignment to the failed or non-failed links connecting the company with workforce, import and export trips. We found that the company undertaken
for analysis would have disruption in importing and export of materials, but the workforce access was found to be not impacted as much. The routes that were found critically impacting the accessibility for the import and export were found to be SC 28 link, US 29 link, Highway 355 (New Pond Road link). This study highlights commonalities in road criticality across phases to support resilient transportation planning and sustainability. Based on both studies SC-28 link was found to be critical for flood disaster management phases, workforce accessibility, import and export and was found to be blocked due to 500-year flood.
DEDICATION

I dedicate this thesis to my parents for their immense love and support throughout this little journey called life.
ACKNOWLEDGMENTS

I would like to express my thanks to my advisor Dr. Pamela Murray-Tuite for providing me with the opportunity to research on this interesting topic along with helping me throughout the research through direction, suggestions, and constructive comments on my research and writing process.

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I want to thank my committee for their invaluable suggestions which helped shape the thesis.

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CHAPTER 1

INTRODUCTION

Transportation is a lifeline infrastructure (FEMA, 2023), central to the functioning of individual lives and community operations. Transportation infrastructure facilitates and makes feasible the mobility aspect of many community activities, including emergency travel, commuting, engaging in recreational and social activities, and traveling to and from school. It promotes evacuation and disaster recovery and makes important locations (including hospitals, schools, and workplaces) easier to reach. The accessibility of a community's facilities is determined by the effectiveness and availability of both public and private transportation that uses this infrastructure.

Floods impact various sectors of a community (Watson & Ahn, 2022) and have a large share of the total losses caused by natural disasters (Adikari & Yoshitani, 2009). Floods have significant impacts on transportation systems and society, affecting infrastructure, disrupting travel, and causing economic losses. The damage caused by floods to transportation systems can lead to road closures, rendering roads impassable and disrupting routine transport needs ((Jacobs et al., 2018) (Ntakiyimana & Twagirayezu, 2022)). In addition to destroying pavement, bridges, and tunnels, flooding can also isolate populations and result in submerged or debris-blocked highways impacting people’s livelihoods, health, housing, education, and mobility (Boakye et al., 2022). Additionally, floods can strain transportation networks through delays, infrastructure damage, and recovery efforts, potentially affecting economies (Rebally et al., 2021). Transportation disruptions make it
more difficult to conduct search and rescue operations, distribute help, evacuate survivors, and gain access to critical facilities (Ulusan & Ergun, 2018), thereby exacerbating the disaster. From total accessibility obstruction to partial network interruption, increasing travel times and distances, the type and severity of disruptions differ from event to event and location to location (Bhatta et al., 2024).

Studies have emphasized the need to consider changes in population, transport modes, and climate conditions when assessing the impact of floods on road transport systems (Weiping et al., 2020). Climate change is expected to increase flood frequency and intensity (Stocker & IPCC. Working Group I., 2013). The increment in frequency of floods can lead to delayed recovery, if the disaster response plans are not in place (Alexander, 2015). Given the severe effects of flooding and the significance of transportation, a resilient transportation system is essential. Resilience is defined as the capacity to anticipate, plan for, and adapt to changing conditions as well as rapidly respond to and recover from disturbances (FHWA, 2014). In the transportation sector, resilience is critical to preserving social connectedness (Boakye et al., 2022), mobility, economic stability, and emergency response capabilities (Ganin et al., 2017). Resilience contributes to a community's general well-being and stability by ensuring transportation networks can tolerate disruptions and recover rapidly (Wang et al., 2020). Various dimensions of the system need to be identified to improve a system's resilience. Redundancy, diversity, efficiency, adaptability, safety, mobility, and the capacity for rapid recovery are a few of the ten dimensions of resilience provided by Murray-Tuite, (2006). Resilient transportation systems can minimize
disruptions, ensure the continuity of services, and facilitate efficient emergency response during and after flood events (Koks et al., 2019). Identifying the risk and the type of disruptions it may cause to the system is the first step toward enhancing resilience. The resilience decisions and approaches can be different for different disasters (Crutchfield, 2013). Time is of the key when it comes to responding to and repairing the damaged road networks after flooding, delayed recovery leads to greater the cost to the community (Colon et al., 2021a). Assessing the effects of floods on transportation networks is vital for mitigating risks, enhancing resilience, and ensuring the continuity of essential services during and after flood events. By improving the resilience of transportation systems to floods, communities can strengthen their ability to absorb disturbances, recover quickly, and maintain essential functions, such as transportation, housing, and economic activities (Postance et al., 2017). Identifying and prioritizing important road locations that serve multiple uses is a reasonable strategy for investing in resilience, given the extensiveness of road networks and the time, effort, and resources needed for restoration. Prioritization facilitates an efficient response strategy and minimizes disruption and enables the recovery of normal community function in these critical areas. Rosenzweig et al. (2018) also emphasizes that for increasing resilience in transportation network and targeted mitigation, the critical network segments that support socio-economic activities should be identified (Rosenzweig et al., 2018).

Criticality analysis is a method used to assess a community’s reliance on various infrastructure for its daily (Oh et al., 2013b) and emergency operations. Criticality in
transportation network measures importance of a road section to an entire network, system, or region (SEMCOG, 2020). The criticality depends on the role that a particular road fulfills for a community (Hallegatte et al., 2019). If a road section supports access to critical facilities such as hospitals, power supply, and evacuation facilities, it can have higher criticality than other major roads that only add to general mobility. Jafino et al. (2020), mention two characteristics of criticality analysis. The first being the ranking of the network components based on their criticality scores and second is that the analysis components are the nodes and links instead of the user (Mattsson & Jenelius, 2015). The easy use along with the wide variety of criticality metrics has facilitated in its frequent use across transportation sectors for various purposes related to transportation networks, traffic, accessibility, and connectivity. Criticality analysis supports risk management, resource allocation, decision-making, and resilience planning initiatives (Oh et al., 2013a), all of which are critical to improving the resilience of transportation networks.

Understanding the events leading up to a catastrophic failure in a system involving critical infrastructures, or the basic cause of failures, is an essential aspect of resilience. The root cause is an important aspect of failure. Knowledge of basic events that lead to the whole system failure through various scenarios is needed to identify the root cause of the failure (Roberts et al., 1981). Root cause identification comes with recognizing the intricate connections within transportation networks, where a single failure can cascade into widespread consequences affecting various aspects of community life. A study by Fotouhi et al., (2017) emphasizes the need to account for interdependencies to assess transportation
resilience accurately. Visualizing the potential failure scenarios, cascading effects to different systems and their underlying causes can help identify critical events of failure, evaluate risks, and implement targeted strategies to enhance resilience.

1.1 Problem Statement

Transportation resilience research addresses railway (Jin et al., 2014), road (Osogami et al., 2013), freight (Miller-Hooks et al., 2011) or transportation in general (Gonçalves & Ribeiro, 2020). But evaluations frequently overlook the network's primary goal, which is to facilitate people traveling over it for a variety of purposes (Anderson et al., 2022). To better incorporate resilience in planning, an approach is therefore needed for understanding the specific and collective effects of floods on a variety of community operating trips, including trips to hospitals, schools, colleges and universities, parks, workplaces, law enforcement locations, grocery stores, along with evacuation routes.

1.2 Research Objectives

The first objective of this research is to help communities build resilience by identifying the critical road links before, during, and immediately after floods. This assessment can assist stakeholders in prioritizing the infrastructure for repair and rebuild activities which provide maximum benefit along with indications of where resilience can/should be added to the transportation sector of a community. To prioritize the infrastructure, the criticality of the road sections before, during, and after flood is needed so that the policy makers can understand which road sections are critical during those disaster phases and which ones to
prioritize. The study area is Anderson County, South Carolina, in which a 100-year flood of the Savannah River potentially impacts all trip types.

A second objective of this study is to identify whether a company is at risk of substantial economic impact because of floods by analyzing the accessibility failure for trips related to the company’s activities. The economy of a community greatly relies on the dominant economic activity of that community. Due to disasters, such economic activity can change, leading to a significant shift in the economy. If most of the prominent industries in the community are impacted by the flood or lose accessibility of raw materials or workforce for a long enough period of time, then the community's primary economic activity can change. Therefore, an approach to determine the probability that the activity would be impacted and could change based on the disaster is needed to understand more of the effects of disasters in a community. This analysis can provide the extent of potential impact to a specific type of industry or trips which can be prioritized based on requirements to keep the economy vibrant.

1.3 Outline of Thesis

Overall, the thesis consists of four additional chapters. Chapter 2 presents a review of literature relating to criticality of roads, flood impacts on transportation, and resilience related to transportation in a community along with dependence of the economy and companies of a community on transportation. Chapter 3 is a manuscript titled Dynamics of Link Importance through Normal Conditions, Flood Response, and Recovery. This manuscript has been published in a special issue of Sustainability, addressing the first objective. Chapter 4 presents a draft manuscript on the Potential of Flood induced change
in company operation trips, which addresses second objective. Chapter 5 summarizes the thesis by providing conclusions, contributions, limitations, and future directions.

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CHAPTER 2

LITERATURE REVIEW

Floods have direct and indirect impacts on transportation (Pyatkova et al., 2019) (Tachaudomdach et al., 2021). The direct impacts are infrastructure damage caused by direct contact with floodwater, whereas the indirect implications include route change congestion, economic losses, social and psychological loss, and so on. Roads and bridges may get obstructed, necessitating rerouting, if available. Because of the obstruction, the consequences are not limited to the directly inundated area; distant locations relying on the inundated areas may also be impacted (Bhatta et al., 2024). The increased rerouting distance may be lower in urban surroundings than in rural environments due to the availability of several alternatives (Bhatta et al., 2024; Suarez et al., 2005). In contrast, in places with limited transportation alternatives, excessive rerouting results in enormous delays and economic, temporal, and efficiency losses (Bhatta et al., 2024). For example, According to Affleck & Gibbon, 2016, a 15-minute travel took two hours due to interruption and congestion caused by the temporary closure of many bridges. Rerouting can have impacts on businesses since it increases transportation costs.

Businesses may suffer when important business routes are closed because of shortages of workforce, difficulties with exporting goods, or difficulty accessing raw materials (Bhatta et al., 2024). For instance, 2011 flooding in Thailand led to a shortage of auto parts, which caused inside and outside the flood zone automobile manufacturing to stop. Bubeck et al. (2017) found an indirect loss of $4.17 million due to delays in commuting caused by storm Desmond. Even though losses are unavoidable, they can be minimized.
Floods significantly disrupt various aspects of community life. The study on the impacts of flood on accessibility mainly focuses on emergency response services (Yin et al., 2021)(Tsang & Scott, 2020)(Yu et al., 2020)(Dong et al., 2020). Before, during, and after a crisis, it's critical to ensure accessibility to emergency facilities, such as hospitals and urgent care centers. For people who require emergency treatment, longer travel times to get care may be harmful. The travel time to access critical facilities was found to increase by 2.23 minutes in a study on 100-year return period floods in Delaware’s coastal areas(Gangwal et al., 2023). Given the importance of these trips, even a small delay might have serious consequences. In certain places, flooding might also render hospitals unreachable, which can have much more dire consequences. Dense pockets of communities were found to lose access to the hospitals in the study by Gangwal et al., 2023.

Additionally, flooding presents difficulties for public transportation networks, resulting in obstructions that disproportionately impact households with lower socioeconomic status, as they frequently lack alternative means of transportation (Bhatta et al., 2024). Research on the urban transit system in Kinshasa revealed that delays caused by flooding resulted in longer headways for public transportation, slower speeds, and the need for rerouting (He et al., 2021). These changes resulted in travel delays and reduced work accessibility, inflicting a considerable societal impact. He et al., 2021 calculated $1.2 million per day economic losses due to the public transportation delay.

Evacuation is a vital component of the response phase of a disaster and can be difficult when faced with floods that render evacuation routes inaccessible(Bhatta et al., 2024). Thorough analyses of the evacuation routes in flood scenarios are necessary (Burnside et
al., 2007)(Trumbo et al., 2014)(Tanim & Tobin, 2018). This involves understanding the flood condition of the evacuation routes and rerouting consequences of blockages.

One often overlooked indirect impact of floods is loss of social connectedness, a feeling of attachment towards people’s place of living (Bhatta et al., 2024). People's sense of belonging to their community is very important for the well-being and prosperity of a community (Theodori, 2001). According to Cox and Perry (2011), physical and social changes brought on by a disaster can lead to feeling of loneliness and isolation (R. S. Cox & Perry, 2011). Having access to parks and other natural areas can contribute to a feeling of community and home (Silver & Grek-Martin, 2015). Floods have the potential to create new social exclusion areas by disrupting access (Boakye et al., 2022), thus compounding the psychological impact on the population.

2.1 Resilience in transportation

The concept of resilience was introduced first by (Holling, 1973) in the field of ecology and since then, the concept has been applied to other disciplines (Jafino, 2021). There are various measures to define resilience based on the requirements. Bruneau et al. (2003) presented a resilience framework based on the 4R characteristics; Robustness, Redundancy, Resourcefulness, and Rapidity. Robustness is the ability of the transportation network nodes or links to withstand the disruption. Redundancy is the availability of alternative routes in the transportation network. Resourcefulness is the availability of resources in the transportation system for its restoration, and rapidity is the ability to return to normal functioning in a timely manner (Du et al., 2022). Ouyang et al. (2012) introduced
three staged frameworks; resist, absorb, and recover, that includes occurrence of joint hazards considering the system’s resistive, absorptive, and restorative capabilities. There have been continuous additions to the traditional 4R framework. Berle et al., (2011) introduced preparedness which is subdivided as emergency preparedness and response preparedness, and it helps in reducing potential negative impacts of disruptions in transportation systems.

Within the concept of resilience, various analysis frameworks and transportation resilience metrics were developed. Murray-Tuite and Mahmassani (2004) proposed a disruption index by combining the vulnerability indexes of all origin - destination pairs in a transportation network and used the index to measure the extent of disruption that a link’s removal can impose onto the network. Scott et. al. (2006) evaluated the performance of the network based on the travel time delay due to link closure using a network robustness index and identified the critical links in the network. Murray-Tuite (2006) evaluated the system optimum and user equilibrium traffic assignment methods for their impacts on resilience based on proposed indicators to quantify the transportation resilience in terms of adaptability, mobility, safety, and recovery. Cox et al. (2010) measured the resilience in transportation systems based on the mode shifts in passenger journeys under disruption, such as terrorist attacks. Ip and Wang (2009) assessed resilience by calculating the node resilience in the network based on redundancy of links, where the node resilience is the weighted sum of independent paths with all other city nodes in the network. The independent paths are identified by making sure that multiple paths for the same origin destination pair do not share any common links (Ip & Wang, 2009).
Finding the network's vulnerabilities or most important segments is the first step in adding resilience. It is challenging to estimate the system's performance under normal circumstances and predict how well it will function during disruptions (Ganin et al., 2017). Disaster management includes setting priorities and making the most of investments made both before and after a disaster. The ultimate goals of disaster management are to reduce losses from disasters, enhance the system's resilience to shocks, and restore performance. (Futurechi & Miller-Hooks, 2015a). Pant et al., (2017) highlighted the significance of spatial network models in identifying critical infrastructures at risk of flooding, emphasizing the need to prioritize flood protection investments to enhance city resilience. Resilience in the transportation network can be increased by understanding the type and extent of disaster impacts and conducting criticality analyses that take those impacts into account.

### 2.2 Criticality analysis and metrics in transportation

Criticality in transportation has gained extensive use in transportation recently (Jafino et al., 2020) and both qualitative and quantitative techniques can be used to evaluate criticality. Qualitative assessments are elaborate descriptions that help one in understanding the impacts and management techniques. proposed a decision-support system framework to lower the vulnerability of locations and infrastructure systems through stress-mitigation techniques for disasters. In order to reduce the vulnerability of places and infrastructure systems to disasters, Croope and McNeil, (2011) presented a decision-support system framework that includes stress-mitigation strategies. Quantitative assessment can be mathematical models for assessment (Murray-Tuite, 2006), models for management (Futurechi & Miller-Hooks, 2014), or decision support tools (Adams, Asce, et al.,
2012) that can provide direct measurements or suggest decisions that help analysts in assessing or predicting the disaster impacts (Faturechi & Miller-Hooks, 2015a). These assessments can be of component and system level performance (Faturechi & Miller-Hooks, 2015a). Metrics are needed to quantify criticality in transportation quantitatively. Some of the metrics generally used in transportation for criticality analysis are provided below (Almotahari & Yazici, 2021a), (Jafino et al., 2020).

