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<tr><td colspan="2">7. Author(s)
Qianwen (Vivian) Guo (https://orcid.org/0000-0003-2180-0368);
Jiaqing Lu (https://orcid.org/0009-0005-2993-0863);
Ziyue Li (https://orcid.org/0009-0004-3677-2886).</td><td>8. Performing Organization Report No.</td></tr>
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Florida State University
2525 Pottsdamer St
Tallahassee, FL 32310</td><td>10. Work Unit No. (TRAIS)</td></tr>
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<tr><td colspan="3">16. Abstract
The functionality of Bridge and Road Infrastructure Networks (BRIN) is indispensable for facilitating the recovery process of low-lying coastal communities in the aftermath of hurricanes. By ensuring the efficient distribution of disaster supplies and providing access to essential services for affected residents, BRIN plays a critical role in restoring normalcy post-disaster. Despite the existence of various optimization methods aimed at expediting post-hurricane recovery, a considerable research gap persists, particularly concerning equity considerations across diverse population groups and geographical regions. In response to this gap, this project endeavors to address the disproportionate impacts of hurricanes on underserved communities, with a specific focus on the densely populated metropolitan area of Greater Miami. The proposed tool represents a novel approach by integrating equity considerations directly into transportation infrastructure restoration decisions. Key tasks encompass the development of a comprehensive flooding map utilizing historical data from the Federal Emergency Management Agency (FEMA), the optimization of restoration models to prioritize equity, and the active engagement of multisector stakeholders in the planning and implementation of recovery efforts. Research activities include understanding the impacts of hurricanes on infrastructure, with a particular emphasis on identifying and mitigating disparities in access and service provision. By prioritizing equity in restoration plans and collaborating closely with local stakeholders, the project aspires to ensure the inclusivity, sustainability, and resilience of transportation infrastructure in the face of natural disasters. Ultimately, the goal is to mitigate the disproportionate impact of hurricanes on underserved communities and foster the development of more equitable and resilient infrastructure systems.</td></tr>
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Equitable Restoration Strategies for Bridge and Road Infrastructure Networks after Hurricanes in Coastal Communities

Final Report

April 2024

Principal Investigator:
Qianwen Guo, Ph.D.
Department of Civil and Environmental Engineering
Florida State University

Graduate Student:
Jiaqing Lu
Department of Civil and Environmental Engineering
Florida State University

Ziyue Li
Department of Civil and Environmental Engineering
Florida State University

Sponsored by
Accelerated Bridge Construction University Transportation Center

A report from
Department of Civil and Environmental Engineering
Florida State University
2525 Pottsdamer St
Tallahassee, FL 32310
Phone: (850)-410-6252 / Fax: (850)-410-6546
https://eng.famu.fsu.edu/cee/people/guo

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CONTENTS

(update table for body, manually add the Appendix Titles and page numbers)

LIST OF FIGURES

LIST OF TABLES

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CHAPTER 1: INTRODUCTION

1.1. Project Motivation

For low-lying coastal communities, hurricane-induced hazards, especially storm surge, often represent the greatest threat. Major hurricanes result in large casualties, enormous property damage, and severe socio-economic disruption. Lifeline infrastructure systems, including roadway networks, are not immune to such devastating consequences of hurricanes. The diminished functionality of roadway networks, because of wind and water damage, directly impedes the entire hurricane recovery process. The essential role of roadway networks in hurricane response is evident: the distribution of disaster supplies from federal and state emergency management agencies depends on functioning roadways; affected residents also need reliable transportation to access essential services, such as healthcare, grocery, and employment. Therefore, it is widely recognized that effective planning for roadway network restoration and associated resource allocation to different regions is a critical task to ensure a rapid recovery of coastal communities in the aftermath of hurricanes.

Given the significance of the post-hurricane recovery of transportation systems to the recovery of many other systems within the community, substantial research efforts have been made to advance the related literature. For instance, various optimization methods have been proposed for selecting, sequencing, and scheduling roadway repair projects, subject to materials and human power constraints. Those methods, once implemented, can significantly reduce the post-hurricane recovery timespan. However, one major research gap remains, which is the lack of consideration of equity across different population groups or over different geographical regions. **It is increasingly important to ensure all residents, regardless of their socio-economic status, should have comparable access to essential services and resources during hurricane recovery.** Unfortunately, several recent studies suggested otherwise, as the government response to natural disasters has been shown largely inequitable: underserved communities tended to receive significantly less support, experienced greater impacts, and thus took much longer to recover. This issue is especially important to the most populated metropolitan area in Florida. Florida experiences significant economic losses from floods, with over $10 billion in losses from 1990 to 2022. Florida has the highest risk for flooding in the United States. The U.S. Census Bureau identifies 68% of the population in Greater Miami is Hispanic, and 16.7% of the population is in poverty, which is 4% higher than the national average. When hurricanes made landfall in Greater Miami, vulnerable populations in underserved communities often faced higher risks of flooding than others because they usually lived at lower elevations, which eventually led to hurricanes' disproportionate impacts on them. As Greater Miami is extremely susceptible to hurricane threats, additional research efforts are urgently needed to ensure bridge and roadway network restoration can be conducted rapidly and equitably.

1.2. Research Objectives, and Tasks

The **primary goal** is to develop a tool to evaluate community resilience in terms of the ability to access critical services following hurricanes and provide a decision-making framework to integrate equity into road network restoration activities after hurricanes. **The specific objectives include**: (1) to develop a flooding map to identify vulnerable roads and bridges; (2) to develop an effective optimization model by integrating equity in the restoration stage of the coastal bridge and roadway networks; (3) to develop multisector stakeholder collaborations to provide optimal recovery sequences. These objectives were accomplished through the following research tasks.

Task 1 – Development of a 2D Flooding Map for Bridges and Roadway Networks

In this task, the FEMA historical data will be used to generate 2D flooding maps to determine the roadway segments that may flood by; and how high floodwaters may get. The 2D flooding inundation map could be developed by the following steps:

a) Identify the study area and define the scope of the mapping project.
b) Collect data on the transportation network, including road and bridge locations, elevations, and characteristics.
c) Gather historical data on previous flooding events and their impacts on the transportation network.
d) Use GIS software to integrate the transportation network data and the natural features data to develop a base map.
e) Overlay the historical flood data on the base map to identify areas that are prone to flooding and to determine the severity and frequency of flooding in the study area.
f) Analyze the collected data to identify vulnerable sections of the transportation network and to determine the potential impacts of flooding on transportation.
g) Develop a flooding map for bridges and roads, highlighting vulnerable areas.

Task 2 – Quantification of Equity for Roadway Networks After Hurricanes

A number of studies have examined both individual-level risk factors and community-level drivers associated with spatial patterns in local transmission of COVID-19 (Andersen et al, 2021). Further, recent research has studied the potential access to health care (e.g., access to ICU beds) both in terms of the accessibility differences between population sub-groups and in terms of differential access among geographic locations (Cromley and Lin, 2022).

This task will investigate new methodologies to accurately assess the equity in transportation network accessibility of populations. A network topology-based resilience measure will be used to assess transportation system performance and assess accessibility to healthcare resources in the aftermath of hurricane-pandemics. A network connectivity metric that considers attributes