**Travel Cost:** Change in the travel cost due to disruptions is a measure of criticality which can determine the increment in travel cost due to hazards or disruptions. The travel cost study can also include transport users by adding traffic into the analysis. There are various ways in which the change in travel cost criticality is used in literature. The metric can be unweighted travel cost (Z. Wang et al., 2014), or weighted (Balijepalli & Oppong, 2014; Gauthier et al., 2018a) where the weight is calculated based on the distance and traffic flow. The travel cost can be regional as well, where all the origin – destination pairs within an area are analyzed for the increase in the total travel time due to disruptions (Mattsson & Jenelius, 2015). Another metric is the change in expected user exposure where the average impact due to the disruptions experienced by all users is calculated, or worst-case user exposure where the maximum impact of the disruptions to the users are calculated (Mattsson & Jenelius, 2015).

**Accessibility:** Hansen, (1959) defines accessibility as “the potential of opportunities for interaction”. Accessibility can be used as a measure in determining criticality in the network as well. It is measured in terms of either weighted or unweighted accessibility (Y. Wang & Cullinane, 2014). The change in weighted accessibility is the decrease in
accessibility due to disruptions of an element considering the transport demand or flow. Socioeconomic activities of the traffic are used to determine weights in this case (Luathep et al., 2011). The unweighted traffic flow, where the traffic data is not used, is based on the topology of the transportation network.

**Traffic data:** A measure of criticality is based on the congestion in transportation network which uses the empirical traffic flow data along with the network’s capacity. The traffic flow (Zhou et al., 2015) and traffic density (Scott et al., 2006; Zhou et al., 2015) are used as criticality measures.

**Connectivity:** A connectivity approach from origins to destinations in a network has also been used as a criticality measure. Origin-destination connectivity through k distinct shortest paths (Mishra et al., 2012) and unsatisfied demand, which is the amount of disconnected transport activity because of hazard (Qiang & Nagurney, 2012) are also used as criticality metrics.

**Betweenness Centrality:** Betweenness centrality is a measure initially proposed by Freeman (1977) to understand the importance of the links or nodes. It is calculated as the number of times a road section or a node is used to access facilities in a community. Gangwal et al. (2023) modified the betweenness centrality metric and measured criticality where they normalized the betweenness centrality on the node facility. Additionally, the traffic flow can be used to weight the betweenness centrality. However, Gauthier et al., 2018b recommend using betweenness centrality as a metric in the event that the trip demand and travel time are unavailable.
**Indices:** Indices are used in criticality assessments. For instance, if a road segment fails, the system's change in travel-time cost because of rerouting traffic is used to calculate the Network Robustness Index (NRI) for that segment. (Scott et al., 2006). This method is helpful when the travel time can be uniformly computed. The trip robustness index for system-wide robustness and the capacity-disruption values for identifying critical road segments were computed by Sullivan et al. (2010) using the NRI. The network trip robustness is calculated by taking the total of all the NRI values for each connection individually and dividing it by the total trip demand in the network (Sullivan et al., 2010). However, if link disconnectivity occurs, the index cannot evaluate the impacts of isolation. An importance score (IS) for network links was developed by Jenelius et al. (2006) using the cost difference between the link's pre- and post-failure values. There were two ways to weight this score: either all origins and destinations were given the same weight, known as "global importance," or traffic constituted the basis for weighting, known as "demand-weighted importance" (Jenelius et al., 2006). Both numbers cannot be directly compared, but the importance score can be computed with and without disconnectivity (Almotahari & Yazici, 2019). Nagurney and Qiang presented the efficiency index (EI), which considers network topology and travel behavior data to determine the criticality of transportation links and nodes. The efficiency measure assumes that the transportation network's capacity to handle traffic at a given price—which may include trip time—directly correlates with the network's performance (Nagurney & Qiang, 2007, 2008). Since the change in efficiency is regarded as criticality, the criticality metric is considered indirect (Almotahari & Yazici, 2019).
Almotahari & Yazici, (2019) developed the Link Criticality Index (LCI), a metric that measures the increase in travel time on a connection caused by an increase in unit flow. It is a single traffic assignment metric and based on marginalized cost. The OD demand and the travel time on the network link are the two factors that affect the LCI, LCI can function effectively for smaller networks, but processing takes a long time for bigger transportation networks (Almotahari & Yazici, 2021a).

Others: Apart from the abovementioned metrics, the exposure to disaster can be used as a transportation criticality metric, where the disaster is overlayed into the road network to determine criticality of the infrastructures (Kermanshah & Derrible, 2016). Also, from the exposure, average change in the network efficiency (Nagurney & Qiang, 2008) and GIS analysis for the nearby alternative elements was also found to be used as a criticality analysis tool (Snelder et al., 2012).

Various transportation purposes are analysed for their criticality in the research. Colon et al., (2021a) studied how users and supply networks affected criticality on Tanzanian highways by combining a supply chain model with a transport model. They integrated economic and transport modeling by calculating business losses resulting from supply disruptions. The effects of employee absences and delay were examined by Kasmalkar et al., (2020b) through an analysis of the disruption in commuter traffic flow caused by sea level rise. The criticality of the roads to access facilities such as hospitals, emergency care and emergency shelters was measured by Gangwal et al., (2023). The accessibility of pharmacies, grocery stores, and hospitals for 500-year flooding was evaluated by Gangwal & Dong, (2022). Alabbad et al., (2021) analyzed the 100- and 500-year return period flood
to measure the disruptions in accessing hospitals, fire departments and police stations in Iowa. In the coastal areas of Honolulu, Hawaii, Shen & Kim, (2020) examined the vulnerabilities related to travel to work, school, grocery shopping, recreational activities, and emergency services. However, this study was conducted in coastal areas for sea level rise not for fluvial flooding. By analyzing the change in equitable access from block group centroids to supermarkets, medical clinics, and primary schools, Anderson et al., (2022) prioritized network restoration for liquefaction, tsunami, and hurricanes.

2.3 Need for resilience in transportation planning.

Transportation systems are interconnected with various other essential systems such as energy, water, communication networks (Hasan et al., 2015), economy, and social wellbeing. The vulnerability of transportation infrastructure to natural disasters like floods can have cascading effects on critical infrastructures (Pant et al., 2017). The interconnected nature of critical infrastructure systems can result in cascading effects when one system fails, impacting the security, economy, public health, and safety of a region (Setola et al., 2016). For instance, the accessibility of destination markets for the exporting company is determined by the extent and quality of the transportation infrastructure along a certain route (Albarran et al., 2013; Francois & Manchin, 2007). The effects of transportation disruptions extend beyond immediate losses, affecting public transport infrastructure, intercity networks, and freight transport, leading to production shutdowns, supply shortages, and high economic damage (Lordieck & Corman, 2021; Miao & Ni, 2019). Since transportation infrastructure is interconnected with various other essential systems, it becomes necessary that transportation and mobility are resilient in the face of hazards such
as floods. Understanding these interconnections, vulnerabilities, and resilience factors is crucial for effective planning, management, and decision-making in ensuring the robustness and efficiency of transportation infrastructure systems. The current literature does not seem to address the criticality across various trip purposes during or after flood. This thesis addresses the impacts of floods on various activity-based trips such as access to workplaces, hospitals, parks, schools and universities, materials import and export, and emergency facilities based on the shortest routes before a flood along with the change in routing. The criticality of roads for each of the trip purposes is also analyzed and critical roads for a community before, during and after flood are identified along with the critical flooded locations based on unweighted trips. To measure the change in economic activity of a community, the impact of a flood on a company regarding its workforce accessibility along with import and export accessibility also is analyzed using fault tree analysis considering binary value assignment.

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CHAPTER 3

DYNAMICS OF LINK IMPORTANCE THROUGH NORMAL CONDITIONS, FLOOD RESPONSE, AND RECOVERY

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ABSTRACT

As climate change influences flood frequency, transportation damage and disruptions will become more common. Given the network’s expanse and cost of construction, communities’ mitigation efforts should be informed by analyses that span normal conditions and disaster management phases. This paper analyzes road segment criticality in normal, flood response, and recovery phases in Anderson County, South Carolina, considering impacts on emergency services, healthcare, industry, education, recreation, and transit. A 100-year event provides context for analyzing flood impacts to the time-based shortest paths, determined using ArcGIS Pro 3.1.3. Local and secondary roads were especially affected, with rerouting concentrating around the Anderson City area. Blocked road sections identified potentially vulnerable roads, and normalized betweenness centrality metrics identified community dependence on road segments for daily and emergency operations. While the quantity and dispersion of parks and grocery stores mitigated rerouting distance, other purposes faced challenges from impassable routes. The analysis revealed the southeastern and southern regions as most impacted across purposes, suggesting targeted mitigation. I-85, State Routes 28 and 81, and Federal Routes 29, 76, and 178 were the most critical roads before, during, and after the flood. This study highlights commonalities in road criticality across phases to support resilient transportation planning and sustainability.
3.1 Introduction

Transportation is a lifeline infrastructure (Community Lifelines | FEMA.Gov, 2023) essential for sustainable and resilient communities. It facilitates access to key locations (e.g., hospitals, schools, workplaces) and supports disaster management, including evacuation and disaster recovery. With climate-induced changes in flood frequency (Stocker & Intergovernmental Panel on Climate Change. Working Group I., 2013)(Ji et al., 2022) strategic investments are needed. Transportation resilience planning and investment should consider the multi-faceted uses of transportation in conjunction with the hazards.

Floods impact various sectors of a community (Watson & Ahn, 2022) along with the transport infrastructure. Flooding can cause submerged or debris-blocked roads; destroy pavements, bridges, or tunnels; isolate communities; and impact environment and quality of life (Jakubcová et al., 2016). Such disruptions affect people's livelihoods, health, shelter, education, and mobility (Boakye et al., 2022) highlighting the importance of sustainable and resilient transportation systems. The interruption of transportation impacts safety, hampers searches and rescue efforts, hinders survivor evacuation, impedes access to critical facilities (Ulusan & Ergun, 2018), and challenges disaster relief operations (Tachaudomdach et al., 2021), thereby hindering disaster management. The nature and severity of disruptions vary from place to place, ranging from complete accessibility obstruction to partial network disruption, increasing travel distances and times and challenging traffic management.
The frequency and severity of floods are projected to increase due to climate change (Stocker & Intergovernmental Panel on Climate Change. Working Group I., 2013)(Ji et al., 2022). In addition to climate change, abrupt changes in land use and land cover over time play a role in increasing the severity of floods (Zope et al., 2017). Repeated flooding, along with the lack of a proper disaster response plan, can be more problematic leading to poor disaster management and delayed recovery (Alexander, 2015).

In light of the extreme impacts of floods and importance of transportation, the necessity of transportation system resilience is clear. Resilience encompasses the ability to anticipate, prepare for, and adapt to changing conditions, and rapidly respond to and recover from disruptions (FHWA, 2014). To improve resilience, one must first identify the hazard and the nature of disruptions that the hazard can have on the system. However, the resilience decisions and approaches for various disasters can be different (Crutchfield, 2013). In the case of flooding, time is of the essence to respond to and repair the impacted road networks since the longer the recovery time, the higher the cost to the community (Colon et al., 2021a). Given the expansive nature of road networks and the time, effort, and resources required for comprehensive repairs, it is pragmatic to identify and prioritize critical road locations serving multiple purposes. This approach increases the safety and management of the community by facilitating an efficient response strategy, minimizing disruption, thereby enabling the recovery of normal community function in these critical areas.

Criticality analysis is a technique for determining how dependent a community is on key infrastructure for its daily (Oh et al., 2013b) and emergency operations. Transportation
network criticality measures a road section's significance within the context of an entire system or region (SEMCOG, 2020). The criticality is dependent on the function that a particular road fulfills for a community (Hallegatte et al., 2019). For instance, a road can be of higher criticality if it supports access to key facilities such as hospitals, power supply, and evacuation facilities than other major roads that merely augment general mobility.

This paper analyzes the criticality of road segments across normal, flood response, and recovery conditions and how this criticality changes from one phase to another, with a focus on maintaining resilient and sustainable transportation networks. The normal condition assessment includes access to major shipping corridors for light to major industry, employment locations, educational institutions, recreational facilities, and stores. Public transit routes are also considered. For the response phase, we examine connectivity of residential areas to major corridors and to emergency shelters for evacuation purposes. For the recovery phase, we examine connectivity of major shipping corridors to the flood impacted areas. Across phases, we also consider access for emergency services and access from residential areas to healthcare, particularly hospitals and urgent care. GIS supports the analysis to determine the shortest path time and the change in this time when the road system is subject to flooding. The study area is Anderson County, South Carolina, in which all trip types are potentially impacted by a 100-year flood of the Savannah River. The assessment can provide stakeholders with critical roadways, information needed to plan for transportation resilience and prioritize the allocation of limited resources.
The remainder of this paper is divided into four sections. The next section provides a review of flood impacts on transportation, a survey of research utilizing criticality metrics, and their relevance to resilience. This is followed by the analysis methodology employed in this study. Next, the results for Anderson County are presented. The final section provides a summary, conclusions, limitations, and directions for future research.

### 3.2 Literature Review

Floods have direct and indirect impacts on transportation (Pyatkova et al., 2019)(Tachaudomdach et al., 2021). The direct impacts are damage to infrastructure due to direct contact of floodwater and the indirect impacts are changes in route, congestion, economic losses, social and psychological loss, etc. Roads and bridges may be blocked, necessitating the use of alternative routes, if available. Due to the blockage, the effects are not confined to the directly inundated area; distant locations dependent on the inundated areas may also be affected. In urban environments, the rerouting distance might be less due to the availability of many alternatives (Suarez et al., 2005).

Conversely, in regions with limited transportation alternatives, the rerouting is excessive resulting in massive delays, economic, temporal, and efficiency losses. For instance, Affleck et al. (Affleck & Gibbon, 2016) mentioned that a journey that took only fifteen minutes took two hours due to disruption and congestion caused after several bridges were temporarily closed. Rerouting processes indirectly impact businesses by escalating transportation costs.
When business-critical highways are closed, companies may suffer due to the unavailability of raw materials, export challenges, or workforce inaccessibility. For instance, 2011 flooding in Thailand led to a shortage of auto parts, which caused inside and outside the flood zone automobile manufacturing to stop. Bubeck et al. (Bubeck et al., 2017) calculated $4.17 million in indirect economic losses due to commuting delays from storm Desmond. These losses, shouldered by society, underscore the economic toll of floods. While losses can never be wholly eliminated, they can be reduced.

Floods significantly disrupt various aspects of community life. Research on accessibility impacts due to floods mainly focuses on emergency response services (Yin et al., 2021)(Tsang & Scott, 2020)(Yu et al., 2020)(Dong et al., 2020). Ensuring accessibility to emergency facilities like hospitals and urgent care is important before, during, and after a disaster. Increased travel time to reach care can be detrimental for patients in need of immediate medical attention. In a study on 100-year return period floods in Delaware’s coastal areas, Gangwal et al. (Gangwal et al., 2023) found an average increase in travel time of 2.23 minutes to reach critical facilities. Considering the urgency of such trips, even a marginal delay can have grave consequences. Floods can also make hospitals inaccessible in some areas, leading to even more severe outcomes. Gangwal et al. (Gangwal et al., 2023) found dense pockets of communities losing access to hospitals.

Floods also pose challenges to public transit systems, causing obstructions that disproportionately affect households of lower socio-economic status, who often lack alternative means of transportation. A study on Kinshasa's urban transit system showed that flood-induced disruptions led to increased public transit headway, decreased speed,
and necessitated rerouting (He et al., 2021). These changes resulted in travel delays and reduced work accessibility, inflicting a considerable societal impact. The economic loss due to such commuter delays was estimated to be $1.2 million per day (He et al., 2021).

Evacuation is a vital component of the response phase and can be difficult when faced with floods that render evacuation routes inaccessible. Thorough analyses of the evacuation route in flood scenarios are necessary (Burnside et al., 2007)(Trumbo et al., 2014)(Tanim & Tobin, 2018). This involves understanding the flood condition of the evacuation routes and rerouting consequences of blockages.

One often overlooked indirect impact of floods is loss of social connectedness, a feeling of attachment towards people’s place of living. The feeling of people that keeps them attached to their locality is particularly important for the health and happiness of a community. Cox and Perry (R. S. Cox & Perry, 2011) found that loneliness and isolation can arise due to physical and social changes of disaster (Silver & Grek-Martin, 2015).

Access to natural features like parks and recreational facilities can help to establishment the sense of home and community (Silver & Grek-Martin, 2015). Floods have the potential to create new social exclusion areas due to disrupting access to those places (Boakye et al., 2022) compounding the psychological impact on the population.

These studies are important, but to build community resilience, they might not be enough. There are many important travel purposes, such as education, economy, and recreation. Studying all these purposes can provide a better understanding of the overall needed community operations. Prior studies typically focused on one phase, mostly the response
phase, but they do not answer questions about the recovery phase, which is critical for returning the community to the pre-disaster phase with added resilience.

To add resilience, we must first identify the vulnerable locations or most critical sections in the network. It is difficult to predict how well the system will operate when there are disruptions by evaluating the roadways' efficiency under normal conditions (Ganin et al., 2017). Prioritizing and optimizing pre- and post-disaster investments are part of disaster management, which aims to improve the system's ability to cope with shocks, cut down on losses from catastrophes, and restore performance (Faturechi & Miller-Hooks, 2015a). Understanding the nature and scope of disaster impacts and performing criticality analysis considering those impacts can help build resilience in the transportation network.

3.2.1 Qualitative and quantitative approaches

The assessment of criticality can be carried out using qualitative or quantitative methods. Qualitative assessments are elaborate descriptions that help one in understanding the impacts and management techniques. Croope et al. (Croope & McNeil, 2011) proposed a decision-support system framework to lower the vulnerability of locations and infrastructure systems through stress-mitigation techniques for disasters. Quantitative assessment can be mathematical models for assessment (Murray-tuite, 2006b) models for management (Faturechi & Miller-Hooks, 2014) or decision support tools (Adams, Asce, et al., 2012) that can provide direct measurements or suggest decisions that help analysts in assessing or predicting the disaster impacts (Faturechi & Miller-Hooks, 2015a). These assessments can be of component and system level performance (Faturechi & Miller-
Hooks, 2015a). To perform quantitative assessment of criticality in transportation, metrics are required. Almotahari et al. (Almotahari & Yazici, 2021b) mention various criticality metrics which can be broadly classified as topological analysis and development of indices.

3.2.2 Topological analysis

The topological properties of a network can be useful for assessing risks (Zhang & Alipour, 2019). The accessibility of the origin-destination pairs can change by increasing the travel distance, travel time, or isolating the origin and destination. The topological network properties can be used to quantify the resilience and performance of a transportation network, e.g., by determining the contribution of each component to the network before and after any network link fails (Testa et al., 2015). One indicator of the network topological analysis is the shortest path. If a link fails, connectivity can still exist if there is redundancy in the road network.

Betweenness centrality, a measure proposed by Freeman (Freeman, 1977) to understand the importance of the links or nodes, is calculated as the number of times a road section or a node is used to access facilities in a community. Gangwal et al. (Gangwal et al., 2023) measured criticality using a modified betweenness centrality metric. The number of times a link appeared on the node-facility shortest path was normalized. The betweenness centrality can be weighed with the traffic flow as well. However, if the travel demand and travel time are not available, Gauthier et al. (Gauthier et al., 2018b) suggest the use of betweenness centrality as a metric.
3.2.3 Development of the analysis index

Indices can help in criticality assessments. For instance, the Network Robustness Index (NRI) for a road segment is computed as the change in travel-time cost resulting from rerouting traffic in the system should that segment fail (Scott et al., 2006). This method is helpful when the travel time can be uniformly computed. Sullivan et al. (Sullivan et al., 2010) used the NRI to compute the capacity-disruption values for critical road segment identification and trip robustness index for system wide robustness. However, if link disconnectivity occurs, the index cannot evaluate the impacts of isolation. Jenelius et al. (Jenelius et al., 2006) provided an importance score for network links based on the difference of cost before and after the link has failed. This score was based on two weighting options: equal weighting of all origin and destinations, referred to as “global importance,” or the weight was based on traffic, referred to as “demand-weighted importance” (Jenelius et al., 2006). The importance score can be calculated with and without disconnectivity, however both values cannot be compared directly (Almotahari & Yazici, 2019). Nagurney et al. (Nagurney & Qiang, 2007) introduced the efficiency measure for calculating the criticality of transportation links and nodes which includes travel behavior information along with network topology. The efficiency measure assumes that the performance of the transportation network is directly proportional to the traffic handling capacity of the network at a given price—which can be travel time (Nagurney & Qiang, 2007). The criticality metric is indirect in that the change in efficiency is considered as criticality (Almotahari & Yazici, 2019). Another metric based on marginalized cost, which is the increase in travel time on a link due to increase in a unit
flow, is the Link Criticality Index (LCI) developed by (Almotahari & Yazici, 2019). The LCI is a single traffic assignment measure and depends on the OD demand and the travel time of the link in the network. For smaller networks, LCI can be effective, but for larger transportation networks, processing takes a long time (Almotahari & Yazici, 2021a).

3.2.4 Flood analysis.

The flood analysis required for the identification of the potential impacted road sections can be done by various methods. Some researchers use hydraulic and hydrologic models where rainfall runoff and streamflow are used to estimate the flood flow rates and create flood maps. This approach requires extensive data, which might not be readily available. Some researchers (W. Wang et al., 2019) use simulated flood data to study the effects of flooding on road networks. This method alone is not very effective due to the lack of consideration of the network robustness (Gangwal et al., 2023). Another method is used when the depth of flood is unavailable, but the flood extent data is present. Tools that can calculate flood depth based on the flood extent and digital elevation models are used to model the flood for analysis (Cohen et al., 2018).

The flood model or map is overlayed with the road network. The analysis can be based on binary failure criteria which assigns a road section as passable or unpassable due to disruption or the depth of the water above the road surface (Alabbad et al., 2021) or the depth can be used to calculate the delay. For instance, Gangwal et al. (Gangwal et al., 2023) used the depth disruption function provided by Pregnolato et al. (Pregnolato et al., 2017) to identify the delay in the flooded sections where the depth was less than 30cm.
3.2.5 Transportation purpose impact analysis

Some prior research analyzed criticality across various transportation purposes. Colon et al. (Colon et al., 2021b) combined a supply chain model and transport model to investigate the dependency of criticality on users and supply chains on Tanzanian roads. They calculated business losses due to supply disruptions to combine economic and transport modeling. Kasmalkar et al. (Kasmalkar et al., 2020a) analyzed the disruption in commuter traffic flow due to sea level rise to understand the impacts of employee delay and absence. They focused on assessing the workforce accessibility changes due to disaster only. Gangwal et al. (Gangwal et al., 2023) measured the criticality of the roads to access facilities like hospitals, emergency medical care, and emergency shelters. Gangwal et al. (Gangwal & Dong, 2022) assessed the accessibility of hospitals, grocery stores and pharmacies for 500-year flooding. Alabbad et al. (Alabbad et al., 2021) measured the disruptions in accessing hospitals, fire departments and police stations due to 100 and 500-year return period floods in Iowa. Shen et al. (Shen & Kim, 2020) analyzed the vulnerabilities regarding trips to work, school, grocery shopping, recreation activities and emergency services in coastal area of Honolulu, Hawaii. However, this study was conducted in coastal areas for sea level rise not for fluvial flooding. Anderson et al. (Anderson et al., 2022) prioritized network restoration based on the change in equitable access from block group centroids to supermarkets, medical clinics, and primary schools for liquefaction, tsunami, and hurricane.

Transportation resilience research addresses railway (Jin et al., 2014), road (Osogami et al., 2013), freight (E. Miller-Hooks et al., 2011) or transportation in general (Gonçalves &
Ribeiro, 2020). However, assessments tend to ignore the network's larger objective, which is to enable people to travel across it for a variety of needs (Anderson et al., 2022) before, during and after a flood. Therefore, an approach is needed to understand the individual and overall impacts on these trips to better incorporate resilience in planning.

3.3 Methodology

Our goal is to understand the criticality across different trips that help the community function before, during and after a flood. Figure 1 outlines our study's methodology. We assess the impact by analyzing changes in the shortest paths from residential areas to key destinations like hospitals, workplaces, grocery stores, and more. Census block group centroids and major corridor locations serve as origin points, while destination depends on purpose. For post-flood analysis, we calculated flood depth, as we consider roads under more than 30 cm of water as closed. We also employ betweenness centrality to identify crucial roads in both pre- and post-flood conditions. Our analysis encompasses not only the movement of people but also the transportation of goods, using the nearest major cities as origins for goods movement. Additionally, we categorize transportation needs according to different disaster management phases. Maps illustrate these analyses. Further details are provided below.
3.3.1 Route choice in ArcGIS

Using ArcGIS Pro’s network analysis with business analyst 2022 data, we identified the shortest time paths from origins to their destinations. The route selection consisted of several factors and was based on Dijkstra’s algorithm. The costs applied here reflect the road class, turning availability, avoiding hazmat routes, and choosing the car or truck as the mode of travel based on the purpose of travel. The data includes the speed/time taken.
to travel through the section length. Also, the hierarchy of the roads, i.e., local roads, highways, or freeways, was considered; the software looks for higher capacity roads to reach the destination. If high-capacity roads are available nearby, the algorithm chooses such roads, even if the local roads can have less travel time. After a flood, people may try to use the high-capacity roads to avoid flood-induced barriers and reach their destinations faster. The choice of high-capacity roads can also be valid for normal operations.

Once the regular paths were mapped, we included the flood data in the analysis. We noted if any of the destinations were inside the flood area. For the destinations that do not directly fall under the flood hazard, we first checked if they are accessible from the origins. The trips were again calculated to find the shortest path considering the flood locations (barriers). We then compared the before-flood and after-flood travel time to determine the trip's additional rerouting time.

3.3.2 Criticality metric

The choice of metric depends on the study need and the metric's effectiveness within the provided data. Jafino et al. (Jafino et al., 2020) divided 17 metrics into two categories, i.e., derived from transport studies and derived from network theory. We considered time as our travel cost and identified the criticality based on change in unweighted travel cost. The additional travel time can show the impacts of the flood across various purposes but fails to identify the locations that cause such changes. The significance of a node is determined by its use rather than its physical location (Derrible, 2012) and the same applies to links. We selected the unweighted link betweenness centrality metric from
network theory, assuming all trip purposes have equal importance. This allows identification of which links play an essential role for all purposes or the change across purposes. The equation for the link betweenness centrality measure for road section ‘r’ \((B_r)\) is provided by equation (1) (Gangwal et al., 2023).

\[ B_r = \sum_{t \in T} C(t, r), \]  

where ‘T’ is the total trip purposes from various origins to destinations, ‘t’ is the index of trip type and \(C(t, r)\) is the count of trips of type ‘t’ passing through road section ‘r’. For the importance of the links before and after flood we applied the normalized betweenness centrality value \((B_r\%)\) as:

\[ B_r\% = \frac{\sum_{t \in T} C(t, r)}{\text{Max}(C(t, r))}, \]  

where, \(\text{Max}(C(t,r))\) is the maximum number of trip overlaps.

Along with the frequency of use of the road section, we consider rerouting additional time based on individual transportation purposes. The roads with high betweenness centrality are more critical. We also note that access to facilities such as hospitals is critical if the rerouting distance exceeds a threshold. The threshold time is calculated based on the critical ambulance delay.

3.3.3 Threshold time

It is assumed that the facilities should be accessible within the threshold value of delay in an emergency. The allowable delay was associated with a 20% decrease in survival rate,
extrapolated from the survival rate per minute delay provided by (Wilde, 2013). We performed a nonlinear interpolation to calculate the time for a 20% decrease in survival chance because the linear change suggests that after 12.5 minutes of delay, the survival chance is 0%. The formula used to extrapolate the existing 8% decrease in survival rate per minute delay during an emergency to calculate a 20% decrease in survival rate is provided in Equation 3:

\[ S_{rd}(\%) = 1 - \left( 1 - R_{pm} \right)^M \]  

where ‘\( S_{rd} \)’ is the reduction in percentage of survival, ‘\( R_{pm} \)’ is the survival rate decrease per minute, and \( M \) is the time in minutes delay.

The threshold time for was calculated as 2.7 minutes and was considered for all purposes due to the lack of threshold values for individual purposes and for consistency.

3.3.4 Flood depth identification

Our analysis relied on the 100-year return period flood data from the Federal Emergency Management Agency (FEMA). This FEMA flood data uses detailed hydrologic and hydraulic modeling that considers elements like rainfall, watershed characteristics, land cover, and terrain slope (for hydrology) and water flow velocity and elevation (for hydraulics) (FEMA, 2024c). However, the flood data only provides the flood extent (area covered), not the flood depth information we needed for our analysis (Figure 2).
To calculate the 100-year flood depth, we used the Floodwater Depth Estimation Tool (FwDET) (Cohen et al., 2018). The process requires the flood extent map and digital elevation model (Cohen et al., 2018) (see Error! Reference source not found.). The DEM data provides the elevation of the normal water level on the water body along with topographical elevation. The idea is to identify the elevation of the flood extent points and assign them to the raster cells inside the water body. The flood inundation polygon is converted to a polyline and the line layer is converted to a raster layer with the same grid size as the DEM. The elevation data for the flood extent boundary is extracted by the tool.
from the DEM and then the boundary elevation is assigned to the cells within the hazard boundary. Afterwards, the topographic elevation of the cells inside the flood hazard boundary is subtracted from the generated elevation inside the flood hazard boundary providing the depth of flood water in the hazard area. We used 1m resolution DEMs. The tool's output is a raster file with the flood depth (d) along the flood hazard area.

After the depth raster was generated, we found gaps inside the flood hazard area. FwDET codes cells where the elevation generated by the tool is less than the topographic elevation as “no data.” Some of the sections were in the middle of the stream or near the boundary. To find the depth of the empty cells, we interpolated using Focal Statistics in ArcGIS Pro with circular search criteria with the interpolation zone of 3 cells. We used 10 iterations to fill the gaps, generating the final depth raster file (D). This file was overlayed with the road network to identify potentially flooded portions of the road.

FwDET provides the flood water depth from the existing water level or the ground surface. If the section is a bridge, then the bridge deck elevation is needed, given that the bridge does not fail structurally. The depth of water above the bridge surface was calculated based on equation (3):

$$d_b = ((E_{DEM} + D) - E_b),$$

where, $d_b$ is the depth of floodwater above the bridge surface, $E_{DEM}$ is the elevation data of the bridge provided by the DEM, $D$ is the depth of the floodwater provided by the FwDET, and $E_b$ is the elevation of the bridge surface provided by the LiDAR data.
The LiDAR data provided by the USGS did not have the classification of bridges in certain locations. Out of 484 bridges in Anderson County, we could not calculate the bridge deck elevation of 112 bridges, out of which 49 fell inside the FEMA flood hazard area. For these locations, we manually assessed the access roads of those bridges, reasoning that the bridges are unlikely to be lower than the approach roads.

We measured the depth of the flood water on the road surface due to the 100-year return period flood. The depth data was then overlayed with the road network with road elevation data. If the flood depth above the road surface was greater than 30 cm or one foot, then the road section was considered impassable (Pyatkova et al., 2019), otherwise the road was considered passable (equation (4)). The threshold value of 30 cm is considered for two primary reasons. Firstly, it accounts for the interaction of traction and buoyancy forces on a vehicle in still water. Hydrodynamic force analysis conducted by (Smith et al., 2017) established 30 cm as the critical water depth for small passenger vehicles. Secondly, the elevation of the car's air inlet, positioned between 25 and 35 cm above ground level, as identified by (Yin et al., 2016).

\[
\text{Road section} = \begin{cases} 
\text{Passable} & , D < 30 \text{cm} \\
\text{Impassable} & , D \geq 30 \text{cm}
\end{cases}
\]

where, D is the depth of the water above the road surface.

3.3.5 Purpose based trip pairs.

The purpose and the trip’s origin and destination are provided in Table 1. We took the Census block groups to represent residential areas.
3.3.6 Study area and data collection

According to the US Census Bureau, Anderson County, SC has a population of 209,581 as of July 1, 2022, with significant employment in manufacturing (SC Department of Employment and Workforce, 2023). Fifty-nine major manufacturing businesses (Chamber of commerce, 2023) and one general hospital (FEMA, 2023c) serve as major employers. The data about the destinations for all the purposes are mentioned in the process in the results section for each trip purpose which is an elaborate description of Table 1. The sources of data required for the analysis are shown in Table 2.

3.3.7 Public transit

The public transit system was also analyzed for potential impact due to the flood. If the roads were blocked or the bus stops were inaccessible, then new stops were suggested, along with a new route serving all the areas it previously served. The stops should be placed at a walkable distance from the service area, which is 10 minutes (FHWA, 2013) and the new route was selected based on the service area of the existing impacted bus stops. New routes were provided closer to the existing bus routes so that change would be lower, and the new routes would not have any flood barriers. When providing new bus stops, if the stops are placed closer to each other, people can get to the stops by walking less but the transit time increases as bus must slow down at each of those stops. The stop locations were suggested based on the following guidelines.

- Since the new stops will be for a short period, curbside stops are allowed.
• The bus stops will be placed on the far side (of the intersection) in-lane (National Association of City Transportation Officials (NACTO), 2016).

• The bus stop spacing will be in accordance with the Transportation Research Board (TRB) guidelines (Research Board, 1996).

Table 1. O-D pairs

<table>
<thead>
<tr>
<th>Transportation Purpose</th>
<th>Origin</th>
<th>Destination</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hospital Accessibility</td>
<td>Census block group centroid</td>
<td>Hospitals</td>
<td>Un-flooded, Response, Recovery</td>
</tr>
<tr>
<td>Emergency services</td>
<td>Ambulances/Paramedics, Police stations</td>
<td>Census block groups</td>
<td>Un-flooded, Response, Recovery</td>
</tr>
<tr>
<td>Education</td>
<td>Census block group centroid</td>
<td>Elementary school, high schools in the school districts, colleges, and universities</td>
<td>Un-flooded, Recovery</td>
</tr>
<tr>
<td>Daily needs</td>
<td>Census block group centroid</td>
<td>Supermarkets-Walmart and other grocery stores</td>
<td>Un-flooded, Recovery</td>
</tr>
<tr>
<td>Category</td>
<td>Data Source</td>
<td></td>
<td></td>
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<tr>
<td>---------------------------</td>
<td>----------------------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Commute</td>
<td>Census block group centroids Major employers Un-flooded, Recovery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Import and export</td>
<td>Major corridors-Major cities nearby Major employers Un-flooded, Recovery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recreation and social</td>
<td>Census block groups centroid Parks Un-flooded, Recovery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>connectedness</td>
<td>Census block groups (Possible evacuation, nearby the river and having larger flood extent area)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evacuation</td>
<td>nearby the river and having larger flood extent area Major corridors Response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return of evacuees</td>
<td>Major corridors Census block groups (Possible evacuation, nearby the river and having larger flood extent area) Recovery</td>
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<td></td>
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<tr>
<td>Feature</td>
<td>Source</td>
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<td>---------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
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<td></td>
</tr>
<tr>
<td>Roads for Anderson County</td>
<td>South Carolina Department of Transportation (SC DoT, 2023) and Georgia Department of Transportation website (GDoT, 2023)</td>
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<td></td>
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<td>Bridges in Anderson County</td>
<td>National Bridge Inventory 2023 data (FHWA, 2023)</td>
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<tr>
<td>Digital Elevation Model and LiDAR data</td>
<td>United States Geological Survey, 1m resolution digital elevation model, (USGS, 2023)</td>
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<td>Flood hazard extent map</td>
<td>Federal Emergency Management Agency (FEMA), (FEMA, 2023a)</td>
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<td>Census block groups</td>
<td>US Census Bureau (US Census Bureau, 2023)</td>
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<td>Major manufacturing company location</td>
<td>Anderson Chamber of Commerce website, (Chamber of commerce, 2023)</td>
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<tr>
<td>Hospitals, Urgent care facilities</td>
<td>Resilience Analysis Planning Tool, (FEMA, 2023c)</td>
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<tr>
<td>Emergency medical service</td>
<td>Resilience analysis planning tool, (FEMA, 2023c)</td>
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<td>Public Parks</td>
<td>City of Anderson website, Anderson recreation division, (Recreation Department, 2023)</td>
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<td>Recreation area around Hartwell Dam</td>
<td>United States Army Corps of Engineers (USACE) website, (USACE, 2023)</td>
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<td></td>
</tr>
<tr>
<td>Grocery stores, Fire stations</td>
<td>Resilience analysis planning tool, (FEMA, 2023c)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### 3.4 Results and Discussion

The data (Table 2) was mapped in ArcGIS Pro. Then the road segments potentially impacted by the 100-year return period flood were determined. Because of the variability of roadway elevations, tenth mile (approx. 161 meters) segments were created, and the low point of that segment was considered its elevation. The total road sections impacted were 384 tenth-mile sections inside Anderson County (see Figure 4a), including 134 on highways, 250 on local roads, and 12 bridges (see Figure 4b) in local and highway roads.
Figure 3. (a) Potentially blocked roads and bridges in Anderson County; (b) Potentially impacted bridges of Anderson County along with high-capacity roads.

After identifying the unpassable road sections, we considered them as barriers and calculated the routes for the purposes shown in Table 1. The travel times before and after the flood were compared to determine the difference in the travel time due to the flood. The additional time was categorized as above or below the threshold. For discussion purposes, Figure 5 shows Anderson County divided based on direction for the analysis.

![Reference map for the division of Anderson County based on direction.](image)

3.4.1 Phases

The analysis is presented in the three phases: un-flooded condition, response phase, and recovery phase.

*Un-flooded (Before) condition*

The trips mentioned in Table 1 in the unflooded phase are required for normal operations of the community. The road sections that were used most frequently by trips from the
different Census block groups to the destinations were identified with the use of betweenness centrality. The trip purpose, road sections and their betweenness centrality value depicting criticality are provided in Figures 6-10.

![Figure 5. Critical roads for: (a) Workplace accessibility from Census block groups; (b) Materials accessibility to the workplaces from major corridors.](image)

For accessing workplaces (Figure 6a), the routes used most frequently were I-85, State Highway 28 and Federal Highway 29 connecting the interstate and Anderson city. The State Highway shows high betweenness centrality connecting the highway with Anderson city. Federal Highway 178 connecting Honea Path and Belton was also important. Since the companies are spread around the county, local roads are also important, but the major highways are the most important for the normal day accessibility to various workplaces. For the accessibility of the materials (Figure 5b), I-85 and State Highway 28 connecting the interstate and neighboring county Abbeville had high betweenness centrality.
Figure 6. Critical roads for: (a) Hospital accessibility; (b) Urgent care facilities accessibility.

For hospital accessibility the roads in Anderson city had more importance (Figure 7a) as the general care hospital is located near to the city. For urgent care accessibility (Figure 7b), I-85 along with Federal Highway 29 and State Highway connecting the interstate with Anderson city had high importance.
Figure 7. Critical roads for: (a) Schools accessibility in school districts; (b) College’s accessibility

For general schools’ accessibility for each school district the critical roads are presented in Figure 8a. The most important roads were State Highway 28 and State Highway 81 connecting the Anderson city area with other areas in school district 5. For school district 4, I-85 and State Highway 187; for school district 3, State Highway 81; for school district 2, Federal Highway 178; and for school district 1, I-85, Federal Highway 29 and State Highway 8 were more important and represented by thicker lines in Figure 7a. For colleges accessibility, Federal Highway 76 crossing I-85 and connecting Pendleton to Anderson city was more important and represented by thicker lines in Figure 8b.

For groceries accessibility (Figure 9a), roads had low betweenness centrality because the grocery stores are spread throughout the county, allowing shorter trips. For accessibility of materials to the grocery stores, I-85 had high betweenness centrality (Figure 9b). Along with the interstate, State Highway 181 and 187 were more critical as they connect the interstate to Anderson city, where higher numbers of grocery stores are located.
Figure 8. Critical roads for: (a) Groceries accessibility; (b) Materials accessibility from major corridors to the grocery stores.

For accessibility to the parks in Anderson County, Federal Highway 29, State Highway 81, State Highway 28 had high importance (Figure 10a). For ambulance accessibility, a State Highway 28 section in Anderson city had high importance (Figure 10b). Since ambulances and paramedics are located mostly at fire stations, the results were similar.
Response phase

During the flood, rescue operations may be needed in the impacted area. Here, the accessibility of the fire rescue services to the various Census block groups is needed. The accessibility of the ambulances to the impacted Census block groups is also essential to transport flood victims to hospitals as well as other medical emergencies. Also, the accessibility of law enforcement to all the Census block groups is needed to maintain security during disaster times. Evacuation from the probable evacuating regions is the final element of the response phase considered in this study. We assumed the Census block groups sharing the border with Lake Hartwell and the Savannah River (since the flood is riverine) as the probable evacuation regions. Figures 11a to 12b show the criticalities of road sections for the response phase.
(a)  

(b)  

**Figure 10.** Critical roads for: (a) Accessibility from the police station to the Census block groups avoiding the flood barriers; (b) Accessibility of the ambulances/paramedics to the Census block groups avoiding the flood barriers.

Figure 11a represents the critical roads for accessibility of the police stations from the Census block groups in Anderson County. Road sections in Anderson city had high importance along with the section of State Highway 8 connecting with Federal Highway 29 and a section of State Highway 28 connecting Pendleton with Federal Highway 76 (see Figure 11a). Since the police stations are spread throughout the county, the availability of the police near the Census block groups is high. For the accessibility of ambulances/paramedics (Figure 11b), the importance of road sections was similar to the un-flooded condition (Figure 10b). One important change was that the Federal Highway 29 was used more often, suggested by its increase in betweenness centrality after the flood (Figure 11b).
Figure 11. Critical roads for: (a) Accessibility of the hospital from Census block groups avoiding flood-barriers; (b) Evacuation from evacuation prone areas (green) and fire rescue team’s accessibility (brown).

For accessibility to hospitals in the response phase (Figure 12a), due to the flood created blockage on some roads, I-85 and the highways connecting I-85 to the hospitals had more importance (State Highway 28 and Federal Highway 178). The roads in Anderson city also play a great role because of the location of the hospital being in Anderson city. Criticality of roads for hospitals for response and recovery phase were the same. So, in the recovery phase, we skipped discussion on hospitals. For evacuation (green in Figure 12b), I-85 had high importance, along with State Highway 28. For fire stations accessibility (brown legend in Figure 12b), due to the stations’ spread in Anderson County, most of the roads close to the facility, showed equal importance.

Recovery phase

During the recovery phase, evacuees return to the community. Importing recovery materials to the impacted areas is also an important trip. As facilities and infrastructure are restored, people start to resume their normal activities. Accessibility to the hospitals and urgent care areas, grocery stores, workplaces, parks, schools, and colleges are needed. Also, the accessibility of the materials to the Census block groups for the repair and restoration of possible damage in each Census block groups is needed. The change in route due to flood impacts and change in betweenness centrality of the roads are mapped
in Figures 13-16 for various purposes. This analysis pertains to the beginning of the recovery phase; as recovery progresses, conditions return to the pre-flood phase.

For workforce accessibility (Figure 12a), I-85, State Highway 81 connecting the interstate to the Anderson city, State Highway 29, and two sections of State Highway 28 had high betweenness centrality. For materials accessibility to the workplaces, I-85 played a great role along with State Highway 28 connecting Anderson city with the interstate. Another important road with high normalized betweenness centrality is a small section of State Highway 81 (Figure 13b).

The importance of roads stayed almost the same before and after the flood for grocery stores accessibility by customers (Figure 9a). For materials accessibility to grocery stores, I-85, State Highway 28 connecting the interstate and neighboring Abbeville County had high criticality. For park accessibility in the recovery phase (Figure 14b), the important roads were State Highway 81, State Highway 28, and I-85. The previous critical road, Highway 29 had less importance after the flood.
Figure 12. Critical roads for: (a) Workplace accessibility avoiding flood barriers; (b) Materials accessibility to workplaces from major corridors avoiding flood barriers.

Figure 13. Critical roads for: (a) Materials accessibility to grocery stores avoiding flood barriers; (b) Parks accessibility avoiding flood barriers.

The major roads after the flood for school accessibility (Figure 15a) remained almost the same as before the flood (Figure 8a), with minor changes in the local and secondary roads being rerouted due to the blockage. For college campus accessibility (Figure 15b), the road sections that were important before flood also have high criticality after the flood, with the addition of Highway 178 connecting Anderson city with Highway 76.
Federal Highway 178, State Highway 8, and I-85 had high criticality for the accessibility of the materials to the Census block groups after the flood (Figure 16). For evacuees returning home, I-85, along with federal highway 178 was highly critical (Figure 16).

Since the evacuees return from major corridor routes, the materials for repair and evacuees route choice remains almost the same. In this context, the origin for repair and recovery supplies is the same as that for returning evacuees, but since the destination for the former is a subset of the latter, we only display the map for repair and recovery supplies.

Figure 14. Critical roads for: (a) School accessibility in school districts avoiding flood barriers; (b) College’s accessibility avoiding flood barriers.
Figure 15. Materials for Repair/Recovery supplies avoiding flood barriers/evacuees returning home.

Flood impacts and prioritization of the road sections.

3.4.2 Hospitals

There is only one general care hospital. The additional time it takes for people from various Census block groups to reach the hospital is presented in Figure 17a. The Census block groups of the county's eastern, southeastern, and northeastern portions are more impacted and have a higher rerouting time to access the hospitals. The maximum additional time due to rerouting to access hospitals was 41.61 minutes, situated on the southeastern side of the county as shown in Figure 17a. This high rerouting time is due to the blockage of a bridge near Anderson city, labelled as 16 in Figure 17b. For most of the high additional travel time areas in Figure 17a, this road section (labelled 16 in Figure 17b) plays a great role, implying that this section is highly important for hospital accessibility.
Not all road sections and bridges that are impacted (Figure 4) play a role in the change in hospital travel time. The betweenness centrality provided in Figure 17b suggests the highly critical road sections are nearer to the hospital (points labelled as 35 and 16).

![Figure 16](image)

**Figure 16.** (a) Additional time to be traveled after the flood to access the hospital from Census block group centroids. (All labeled values are time in minutes); (b) Blocked locations requiring changing routes for hospital accessibility.

3.4.3 Urgent care centers

Three urgent care facilities are in Anderson County, and to examine the impacts of the flood, we checked the accessibility of each facility from all Census block groups. The accessibility changes of urgent care facilities 1 and 2 were similar because they are located close to each other – one map is provided in Figure 16a. To access these two facilities, the maximum impact falls upon the Census block groups lying in the eastern,
northern, and northeastern area of the county (see Figure 16a). The maximum additional travel time was also from the southeastern location, with a maximum value of more than 14 minutes which is because of the potential blockage of the bridge labelled as 38 in Figure 18. This section is the same as the section labeled 16 in Figure 17b. This similarity is because the hospital and the urgent care facilities 1 and 2 are located close to each other.

For the third urgent care facility, since the facility is located on the northeastern corner of Anderson County, the southwestern Census block groups must travel longer and face many barriers in between. The highest additional time required was 55 minutes from the Census block group nearer to Anderson City (Figure 18b). This high additional time is because more barriers are situated near the city and rerouting involved using I-85 (see Figure 19). To access the interstate within less time, the route leads out of Anderson County and to the western neighbor (i.e., Hart County) which has no barriers in consideration. Using the interstate as the route was common for most of the high additional travel time Census block groups in the southern part of the county. Therefore, because the route goes through a neighboring county without flood barriers in consideration, the maximum additional travel time for accessing urgent care facility 3 can be even greater if Hart County is also flooded. Figure 19 shows the locations of blockages and the impact on various Census block groups while accessing the urgent care centers after the flood. The labels are cumulative for all three urgent care centers. The highest impact location was a bridge over Rocky River in highway US 178 (labeled 38 in Figure 19).
Figure 17: (a) Change in accessibility from various Census block groups for urgent care facility 1 – Anmed Urgent Care; (b) Change in accessibility from various Census block groups for urgent care facility 3 – Crossroads Urgent Care.

3.4.4 Evacuation shelters

Figure 18: Blocked locations changing routes for Urgent care accessibility.

The maximum additional time to access the nearest evacuation shelter during the flood is 7.47 minutes. This is because the shortest route to the nearest shelter is blocked due to
flooding, and there are no nearby shelters, so the route takes longer to access the same shelter. Other than a few (seven) of the Census block groups showing additional travel time above threshold, no high impact was seen for accessing the evacuation shelters. Since many evacuation shelters exist in Anderson County, residents have options when access to the closest shelter is blocked.

The evacuation from the Census block groups to the major corridors to leave the county during the disaster is also analyzed. Four major corridors lead to the larger cities of Columbia and Charlotte, Augusta, and Atlanta. The impacts would have been higher if the barriers outside Anderson County were also considered.

**Columbia:** To travel to Columbia from each of the Census block groups in Anderson County, the maximum additional time needed because of blockages in this county was 64 minutes. This high additional time is related to the discussion for urgent care 3, i.e., more barriers are situated near the city, because of which the best route considering high-capacity roads after the flood for accessing Columbia becomes the interstate (Figure 20a). To access the interstate, the route leads out of Anderson County back to the western neighbor (i.e., Hart County). Most of the Census block groups on the southern side accessed the interstate after the flood. For the Census block groups in the southeastern part of the county, the high additional time was mostly influenced by blockage of the section labelled as 73 in Figure 22. For evacuation from, more Census blocks groups in the county's southern and southeastern regions were more than 2.7 minutes (see Figure 20a).
**Charlotte:** Access to Charlotte faced less severe impacts than Columbia. The Census block groups on the southern side were impacted more. The maximum estimated additional time was 55.52 minutes (see Figure 20b) from the same Census block group having the most additional time to access Columbia, i.e., 64 minutes (see Figures 20a and 20b) due to the high number of blockages in the Anderson city area.

**Augusta:** The change in accessibility to Augusta for evacuating was different from that of Columbia and Charlotte. Columbia, Charlotte, Atlanta, and Augusta all fall on the interstate network; the travel time to get to Columbia, Charlotte and Atlanta is shortest using the interstate network. However, for Augusta the shortest travel is not through the interstate network but through highways between Anderson and Augusta, i.e., US-25 and US-178. The southern, northeastern, and Anderson city areas were impacted. The maximum additional time was 26.86 minutes for the block group near Anderson city (see Figure 21a). The route choice before the flood was through major highways, but after the flood, the route involved accessing the interstate. The interstate was used by choosing the route out of the county avoiding barriers, causing a shift in before and after flood routes. The city has many barriers due to flooding, which results in the higher additional time concentration in the Anderson city area. The routes on the southern side initially went to the western neighboring county and then travel proceeded from there, avoiding barriers.

**Atlanta:** Before and after the flood, the general trend was to access the interstate and then go to the city. The most impacted Census block groups are in the southern, southeastern, and western areas of Anderson County. Most of the Census block groups had additional time to access the interstate. The southern and southwestern areas traveled
to neighboring Hart County and went to I-85 from that county. The maximum additional
time needed for evacuating to Atlanta was 28.04 minutes (see Figure 21b) because of the
blockage of a bridge labelled as 73 in Figure 22. Since Atlanta is on the western side of
the county, the route for the Census block groups on the northern side leads them to the
interstate causing low additional travel time. The Census block groups on the
southwestern side must travel on several local roads along with barriers before getting to
the interstate causing the higher additional time.

No barriers existed on the interstate and the number of barriers was usually high for the
lower-class roads (i.e., local roads). The more a vehicle is on higher-class roads, the less
the chance of encountering a barrier. The choice of route and the impacts of certain
barriers to access the major corridors is provided in Figure 22.

3.4.5 Grocery stores

The impact on access to the nearest grocery stores was measured before and after the
flood, and the travel time change was noted from each Census block group. Given the
proximity of existing stores and multiple alternative grocery options rerouting to either a
current closest store or the nearest alternative store does not incur a significant additional
time cost following a flood. The maximum additional travel time to access the nearest
grocery store was 3.3 minutes.
Figure 19. (a) Change in accessibility from various Census block groups to Columbia; (b) Change in accessibility from various Census block groups to Charlotte

Figure 20. (a) Change in accessibility from various Census block groups to Augusta; (b) Change in accessibility from various Census block groups to Atlanta.
3.4.6 Recreation

Because of the higher number of parks and their distribution around the county, the flood did not have a major impact on most Census block groups’ access to the nearest park facility. The highest additional travel time was 13.7 minutes after the flood because there was only one park nearby for the Census block group. The road leading from the Census block group with the 13.7 label was blocked. Recreation based on the Hartwell Dam was not considered because the lake would not be safe during the flood phase.

3.4.7 Workforce accessibility

There were 59 major employers in Anderson County (Chamber of commerce, 2023) with more than 100 employees, and none of them were directly inside the flood hazard area. We identified the routes from Census block group centroids to major employment locations and the routes from major transportation corridors to major employment locations before and after the flood. To consider out-of-the-county workers, we took the

Figure 21: Number of routes affected while accessing the major corridors from various Census block groups.
entry points to Anderson County from all directions and analyzed the accessibility of these points to the workplaces in the county.

The average travel time increased by 4.24 minutes after the flood, with the median of the change being 3.28 minutes and a standard deviation of 3.67. The range was from 0 to 25.84 minutes. For all 3,675 changed routes from 141 Census block groups to 59 workplaces, the additional travel time frequency is provided by Figure 23. However, the histogram did not indicate which area was more vulnerable or which workplace would endure more impact. Answering such questions required analysis of the individual workplaces.

**Figure 22.** Histogram for the additional time of changed routes while accessing various workplaces from Census block groups in Anderson County.
Figure 23. (a) Workplaces in Anderson County (59 locations); (b) Clustering of the nearby companies (19 locations)

We grouped the workplaces into 19 clusters to facilitate discussion. The clustering was done for the workplaces that were close to each other and did not have any barriers in the enclosing boundary polygon (see Figures 24a and 24b). The labels in the clusters in Figure 24b represent the number of workplaces in that cluster.

To illustrate the analysis, a map for Anderson Industries (workplace 2) and Taylor and Pallets Recycling Inc (workplace 18) are presented in Figures 25a and 25b, respectively. These two employers are in different directions of Anderson city and show varied results for the Census block groups’ accessibility. The Anderson city area had a great role in the accessibility of the workplaces. Anderson Industries is in the north of the Anderson city area which resulted in the high additional travel time for the Census block groups on the opposite side of the city i.e., southern side southwestern side (see Figure 25a). Similarly,
workplace 18 is which are located on the southern side and impact was seen on the northern, northeastern, and northwestern Census block groups (see Figure 25b).

Figure 25a and 25b show that the additional time for the entry or exit points is similar to their adjacent Census block groups. The variation on the Census block groups being impacted highly is largely dependent on the location of the workplace.

![Figure 25a and 25b](image)

**Figure 24.** (a) Change in accessibility of workplace 2 in Anderson County from Census block groups and various county entry and exit points; (b) Change in accessibility of workplace 18 in Anderson County from Census block groups and various county entry and exit points.

For workplace accessibility the betweenness centrality value of at road barriers after the flood from Census block groups and entry and exit points are provided in Figures 26a and 26b. The higher values indicate that points have higher criticality. Most of these barriers important for workforce accessibility were concentrated in Anderson city (Figure 26).
From the individual workplace analysis, the general trend of impacts on each Census block group showed the southern and southeastern region as the most impacted regions and the least impacted was the northeastern region. The impact on the entry and exit locations, as marked by circles in Figures 25a and 25b follows the general trend of impact in the Census blocks groups.

3.4.8 Materials accessibility to workplaces

The accessibility of materials is very important to the companies whether that is raw materials for manufacturing or the shipping of final products. To understand the impact of the flood, we conducted a truck accessibility analysis from major corridors to/from Atlanta, Augusta, Columbia, and Charlotte (see Figure 27b) to the workplaces in Anderson County. The additional travel time for each workplace from Columbia is provided by Figure 27a. The points are the companies, and the labels are the additional travel time. Companies closer to I-85 were less impacted compared to the companies farther from the interstate because no barriers were on the interstate. The companies in Anderson city also have a large amount of additional travel time associated with them because of the high density of flood-impacted roads and bridges (see Figures 27a and 28). The maximum additional travel times from each of these cities to the workplaces were 17.05 minutes from Columbia for a workplace situated on the southern side of the county (see Figure 26a), 11.72 minutes from Charlotte for a workplace located away from I-85 in the northern corner of the county, 15.21 minutes from Atlanta for a workplace near Anderson city, and 20.87 minutes from Augusta for a workplace near Anderson city.
Figure 25. (a) Number of routes impacted due to flood for accessibility from Census block groups to various companies in the county; (b) Number of routes impacted due to flood for accessibility from entry points to workplaces in the county.

Figure 26. (a) Additional time needed to arrive at the workplaces in Anderson County from various corridor locations (Columbia); (b) Major corridors.
Figure 28 shows the road sections blocked by the flood and the number of routes that use those sections. A greater number of routes were impacted near Anderson city and far away from the interstate (See the labels 49, 22 and 44). Figure 28 shows that the barriers near Anderson City are important for materials accessibility to the workplaces as well.

3.4.9 Education

Flood-related increases in travel time can lead to more student absences.

- Colleges

There are five colleges in Anderson County, but two (Tri-County College and Anderson University) have enrollments of more than 500 (FEMA, 2023c). For Tri-County College accessibility, the southern and southeastern parts of the county were highly impacted (see Figure 29a). Most of the Census block groups and entry points with additional time higher than the 2.7-minute threshold lie on the eastern, southeastern, and southern sides. The maximum additional time was 15.43 minutes (see Figure 29a). To access Anderson University, the maximum additional time was 40.78 minutes, which is greater than Tri-
County College because of the college's location (see Figure 29b). Anderson University is located near Anderson city, which has many barriers (see Figure 30). Hence, routes traveling to Anderson University must change near the university. The sections most impacted were the eastern, northeastern, and the northern part of the county (see Figure 29b).

Figure 28. (a) Additional travel time to access a college in Anderson County after the 100-year flood; (b) Additional travel time to access a college in Anderson County after the 100-year flood.

- Schools.

The accessibility to elementary, middle, and high schools from each school district had higher additional travel time in the Anderson city area. The maximum value of additional travel time for accessing elementary schools was 16.3 minutes in school district 5 (see Figure 31a), for middle school it was 12.38 minutes in school district 5 (see Figure 31b)
and for high school, it was 9.38 minutes in school district 5 (see Figure 32a). School district 5 was the most impacted. Figure 32b shows the locations and the number of routes passing through the blocked sections before the flood. One entry point is also considered because of the extension of that school district to the adjacent Greenville County. The was a barrier near the entry point (see Figure 32b) causing a greater additional time of travel after flood.

Figure 29. Number of routes being impacted due to the blocked locations for college accessibility.
3.4.10 Public transit

*Before flood*

Public transportation is essential to people who do not own cars or other means of transport. Public transportation routes are predetermined, and buses operate along these fixed routes within their scheduled timeframes. The six public transit routes - gold route, orange route, purple route, red route, blue route, and green route – in Anderson County are shown in Figure 33.
Flood response and recovery

The routes were impacted differently based on the barriers on the individual routes. Orange and red routes were not affected by the flood. Figures 34a, 34b, 35a and 36b show how the bus routes were impacted and how the stops can be served by changing the route.

Figure 31. (a) Additional travel time to access high schools in Anderson County after the 100-year flood; (b) Blocked locations and the routes impacted for accessing school from school districts.
Figure 32. Public transit routes in Anderson County.

To serve all the stops in the gold route, the existing route can be changed, as shown in Figure 34a. No new bus stops need to be introduced. The existing population can be served by the addition of the segment of 1.90 miles (3.06 km).

Two barriers in the purple route caused the change in route. Due to the blockage, a route segment of 5.44 miles (8.75 km) should be taken instead of 1.88 miles (3.02 km) for the first barrier increasing the route by 3.56 miles (5.73 km). For the second barrier the route segment could be changed from 1.13 miles (1.82 km) to 2.65 miles (4.26 km) (increment of 1.52 miles (2.44 km)) to serve all bus stops (see Figure 34b). New bus stops can also be incorporated in these new added route sections to serve even more of the population.

While the blue route can be changed to serve most of the existing bus stops, seven stops cannot be served by the existing route or minor changes in the route (see Figure 35a). To serve the bus stops other than those seven, a new length of 2.05 miles (3.30 km) was introduced to avoid the potentially impacted region and serve the existing servable bus
stops. The area on the eastern side of Rocky River was highly impacted because of the barriers near the Rocky River. If these barriers are removed, most of the area can be served except the bus stop on the northern side of the highly impacted region (see figure 35a).

The green route faces the most challenges to reroute around the barriers. Even then, three bus stops were unserviceable due to the barriers marked by a red pin in Figure 35b. To accommodate people near the bus stops, a new bus reroute is suggested and new bus stop noted by a green pin (see figure 35b). An addition of 2.67 miles (4.30 km) of new road sections is needed to serve all the serviceable bus stops.

Figure 33. (a) Gold route impacts due to 100-year flood; (b) Purple route impacts due to 100-year flood.
Figure 34. (a) Blue route impacts due to 100-year flood; (b) Green route impacts due to 100-year flood

3.4.11 Change in criticality of roads

To visualize the critical roads across various phases of disaster management, we merged the important roads for all the purposes in each phase. We show only normalized betweenness centrality values greater than 25 for each phase (see the legend “Low trips” in Figures 36a, 36b, 37a). For identifying critical roads, we merged those from each trip purpose's analysis: for un-flooded conditions (Figure 36a), we combined roads from Figures 5-9; for response conditions (Figure 36b), we combined Figures 11-13; and for recovery conditions (Figure 37a), we combined Figures 14-19.

Figure 36a illustrates the un-flooded condition routes, showcasing the typical daily route choices for community operations. In this context, major highways, including state and federal highways, as well as interstates, take on a significant role.
In the response phase, since the local and secondary roads were mostly impacted by the flood, the route choice diverted mostly to the major highways. I-85 became important and the routes leading from the interstate to Anderson city were also critical (Figure 36b).

In the recovery phase, most of the high-capacity roads that were previously being used before the flood in high numbers were being used in recovery phase as well. Also, since Anderson city has many barriers, the route choices to enter the city decreased which can be seen by comparing Figures 36a and 37a. The thicker routes in the Anderson city area are less in Figure 37a than in Figure 36a because of the barriers present in those other roads. Because of the limited choices, the few roads that let people enter the city were critical. Also, comparing Figures 36a and 37a shows how the flood impacts the normal routes of people or materials delivery.

\[\text{Figure 35. Critical roads for (a) Un-flooded phase; (b) Response phase.}\]
Figures 36a, 36b, and 37a show the criticality of road sections changing across the flood phases. As the common roads for all the phases are very critical for a community, we identified the common roads that have high normalized betweenness centrality values across all three phases which were found to be I-85, SC-81, SC-28, US-178, and SC-8. Figure 37b shows the roads that have high criticality across all phases.

3.5 Discussion and Conclusion

This study analyzed road criticality for diverse transportation purposes across un-flooded, flood response, and recovery phases. Road usage and rerouting needs differ by trip purpose within each stage of the disaster. A 100-year flood served as an illustrative hazard to model network disruption.

Flooding affects various road sections, rendering them impassable and causing traffic to reroute, incurring additional travel time. The additional travel time varies depending on
the transportation purpose and the number of routes from origin to destination. The availability of alternate routes helps to reduce the rerouting distance. However, the severity of impacts on major arterials and highways like interstates, federal or state highways, can significantly increase the rerouting distance, especially if options are limited.

The criticality of roads in our study area changes across the un-flooded, response, and recovery phases. In the un-flooded phase, major highways like I-85, State Highway 28, State Highway 81, and Federal Highway 29 are most critical for regular activities like accessing workplaces and materials movement. Roads in Anderson city are critical for hospital accessibility. For the response phase, the criticality shifts slightly - roads within Anderson city also become very important for police accessibility and ambulances; routes like Highway 29 increase in criticality. Evacuation routes like I-85 also become more critical. Major highways like Highway 178 and State Highway 8, connecting to hospitals, are essential for medical access. In the recovery phase, accessibility needs change again. While I-85 and major highways like Highway 29 remain critical for activities like work commutes, roads like Highway 81, 29, 76, 178 and sections of 28 become more important for school, workforce, and park access. Throughout the phases, I-85 stands out as consistently highly critical, as a major interstate facilitating movement. Some local roads fluctuate in importance, depending on needs. Roads facilitating evacuation and hospital access are most critical in the response phase specifically.

This analysis can also help identify the critical roads that are common during the un-flooded, response and recovery phases of disaster. These roads should ideally be in
operating condition during any of the disaster phases to support efficient traffic
management. If these road sections are blocked or are unpassable then the community
will be impacted highly in terms of the rerouting time. Based on the criticality of the
roads, the high-capacity roads coming to Anderson city or going out of the city were
more critical. The major highways connecting the central business districts to the other
regions are critical for either the normal functioning of the community or response and
recovery of the disaster. The criticality of roads also depends on the spread of the
facilities. As we found for grocery stores and fire stations, as the facilities are distributed
across the county, the roads start to show almost equal criticality. The interstate (I-85)
was critical to the functioning of the study area. Various highways such as SC-81, US-29,
US-178, US-76 to SC 28, connecting the interstate to Anderson city were also critical
across all phases.

The analysis for parks and grocery stores indicated that the spread and higher number of
facilities significantly reduces the additional travel time due to the availability of more
choices. The Anderson city area, southeastern and southern areas seem to contain the
highly impacted Census block groups for multiple purposes. For public transit the
impacts can be such that some bus stops could be unserviceable and the routes non-
traversable. The change in routes can be small (gold route) or larger with greater impact
(green and blue route). This study can help identify such disruptions beforehand and plan
to improve the transit line’s resilience.

There are commonalities in the impact area for transportation purposes; these
commonalities are more crucial for building resilience in the community. Maintaining
and rebuilding (if needed) the roads that are common to most of the trip purposes based on the high betweenness centrality value, can provide broader benefit to the community for a given investment level. Also, by identifying the blocked locations for each purpose, we can prioritize the locations for recovery actions so that most of the trip purposes benefit. For instance, the bridge on the Rocky River near Anderson city impacted most of the trip purposes and caused high rerouting time in our analysis. If that bridge is disrupted, then the priority of repairing that bridge should be high so that the community can recover faster. Taking such prioritization decisions can help to manage the transportation disruptions efficiently. Also, in a case that any community chooses to prioritize one purpose over the other, then similar analysis can help them locate the sections critical for their focused transportation purpose. This overall methodology with consideration of limitations can be replicated to see the impacts of flood on transportation in a community to aid in making plans and resilient decisions.

Cutter (Cutter, 2014; Cutter et al., 2015) mentioned that for society to be sustainable, disaster risk management and resilience plays an important role (Cutter et al., 2015). This study supports sustainable transportation and planning for community resilience by identifying the critical road links for a community. The analyses can inform traffic management during flooding and prioritization of recovery at disrupted locations.

In sum, this study provided a comprehensive synthesis of how road criticality varies across un-flooded, flood response, and recovery phases, particularly in the context of a 100-year flood scenario in Anderson County, South Carolina. By examining the differential impacts of flooding on various road segments and the consequent rerouting
challenges for different transportation purposes, this study underscores the necessity of identifying critical roads that maintain functionality across all disaster phases, thereby supporting efficient traffic management. This analysis contributes to planning for transportation and community resilience and to prioritizing resource allocation.

Some limitations to the analysis exist. The first is that during a disaster, the roads might be crowded causing the traffic to diverge to reduce congestion. Congestion was not considered in this analysis. Another limitation is that only barriers in Anderson County were considered, due to which the full picture of the impacts was not shown. Another limitation is that we considered the cutoff depth for road blockage as 30 cm, but some of the vehicles could be higher than 30cm. In the case of larger vehicles, the road blockage might not be applicable, given that the road is not destroyed in some manner. Another limitation is the use of a uniform threshold value of 2.7 minutes for all transportation purposes. This decision was made due to the absence of research establishing specific thresholds for individual purposes and to be consistent. Future studies could enhance the accuracy of the analysis by determining purpose-specific thresholds. A final limitation is the assumption that the vehicle will have prior knowledge about the barriers, which might not be true for the first few trips, when people tend to use their original routes and change based on the barriers faced.

In the future, travel demand could be added to the analysis to consider the congestion. The whole river basin could be analyzed to provide more accurate results about the materials and out of county trips. The depth disruption function provided by (Pregnolato et al., 2017) can be used to decrease the speed of vehicles while travelling on the flooded
road section with depth less than 30cm. This threshold can be adjusted for goods and passenger movement, considering the higher ground clearance of trucks. Furthermore, research could investigate the potential for road destruction due to flooding, considering factors like existing design and quality of the road. Additionally, exploring rerouting behavior in the first few trips after a flood, starting from the initial blockage, can shed light on how traffic adapts during the critical flood response phase.

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CHAPTER FOUR

ASSESSING THE HINDERANCE IN OPERATIONS OF A COMPANY IN THE FACE OF FLOOD

4.1 Introduction

Transportation infrastructures facilitate general mobility, which supports different critical elements of a community, such as emergency services, economic activity, education, and many more. Hazards can disrupt a community's transportation network, which can, in turn, indirectly affect different economic sectors and critical infrastructures dependent on transportation. Therefore, an approach to understanding the dependencies and interdependencies is needed to help mitigate cascading effects during disasters and improve a community's resilience.

Transportation infrastructure disruptions can significantly impact the system and cause cascading effects on other interconnected critical lifelines (Faturechi & Miller-Hooks, 2015b). Understanding the criticality of resources, networks, and systems, and the related dependencies and interdependencies of vital infrastructure, is necessary for effective risk management (FEMA, 2024b). Yadav et al. (2020) have shown that transportation networks are functionally interdependent with each other and with other infrastructure systems, such as the power grid and communication networks. Also, by bringing people, companies, and resources together, the transportation sector plays an important role in linking the economy and society (Ali et al., 2018). For instance, if certain roads are blocked, hindering import or export of materials, then the industry of a community would be impacted. Similarly, if
the roads to access the companies are blocked, the workforce might not be able to access the workplace, which could lead to economic losses in a community. Dependencies and interdependencies between components of critical infrastructure increase risk since they can pose a threat or hazard in and of themselves, impact the system's resilience and protection capabilities, and cause failures to cascade and intensify (Petit & Verner, 2024). To visualize and analyze such effect propagation due to a basic event that leads to a system failure, fault tree analysis is performed in this chapter.

Fault tree analysis is an analytical technique that specifies an undesirable state for the system and works its way through the system's surroundings and operation to identify different plausible scenarios in which the undesirable event could occur (Roberts et al., 1981). The failure of a system is considered as a top failure event of the fault tree diagram which relates to intermediate and basic event using logic gates such as AND and OR (Yuhua & Datao, 2005). A fault tree is adapted to its top event, suggesting that it is not a model of all potential system failures or all potential causes for system failure but a model that corresponds to a particular mode of system failure; as a result, it only includes those faults that contribute to this top event (Roberts et al., 1981). There are various approaches through which fault trees can be analyzed and generally grouped under qualitative and quantitative analysis of a fault tree. For our analysis we conduct quantitative analysis of fault tree using binary value assignment. Fault tree diagrams are explored here to help inform decisions related to enhancing resilience within a community, serving as a tool for analyzing and mitigating potential vulnerabilities.
Resilience is the capacity to tolerate and bounce back from shocks, whether they originate from man-made or natural disasters, technological malfunctions, or other interruptions (FEMA, 2023b). A part of resilience is to determine the root cause of failures, or the events that led up to the major failure in a system related to critical infrastructures. Understanding the importance of fault tree diagrams begins with recognizing the intricate dependencies within transportation networks, where a single failure can cascade into widespread consequences affecting various aspects of community life. A study by Fotouhi et al., (2017) emphasizes the need to account for interdependencies to assess transportation resilience accurately. Fault Tree Diagrams (FTDs) visually represent the potential failure scenarios, cascading effects to different critical infrastructures and their underlying causes, which helps to identify critical events of failure, assess risks, and implement targeted strategies to enhance resilience.

The economy of a community greatly relies on the dominant economic activity of that community. For instance, if a community has several textile manufacturing companies, then major economic activity in the community would be related to textile production. Due to disasters, such economic activity can change, leading to a major shift in the economy, if impacts are severe enough or last long enough for a company to exit the area. In the above example, if most of the textile companies are impacted by a disaster, then the community's economic activity is significantly impacted, leading to loss in such activity. The operation of a manufacturing company is dependent on the accessibility of the raw materials to the company, final product from the company and workforce to the company for daily operations. If the accessibility of any of these three operations is stopped due to the
blockages, then the operation of that company is disrupted causing potential economic losses and changes in the economic activity of the community. Therefore, an approach to determine the probability that the activity could change based on the impact of a disaster is needed to understand the hidden impacts of disasters in a community.

This paper illustrates the impact of a 500-year return period flood on the general operation of a company dependent on the import, export and worker accessibility using fault tree diagrams. The possibility of failure is calculated based on the flood and potentially impacted locations blocking the roads used for materials and workforce transport. The probabilities of such failure are assigned as binary values in the analysis, given the severity of the flood.

The remainder of this paper is divided into five sections. First, we conduct a literature review to investigate what has already been done in transportation network dependency concerning hazards. The second subsequent section presents the methodology used in the analysis, and the next sections provide the results and discussion, respectively. The final section provides the paper's conclusion, limitations, and future research directions.

4.2 Literature Review

Transportation is one of the critical infrastructures of a community facilitating various activities such as economic, educational, social recreational, and many others. Since such activities are dependent on transportation infrastructures, if transportation infrastructures are harmed, then these activities could also be disrupted. For instance, if the roads that connect people to the workplaces and hospitals are damaged, then people may not be able
to access those facilities. Therefore, it is essential to understand the failure of road links that are facilitating trips for various transportation purposes.

Floods can impact transportation networks, supporting critical socio-economic activities at local or regional levels (He et al., 2021), and infrastructures, directly and indirectly. Directly by destroying and disrupting the networks and indirectly by impacting the infrastructures dependent on the transportation network (Hammond et al., 2015). Transportation infrastructure such as roads, transit, aviation, etc. are vulnerable to disasters such as floods (He et al., 2021). The economy of a community is dependent on the connectivity of road network and vice versa (Kadaverugu et al., 2021). Flood events affect the transportation network’s connectivity by disrupting the travel for goods, passengers, and services because of the road being partially or fully submerged, destroyed or made unsafe to travel (He et al., 2021). The impact of flooding on road networks can cascade to different community operations. Borowska-Stefańska et al. (2019) found that floods can cause indirect damage by decreasing potential accessibility. Due to such disruptions, floods can cause lengthened commutes, reduce job accessibility, and increase economic costs because of the delay (He et al., 2021) along with the employees’ absences causing losses to a community (Kasmalkar et al., 2020b). Such workforce absences and connectivity disruptions can result in hinderance of manufacturing company operations, since for a manufacturing company to operate, it needs the workforce and raw materials to work, and products to export. Poor mobility due to submerged roadways further challenges the adaptation capacity of flood-affected cities and communities (Kadaverugu et al., 2021). It can be said that floods can have devastating impacts on lives and property along with an
increased uncertainty regarding the regular operations of a community (Alabbad et al., 2021).

Due to projected increase in extreme events, such as flooding (Kermanshah et al., 2017), methods and approaches to increase the resilience of transportation in a community are needed. Resilience of transportation infrastructure has been defined by many researchers (Adams, Bekkem, et al., 2012; L. Chen & Miller-Hooks, 2011; Freckleton et al., 2012; Jin et al., 2014). The general understanding is that resilience is an ability to absorb or withstand disruptions and recover from such disruptions quickly returning to normal functions with no or acceptable disruptions. It was also found that redundancy in the transportation network (Hughes & Healy, 2014; Morshed et al., 2021) is essential for resilience since when one link fails, another one can serve the demand. Therefore, the reliability of any link or a set of links connecting two points in a transportation network, during the hazardous event or after, becomes essential for resilience.

This study focuses on the concept of fault trees used in reliability theory to capture the dependency of a component of a community on transportation infrastructure. Fault tree analysis (FTA) is a widely used method in various industries to assess system reliability and safety. Fault tree analysis has been applied in multiple contexts such as cyber-physical systems (Lazarova-Molnar et al., 2020) and aviation accidents (Coury & Schulze, 2004). Through the application of FTA, management guidelines can be developed to prevent disasters, as demonstrated in instances like bridge collapses (Tan et al., 2020). FTA has been extensively utilized in risk analysis studies, showing its efficiency in analyzing disasters such as the Bhopal tragedy (Labib, 2015). The method has also been used in
reliability engineering, offering a systematic approach to analyze failures and derive lessons from disasters (Labib & Read, 2015). Fault tree analysis plays a critical role in disaster management and transportation safety by offering a structured approach to identify and analyze potential failures.

Fault tree analysis can be qualitative and quantitative. An overview of fault tree analysis models, including repairable, extended, and dynamic fault trees, is given by Ruijters and Stoelinga (2015). They also go over qualitative and quantitative analysis methodologies, like using stochastic methods to calculate failure probabilities. The most common qualitative analysis measures are cut sets, path sets and common cause failures (Ruijters & Stoelinga, 2015).

A cut set is a set of events and components of a fault tree whose happening will cause the system to fail and a minimal cut set is the minimum combination of basic events which will cause the system to fail. To determine the cut sets, Boolean manipulations and binary decision diagrams are frequently used while there are some other algorithms provided by researchers that may be efficient based on their stated condition. Bottom-up and top-down algorithms are commonly used for determining minimal cut sets (Roberts et al., 1981; Ruijters & Stoelinga, 2015). These methods use Boolean manipulation, such that the fault tree is converted into a Boolean expression based on the logic gates and these expressions are then simplified so that the top event is represented by basic events only in a simplified form. Bottom-up methods start with the expressions for the gates at the base of the fault tree. Although it frequently requires more processing power, it has the benefit of offering the minimal cut sets for each gate (Ruijters & Stoelinga, 2015). Binary decision diagrams are
an efficient way of determining minimal cut sets by converting fault tree diagrams into binary decision diagrams by using the Shannon expansion formula as explained by Akers (1978).

Some other methods exist. One is the minimum cut vote, representing an arbitrary combination of k elements applied for fault trees with voting gates (Xiang et al., 2011). Monte-Carlo simulation can also be used to find the minimal cut sets by randomly selecting components of the fault tree and assigning them a failed state and calculating the top event; if this leads to top event failure then the subset is marked as a cut set (Ruijters & Stoelinga, 2015). A minimal cut set helps in identification of the critical failure which leads to the top event failure. In transportation, it could be a link failure causing a disruption in the accessibility of a house or any other infrastructure of a community.

Minimal path sets are also used as a qualitative analysis of fault trees where a minimal set of components are chosen such that the system will remain operational given that these events do not fail. This can be computed by the same algorithms which identify the minimum cut sets by incorporating some changes in the gates and basic events of the fault tree as mentioned by Ruijters and Stoelinga (2015).

Common cause failures are the qualitative aspect in the analysis of fault trees where a condition or event causes multiple basic events and a cut set where all the events in the cut set are caused by common cause is called a common cause cut set (Kumamoto et al., 1996). For instance, if a company imports raw materials and exports final products through a section of the road and if that road link is interrupted by a flood or other event, then the
effect of such link failure will be shared to potential raw materials import failure and final product export failure. The analysis of common cause failures can be done using subcomponent level analysis, beta factor model, basic parameter model, multiple Greek models, binomial failure rate model, and Markov mode as explained by Kumamoto et. al (1996). These common event failures are also critical to any analysis since one event failure is cascading to many component failures which potentially increases the chance of system failure.

The quantitative analysis of fault trees is based on probability theory. The probability of the fault tree components is calculated based on the basic event probabilities and the process is continued until the top failure event probability is identified, which is usually the goal. While stochastic measures provide failure probabilities, importance measures provide information on how vital a component is to the whole system. Binary decision diagrams, as discussed in qualitative analysis approaches (Codetta-Raiteri, 2006; Remenye-Prescott & Andrews, 2008), are used in quantitative analysis as well. Another approach for improbable failure is rare event approximation, where the unavailability of a system is approximated by the sum of unavailability of all minimum cut sets (Ruijters & Stoelinga, 2015; Stamateatos et al., 2002). Bayesian network analysis (Ben-Gal, 2007) is used to calculate reliability when there are statistical dependencies in between events (Bobbio et al., 2001). Monte Carlo simulations are used to compute system reliability where each component of the fault tree is randomly assigned a failure state depending on its failure probability and, afterwards, the fault tree is evaluated for top event failure (Ruijters & Stoelinga, 2015). This method can be used for static time or continuous time (Crosetti, 1971;
Durga Rao et al., 2009) analysis of a fault tree along with qualitative or quantitative analysis (Ruijters & Stoelinga, 2015).

There are a few extensions of the fault tree. Dynamic fault trees (Dugan et al., 1992) are an extension to the static fault trees to capture the sequence dependent dynamic behavior (Kabir, 2017). Component fault trees are used to manage complex systems where smaller fault trees of system components are defined and organized into hierarchical structures (Kaiser et al., 2003). State event fault trees are an extension to conventional fault trees by representing the states and events in a fault tree (Grunske et al., 2005; Kaiser et al., 2007). Here, state is a condition that lasts for a period while an event is an instantaneous phenomenon causing state transition (Kabir, 2017). Pandora temporal fault trees extend the capacity of standard fault trees with temporal laws, which helps in adding the sequence-dependent behavior to the standard fault trees assuming the event goes from fail to no-fail instantaneously (Kabir, 2017).

Calculation of the probabilities of the basic events can be challenging. Another type of fault tree analysis when probability values are not available is fuzzy fault tree analysis (Tanaka, 1983), where instead of the probability of failure, the possibility of failure (fuzzy number) is considered for the basic event in the range of zero and one and analysis is conducted. Here, the fuzzy number can take many forms, such as the commonly used triangular and trapezoidal fuzzy number (Mahmood et al., 2013). This approach is applicable to complex systems where the component’s probability of failure is hard to find, as in our case. But we do not directly use a fuzzy approach but rather a state definition approach where the basic event will have either a failed state or a working state regarding a disruption.
The research on transportation reliability often focuses on travel time reliability (TTR). There are two ways to develop travel time reliability evaluation, direct evaluation using travel time datasets, and assuming the sources of uncertainty and calculating travel time reliability (Zang et al., 2022). There are various studies done for travel time-based traffic assignments. These studies are helpful in route choice to identify the optimal reliable path for adding travel demand to the network analysis (E. Miller-Hooks, 2001; E. D. Miller-Hooks & Mahmassani, 1998, 2000; E. Miller-Hooks & Mahmassani, 2003; Opasanon & Miller-Hooks, 2006). One major challenge in modeling TTR in transportation networks is uncertainty propagation, or the propagation of uncertainty from its source to TTR at many spatial levels (Zang et al., 2022). Zang et. al, 2022 mentioned that these uncertainties are determined using the central limit theorem (A. Chen & Zhou, 2010), convolution integral (Filipovska & Mahmassani, 2020), moment based approaches (P. Chen et al., 2020), copula functions (Yun et al., 2019), Markov chain frameworks (Ma et al., 2017), empirical evidence (Kaparias et al., 2008; Rakha et al., 2010), or Boolean algebra (Al-Deek & Emam, 2006; Emam & Al-Deek, 2006). The literature using fault tree diagrams for reliability was found to focus more on accidents (Joshua & Garber, 1992; Liu et al., 2015; Zaib et al., 2022), evacuation (Access et al., 2023), public transport (Yaghubpour et al., 2016), railway safety (Jafarian & Rezvani, 2012; Usman et al., 2021), mode choice (Derse & Göçmen, 2021), and oil and gas transmission (Yuhua & Datao, 2005). The research primarily provides in-depth information about an event, such as urban flood, and causes of it (Veldhuis et al., 2011) or potential causes of the hazard. Information of the hazard implications and their cascading impacts on infrastructures dependent on transportation are not explored in detail, yet, to the best of the
author’s knowledge. In this paper, we analyze the roads that link various locations to the workplaces and see if the economic activity of that company is blocked or disrupted by a flood.

4.3 Methodology

The general methodology for the analysis is based on the fault tree analysis and binary value assignment to the basic events of the fault tree. The events are assigned a Boolean value of 1 or 0 as given by equation 1 and connected with logic gates. The logic gates are simplified and solved to find the effect of a flood on the economic activity of a company in Anderson County, SC along with critical road links that are used for raw materials import, final products export, and workforce accessibility. The general methodology of the analysis is provided in figure 1.
Figure 1: General Methodology

**Routes analysis**

The multiple route identification from various origins to a destination, was done with the help of ArcGIS Pro 3.2.2. The “Route” geoprocessing comes under Network analysis in ArcGIS Pro. The “Route” function identifies the shortest route from one point to another based on Dijkstra's algorithm. For our study, routes were constructed to connect potential
housing locations to the company and raw materials import to or final product export from the company. ArcGIS Pro can only identify the shortest route, but we required more than one route for our analysis. For the identification of the ‘k’ number of routes, python programming in ArcGIS Pro was used. The flowchart of alternative route generation is provided in Figure 2.

Figure 2: K number of routes identification methodology in ArcGIS Pro
Flood Barriers

The flood barriers are the locations which would be inundated because of the 500-year flood. To identify the flood barriers, we used flood models provided by FEMA, FIRM (FEMA, 2024a). Since the flood map does not contain flood depth data, we calculated the flood depth based on the 500-year flood extent of the Savannah River watershed.

To calculate the 500-year flood water depth, the Floodwater depth estimation tool (FwDET) (Cohen et al., 2022) was used. FwDET is a python-based ArcGIS tool that calculates the depth of the floodwater based on the area's flood extent and topographical digital elevation model (DEM) (Bhatta et al., 2024). The idea behind the tool is that the elevation of the flood water at a cross section of open channel flow, i.e., flood, remains same. FwDET gets the information of the elevation of the flood water extent by overlaying flood hazard area with the DEM of the area and then assigns the elevation values of the extent to the whole cross-section area by averaging the nearby cell elevation values. The final output of the tool is a raster image which has the floodwater depth above the topography as the cell values.

The routes generated based on figure 2 were overlayed with the flood barriers of the 500-year return period flood of the Savannah River watershed. The blockages because of the flood and links in each route/path were analyzed to find out which links were unpassable causing the failure of the corresponding path.

FwDET calculates the depth of flood water from the topographical level or the existing ground surface. In the case of bridge sections, the depth provided by FwDET would be the
elevation from the river or stream normal water level to the flood water level (Bhatta et al., 2024). The bridge deck elevation is needed to calculate the floodwater elevation above the bridge deck disrupting accessibility, given that the bridge is structurally safe during the hazard. The depth of the water above the bridge surface was calculated based on equation 1 (Bhatta et al., 2024):

$$d_b = ((E_{DEM} + d) - E_b),$$

where, $d_b$ is the depth of floodwater above the bridge surface, $E_{DEM}$ is the elevation data of the bridge provided by the DEM, $d$ is the depth of the floodwater provided by the FwDET, and $E_b$ is the elevation of the bridge surface provided by the LiDAR data.

If the LiDAR data was not provided for the bridges, as happens for culverts or newly constructed bridges, then the approach road elevation was assigned as the bridge elevation assuming that the bridge deck elevation is equal to the average elevation of the approach roads.

If the flood depth above the road surface was found to be greater than 30 cm (one foot), then the road section was considered inaccessible (Bhatta et al., 2024; Pyatkova et al., 2019), otherwise the road was considered accessible (equation (2)). The 30 cm threshold was selected because of two major reasons, the positioning of car’s air inlet, 25 to 35 cm (Yin et al., 2016), and a hydrodynamic force analysis conducted by (Smith et al., 2017), which established 30cm as the critical water depth for small passenger vehicles.
\[ \text{Road section} = \begin{cases} \text{Accessible} & , \quad d < 30 \text{cm} \\ \text{Inaccessible} & , \quad d \geq 30 \text{cm} \end{cases} \]

where, \( d \) is the depth of the water above the road surface (Bhatta et al., 2024).

**Data collection:**

Study area and data collection.

According to the US Census Bureau, Anderson County, SC has a population of 213,076 as of July 1, 2023, (US Census Bureau, 2024), with a large amount of employment in manufacturing (SC Department of Employment and Workforce, 2023). The major employers of Anderson County include fifty-nine major manufacturing businesses (Chamber of commerce, 2023) and one hospital (FEMA, 2023c). The sources of data required for the analysis are shown in Table 1.

**Table 3: Data sources**

<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Roads</strong></td>
<td>South Carolina Department of Transportation (SC DoT, 2023) and Georgia Department of Transportation website (GDoT, 2023)</td>
</tr>
<tr>
<td><strong>Bridges in Anderson County</strong></td>
<td>National Bridge Inventory 2023 data (FHWA, 2023)</td>
</tr>
<tr>
<td><strong>Digital Elevation Model and LiDAR data</strong></td>
<td>United States Geological Survey, 1m resolution digital elevation model, (USGS, 2023)</td>
</tr>
<tr>
<td><strong>Flood hazard extent map</strong></td>
<td>Federal Emergency Management Agency (FEMA), (FEMA, 2023a)</td>
</tr>
</tbody>
</table>
Fault tree preparation and value assignment.

The fault tree is prepared for the paths that lead to the destination. The three routes generated were analyzed to see the links and paths that connect the origin and destinations. Afterwards for each path, the links were identified and linked in a tree form using logic gates for fault propagation.

![Figure 3: A general network from house to industry.](image)

For instance, consider a general network as shown in figure 3. There are two paths possible from home to industry, A-B-C, A-D-C. If any of the links fail in path A-B-C, then the path becomes inaccessible. Therefore, it is generalized that path A-B-C fails if link A, B, or C fails. The fault tree for the failure of path A-B-C is provided in figure 4.
Similarly for path A-D-C, any of link A, D, or C’s failure will result in path failure. Also, the failure of both paths would result in accessibility failure of the location. i.e., path A-B-C and path A-C-D must fail for the location to be inaccessible. The fault tree representation for industry location accessibility failure is provided in figure 5.
Therefore, if multiple links, paths, and locations are inaccessible in a community, the community could experience large losses. The analysis is performed for the accessibility of a company in the face of a flood. The roads and bridges blocked are calculated and overlayed with links identifying the failed and non-failed links to get an idea if the economic activity for the company is affected by the 500-year return period flood.

**Logic Gates and Boolean algebra**

The fault tree was analyzed using Boolean algebra. The various gates used in the analysis, their notations and the expressions are provided below.

**OR Gate:** The OR gate is represented by symbol ‘+’ and the gate is represented by the symbol connecting paths and their links as shown in Figure 5. The output event ‘Path ABC fails’ is written as

\[
\text{Path (A-B-C)} = \text{link A + link B + link C}
\]

**And Gate:** The AND gate is represented by symbol ‘.’ And the gate is represented by the symbol connecting the location accessibility failure with various path fails as shown in Figure 5. The output event ‘Path A-B-C fails’ and ‘Path A-D-C fails’ is written as:

\[
\text{Path(A-B-C) and Path (A-D-C)} = (\text{link A + link B + link C)}. (\text{link A + link D + link C})
\]

There are various other logic gates in the Boolean algebra, but our analysis primarily uses ‘OR’ and ‘AND’ gates.

**Boolean Algebra Properties:**
To solve or simplify the complicated Boolean expressions, we can apply various Boolean algebra properties to reduce the size and complications of such equations. Some of the Boolean properties are stated below (Dhillon & Singh, 1981; Kumamoto et al., 1996).

**Law of Absorption:**

\[ A + (A.B) = A \]  

**Identities:**

\[ A + A = A \]  
\[ A.A = A \]

**Distributive Laws:**

\[ A + (B.C) = (A+B) (A+C) \]  
\[ A.(B+C) = A.B + A. C \]

**Fault tree with repeated events:** While analyzing the fault tree, sometimes we encounter one event that is repeated into many intermediate events. For instance, in figure 5, we see that the events failure of link A and C are common for both path A-B-C and A-D-C failure. In such situations the fault tree can be simplified using Boolean logic. For figure 5, the Boolean algebra to simplify such events is provided in equations 3 and 4 below. See figure 6 for visual representation of the equation 4.
Path ABC fails \((A-B-C) = A+B+C\)

Path ACD fails \((A-C-D) = A+C+D\)

Location Accessibility failure \((P) = (A+B+C) \cdot (A+C+D)\)

The location accessibility failure can be simplified using the Boolean algebra properties.

\(P = A + (B+C) \cdot (C+D)\), Using distributive law,

\(P = A+C+B.D\), Using distributive law,

The simplified fault tree after Boolean simplification is presented in figure 6. The simplification of the fault tree can also be useful in the determination of the cut sets for the failure.

**Figure 6:** Simplified fault tree.
Binary Value Assignment

The basic events are assigned a binary value for the analysis of the fault tree. The assignment procedure as shown in figure 1 is explained below.

Let, the failed or non-failed instance of a link be represented by the link name in figure 7 and is represented by X, where X = Event {A, B, C…, N).

\[
X = \begin{cases} 
1, & \text{Link X fails} \\
0, & \text{Link X does not fail} 
\end{cases}
\]

All three paths from various raw materials import and exporting locations were assigned a value based on equation 5.
Figure 7: An example fault tree diagram for accessibility failure.

Figure 7 shows a general diagram relating accessibility failure to the link failure through various gates and components. In our analysis, the top event is the company location accessibility failure. The locations, representing workforce and materials import/export locations, are used to show the commonality across purposes. From the fault tree diagram in figure 7 we can see that,
Location 1 Accessibility failure = (A + B + C + a) \cdot (A + G + F + a) \cdot (D + H + B + C + a) \\
15

where event ‘a’ is the failure of the driveway of the company. In our case the value of ‘a’ is 0 based on equation 3.

Location 2 Accessibility failure = (K + N + a) \cdot (K + L + F + a) \cdot (J + M + F + a) \\
16

Top event decision simplified = a + A B + A C + B G + C G + B F + C F + A D + A H + F K + F N + K J + K M + N L J + N L M. \\
17

Top event factored = G (C + B) + (N L + K) (M + J) + A (H + D + C + B) + F (N + K + C + B) + a. \\
18

From the simplified and factored Boolean equation, we see that the repeated links across the paths have high importance for the failure of the location accessibility. For instance, the approach road ‘a’ is common to all the paths, and the closure of this approach road will mean that the people or the raw materials or the final products cannot be connected to or exported from the company leading to the failure in operation of the company. This behavior is also represented by the simplified equation which tells that the ‘a’ event will result in the top event. Also, event F is shared across many paths and different locations, showing that event F will have a high influence in the overall accessibility and that is confirmed by the top event simplified equation. Event A has a similar influence on that of event F.
With this analysis, we can identify whether the company's economic activity fails due to an event, a 500-year flood, and identify the common links across the purposes along with whether these links fail due to the hazard.

**4.4 Results and discussion**

The Savannah River watershed includes parts of South Carolina, North Carolina, and Georgia of the US. Due to a 500-year return period flood in the Savannah River watershed, 11,332 different road and bridge sections were found to be flooded. Due to the flood, 136 culverts were found to be closed out of 298 and 537 bridges were closed out of 921 in the hazard zone. The barriers due to the 500-year return period flood are provided in figure 8.
Figure 8: 500-year flood barriers across the Savannah River Watershed
**Routes and links**

Major corridors (Atlanta, Augusta, Columbia, and Charlotte) were considered as the origins for raw materials import and the destination for the final product export. The nearby census block group centroids, around the company, were considered the origins for the workforce arriving at the company. The import routes from each of the corridors are presented in figure 9. Similarly export routes (See figure 10) and workforce routes were also generated and analyzed (see tables 2 and 3).

![Map showing routes](image)

**Figure 9:** Routes for materials accessibility (Raw materials)
The fault tree for the raw materials import failure for the Atlanta location is presented in figure 11. The blocked links are given a value of 1 and non-blocked links are given a value of 0 and top event Boolean value is calculated as (Path 1 fails), (Path 2 fails), (Path 3 fails). The values are mentioned in the arrows in Fault tree diagram represented in figure 11.

**Figure 10**: Export routes from the company.
Here, Path 1 has failed because many links in that path are found to be blocked because of the flood. Path 2 has failed because one or more links are blocked, and similarly path three has also failed because one or more links failed as presented in figure 11. Therefore Path 1 fails, Path 2 fails, and Path 3 fails; all have a Boolean value of 1. This results in the top event failure value to be 1. Therefore, it was found that the accessibility of raw materials from Atlanta to the company and final products from the company to Atlanta will be impacted because of the 500-year return period flood.

Figure 11: Materials accessibility to company failure.
Similarly, the same analysis was carried out for each major corridor and 13 workforce locations that are near the company. The housing locations of the workforce are assumed to be the centroid of the census block groups near the company.

The schematic representation of the full fault tree for the selected company accessibility is presented in table 2 and 3. Here the failure values are noted only in the case of actual failure of the link by making the link name bold and marking it with ‘(1)’ to maintain the clarity and readability of the table. The fault propagation based on logic gates is provided in the first row after the headings of the table. The fault tree representation of the raw materials imports from Atlanta, as mentioned in table 3, is provided in in Figure 11 and the analysis is done based on similar fault trees for each of the location accessibility.

**Table 4**: Schematic representation of fault tree in tabular format for workforce accessibility

<table>
<thead>
<tr>
<th>Trip Purpose</th>
<th>Origin</th>
<th>Path</th>
<th>Links (Failure value assigned, only if failed)</th>
<th>Path failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workforce' Accessibility (To Company Location)</td>
<td>Location 1</td>
<td>Path 1</td>
<td>Marshall Rd, Masters Blvd, Highway 29</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Path 2</td>
<td>Michelin Blvd, Highway 24, Highway 28, Highway 29</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Path 3</td>
<td>Marshall Rd, Highway 22, Monitor Dr., Hwy, 28, Highway 29</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Path 1</td>
<td>New Hope Rd, Highway 24, Highway 28, Highway 29</td>
<td>0</td>
</tr>
<tr>
<td>Location</td>
<td>Path 1</td>
<td>Path 2</td>
<td>Path 3</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Location 3: Masters Blvd, US 29</td>
<td>Location 3: Masters Blvd, SC 81, US 29</td>
<td>Location 3: Masters Blvd, SC 81, Highway 101, Doris Street, US 29</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Location 4: Hall St (1), SR 149, US 29, Doris St, US 29</td>
<td>Location 4: Hall St (1), South McDuffie St., Warlow St., Sayre St., US 29</td>
<td>Location 4: Asbury Ave, Hall St (1), Pecan Dr, SC 28, US 29, Doris St.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Location 5: South Main St., West point Dr., SC 81, US 29, Doris St, US 29</td>
<td>Location 5: South Main St., Manley Dr., SC 81, US 29, Doris St, US 29</td>
<td>Location 5: South Main St., West point Dr., SC 81, US 29, SC 28, US 29</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Path 1</td>
<td>Path 2</td>
<td>Path 3</td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Path 1</td>
<td>Lyonswood Dr., US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 2</td>
<td>Curtis St, Hwy 81, US 29, Doris Ave, US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 3</td>
<td>New Pond rd, Hwy 28, Hwy 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Path 1</td>
<td>W-Reed St., US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 2</td>
<td>W-Franklin St. Hwy 81, US 29, Doris Ave</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 3</td>
<td>Southwood St., US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Path 1</td>
<td>King St., <strong>Glenn St. (1)</strong>, N-Towers St., Hwy 76, US 29</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 2</td>
<td>Appleton St., Hwy 24, <strong>SC 28 (1)</strong>, US 29</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 3</td>
<td>Hwy 24, US 29, Hwy 81, US 29, Doris Ave, US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Path 1</td>
<td>Hillcrest Circle, Flowe Rd, SC 28, US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 2</td>
<td>Southwood St., US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 3</td>
<td>Burdline Rd., Southwood St., US 29, SC 28, Hwy 355, US 29, Doris St., US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Path 1</td>
<td>Hwy 22, Hwy 28, US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 2</td>
<td>W Franklin St., <strong>Southwood St. (1)</strong>, US 29</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 3</td>
<td>Hwy 24, <strong>SC 28 (1)</strong>, <strong>New Pond Rd. (1)</strong>, US 29, Doris Ave, US 29</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Path 1</td>
<td>Beckman Dr., SC 28, US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 2</td>
<td>Beckman Dr., SC 28, US 29, Doris Ave, US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 3</td>
<td>Beckman Dr., SC 28, East Roosevelt Dr., US 29</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 1</td>
<td>Monitor Dr., <strong>SC 28 (1)</strong>, US 29</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Path 2</td>
<td>Path 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>--------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Hwy 22, Monitor Dr., <strong>SC 28 (1)</strong>, US 29</td>
<td>Hwy 22, Marshall Rd., Masters Blved., US 29</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Note: The failed links are formatted as bold in the table.*

**Table 5:** Schematic representation of fault tree in tabular format for import and export

<table>
<thead>
<tr>
<th>Trip Purpose</th>
<th>Origin</th>
<th>Path</th>
<th>Links (Failure value assigned, only if failed)</th>
<th>Path failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Import (To Company Location)</td>
<td>Atlanta</td>
<td>Path 1</td>
<td>I-85 (1), <strong>Hwy 24 (1)</strong>, <strong>SC 28 (1)</strong>, US 29</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Path 2</td>
<td>I-85 (1), US 76, <strong>SC 28 (1)</strong>, <strong>New Pond Rd (1)</strong>, US 29, Doris Ave., US 29</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Path 3</td>
<td>I-85 (1), <strong>Hwy 24 (1)</strong>, Michelin Blvd, Richland Dr., US 29</td>
<td>1</td>
</tr>
<tr>
<td>Augusta</td>
<td>Path 1</td>
<td>I-20 (1), US 78 (1), <strong>GA 17 (1)</strong>, <strong>GA 77 (1)</strong>, US 29 (1)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 2</td>
<td><strong>US 25 (1)</strong>, <strong>SC 72 (1)</strong>, <strong>SC 28 (1)</strong>, US 29, Doris Ave, US 29</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Path 3</td>
<td><strong>US 25 (1)</strong>, Bypass Hwy 72, US 25, US 178, US 76, <strong>US 29 (1)</strong>, US 28, US 29</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Columbia</td>
<td>Path 1</td>
<td>I-385, I-85, Hwy 178, <strong>SC 28 (1)</strong>, US 29</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Export (From) Company Location</td>
<td>Path 1</td>
<td>Path 2</td>
<td>Path 3</td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------</td>
<td></td>
</tr>
</tbody>
</table>
**Note: The failed links are formatted as bold in the table.**

<table>
<thead>
<tr>
<th>Charlotte</th>
<th>Path 1</th>
<th>US 29, <strong>SC 28</strong> (1), US 178, I-85</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Path 2</td>
<td>US 29, Doris St., <strong>US 29</strong> (1), I-85</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Path 3</td>
<td>US 29, <strong>SC 28</strong> (1), US 178, I-85, I-185, I-385, SC 72, I-77</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

Since there are many links for each location’s accessibility to the company, representing all of them in a diagram format will make the diagram hard to read. To overcome the issue, we have tried to find the failure value for each location based on link and path failure. Therefore, the new fault tree diagram constructed will be represented not with the basic events, but with the intermediate events. The equation for the top event failure is given by equation 19.

$$Top\ Event\ Failure = \prod_{p=1}^{m} \prod_{i=1}^{k} \sum_{j=1}^{n_i} L_{ijp}$$

Where, \( p \) is the purpose of trip, \( m \) is the number of trip purposes, \( i \) is the path from origin to destination, ‘\( k \)’ is the number of paths from origin to destination, \( j \) is link of the path \( i \), and \( n_i \) is the number of links in path ‘\( i \)’, ‘\( L_{ijm} \)’ is the \( j \)th link of the path ‘\( i \)’ of purpose ‘\( p \)’.

The fault tree diagram without the links for the company accessibility failure is provided in figure 12. And the common links across purposes are identified using GIS analysis and provided in figure 13.
From tables 2 and 3 and Figure 12, we found that for the chosen company, the accessibility will be lost in terms of raw materials import, final products export, and a part of the workforce accessibility. The top event failure is given by equation 19 which is based on intermediate events.

\[
(W_1 + W_2 + W_3 + W_4 + W_5 + W_6 + W_7 + W_8 + W_9 + W_{10} + W_{11} + W_{12} + W_{13}) + (RAt.RAl.RCo.RCh) + (IAt .IAl.ICo.ICh)
\]
Upon substituting the values, Equation 20 results to be 1.

**Commonality across purposes**

The common links across purposes will be of interest to the company since their failure will result in multipurpose accessibility failure. The links that are critical and are repeated across raw materials import, final products export and workforce accessibility are identified and listed in table 4. These common links are also mapped and provided in figure 13.

**Table 6: Common links across purposes details**

<table>
<thead>
<tr>
<th>No</th>
<th>Common Link Name</th>
<th>Block Status</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SC-24 Link</td>
<td>0</td>
<td>West Whitner Street</td>
</tr>
<tr>
<td>2</td>
<td>SC 28 Link - a</td>
<td>1</td>
<td>Link joining SC 24 and US 29 on North side of the company</td>
</tr>
<tr>
<td>3</td>
<td>SC 28 link - b</td>
<td>0</td>
<td>Link south of US 29 and SC 24 intersection on Northeast of the company</td>
</tr>
<tr>
<td>4</td>
<td>US 29 - a</td>
<td>1</td>
<td>Link crossing Richland creek, South-west of the company</td>
</tr>
<tr>
<td>5</td>
<td>US 29 - b</td>
<td>0</td>
<td>Link North-East of the company</td>
</tr>
<tr>
<td>6</td>
<td>US 29 - c</td>
<td>0</td>
<td>Link with intersection of SC 28 and US 29 south east of the company</td>
</tr>
</tbody>
</table>
4.5 Conclusion Limitations and Future directions

We examined how a 500-year return period flood impacts the accessibility of a company. The analysis helped in understanding the impact of the flood in the community related to the economic sector. We analyzed a company in Anderson County as an example and limited the number of paths for each purpose (material import/export and workforce) to simplify the analysis. The analysis was done using fault tree diagrams and a Boolean value assignment method. The values assigned were used to calculate whether the top event, “Accessibility Failure”, for the company because of the flood. The accessibility of the raw materials will be significantly impacted. We analyzed three alternative routes for each origin and destination pair and found that the export of final products and import of the raw materials is significantly impacted; all the paths fail. This leads to the top event of accessibility failure of that company. We also found that not every workforce accessibility path failed, showing that some employees might be able to make it to the company but without the raw materials coming in and final products going out, it will be difficult to manage the company, unless sufficient raw materials are stored. We found that few of the links were critical across the three purposes and also were being impacted by flood, similarly some links were being used by all three purposes but were safe to travel (See

<table>
<thead>
<tr>
<th></th>
<th>Link Description</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Link US 29 connecting with the approach road of the company on Northeast of the company before SC 28</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Marshall Rd + Michelin Blvd</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>New hope Rd</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Figure 13). We identified the common links for materials export, materials import and workforce access and analyzed them for their failure. We found that various links are critical for a company for its operation as shown in figure 13. The failed links that are common to all purposes and are causing great disruption for the company are SC 28 link, US 29 link, Highway 355 (New Pond Road link) as shown in Figure 13.

Figure 13: Common links across the three company operation purposes.

Considering the analysis, the 500-year flood can impact the company’s activity. If most of the companies in a community are impacted in a similar manner, then the economy of that
community might be impacted highly. The links identified that are crucial for the company for the abovementioned three purposes will be crucial for all of the companies dependent on these links for import, export or workforce access.

This study has some limitations as it considers only three alternatives more can be considered based on the allowable delay of the raw materials and workforce. Another limitation is that we only analyzed one company for illustration purposes. To overcome this limitation, an analysis for all the companies in each industry and then all industries within the community can be done to see the overall impact on the community. The third limitation is consideration of the independent failure. The road links can fail due to other hazards as well and consideration of different hazards and their effects can be a great addition to the research. Also, dependency can be analyzed using probability instead of binary values, with consideration of the independent and dependent failure probabilities. This could be a complicated analysis but will be more informative for decision making.

4.6 References


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basin, Mumbai, India. *Natural Hazards*, 87(3), 1267–1283. https://doi.org/10.1007/s11069-017-2816-4
CHAPTER FIVE

CONCLUSIONS

This thesis analyzed the impacts of flooding on a transportation network and provided a method to help prioritize resources for adding resilience to the community’s transportation system based on the usage of the road links and trip purposes. The analysis also gives insight on the impact of floods on public transit in the area based on the serviceability of existing bus stops during a flood and suggests the critical locations for public transit routes.

The first part of the research provided a comprehensive synthesis of the variations in road criticality across the un-flooded, flood response, and recovery phases, in the context of a 100-year flood scenario in Anderson County, South Carolina. This study emphasized the importance of identifying roads that retain criticality across all disaster phases. It examined the impacts of flooding on road segments and the resulting rerouting challenges for different transportation purposes.

The analysis involved identification of the flooded areas based on the depth of water above the road surface. Using GIS, the before flood and after flood routes were generated for various trips considering different trip purposes, namely, accessing the hospitals and emergency facilities, schools and universities, workplaces, law enforcement, parks, grocery stores, and evacuation, along with accessibility of raw materials to the companies and export of produced items from those companies. The criticality analysis of the roads was conducted for the mentioned trip purposes and the critical locations of the road, and bridge failure due to flood were also identified for each purpose and were assigned a normalized betweenness centrality metric as the importance value.
There were commonalities in the impact area for transportation purposes. The common roads across all of the disaster phases were also identified with the betweenness centrality value. Maintaining and rebuilding the roads that are common to most of the trip purposes based on the high betweenness centrality value, can provide broader benefit to the community for a given investment level. This analysis contributes to planning for transportation and community resilience and to prioritizing resource allocation focusing on trip purposes along with impacts to public transit.

A few of the key results are as follows:

- The major highways connecting the central business districts to the other regions are critical for either the normal functioning of the community or response and recovery of the disaster.
- The criticality of the roads also depends on the spread of the facilities. More spread results in nearly equal criticality.
- The analysis for parks and grocery stores indicated that the spread and higher number of facilities significantly reduces the additional travel time due to the availability of more choices.
- For public transit the impacts can be such that some bus stops could be unserviceable and the routes non-traversable. The change in routes can be small (gold route) or larger (green and blue route). This study can help identify such potential disruptions beforehand and lead to plans that improve the transit line’s resilience.
• By identifying the blocked locations for each purpose, one can prioritize the locations for recovery actions so that most of the trip purposes benefit.

This overall methodology with consideration of limitations can be replicated to see the impacts of floods on transportation in other communities to aid in making plans and resilience investment decisions.

The second part of the research helped in understanding the impact of the 500-year flood on the economic activity of the community. A company was chosen for the analysis and its accessibility for raw materials import, final products export, and workforce accessibility was analyzed to identify flood impacts. Fault tree diagrams and binary value assignment for the accessibility failure were used in the study. An approach of identifying the ‘k’ number of routes from one point to another was based on the shortest route and then assigning a penalty to the links on previously used paths to determine the next shortest path. Flood barriers were then overlayed with the generated paths to identify the links that are potentially blocked because of the flood. For the study, a company was selected in Anderson County, South Carolina along with the major corridor locations and nearby housing locations for the workforce (13 nearby census block group centroids). The routes were generated for each of the origins and destinations and were analyzed for their accessibility to the company with consideration of the flood barriers. The ‘k’ value for the study was taken as 3, meaning that three alternative routes including the shortest route were analyzed. Using the fault tree and Boolean approach, the failure in accessibility for a company was calculated. Links common across purposes are crucial
for the top event, i.e., “location accessibility failure.” Based on the study, floods can severely impact the accessibility of the company for the above stated three purposes, since the result of the study suggested that the company can be inaccessible for the raw materials import and final products export but will still be accessible for part of the workforce.

Based on both of the studies, in Anderson County, the road SC-28 (link joining SC 24 and US 29 on North side of the company) was found to be critical for both selected industry accessibility for materials and workforce and flood disaster phases. This information can be used by the relevant officials for enhancing strategies for overall community resilience.

Based on the review of literature, it was found that current literature focuses on flood impacts and criticality analysis of one or a few transportation purposes. The change in link importance due to flood across the disaster management phases, was rarely explored before this study. This study helps in identifying if a disaster could potentially disrupt the accessibility of a company making it difficult to carry out the operation causing economic loss to the company and hence to the community.

5.1 Future Directions

The future directions for the study could be to include the traffic information in the analysis. Since all the roads are assumed to be of equal importance in this study, the traffic flow dimension is not depicted in the analysis. Including traffic information such as travel demand can improve the study by capturing users and network topology. It was
found that the threshold values of delay for various transportation purposes have not been researched in abundance. A study which relates the travel time delay with various trip purposes providing the acceptable delay for each purpose discussed in Chapter 3 can be an area to explore. Another topic of research could be the travel behavior in rerouting, since the analysis calculates rerouting by assuming that the travelers at the origin will have *priori* information about the barriers in between their origins and destinations. En-route path switching could be incorporated to capture the travelers who change routes only after encountering barriers. This approach could be particularly useful during the flood, or immediately after it.

In the second study, the value of $k$ could be increased, which might increase the analysis time but can also improve the study. Identifying the workforce housing data along with import and export data for each company in a community can help in providing community-specific accessibility analysis for an entire economic sector. Such analyses could also be performed for all the purposes discussed in chapter 3 (e.g., education). Finally, the fault tree analysis of the transportation network with probability of failure by identifying the dependent and independent failure probability is an interesting extension to the study.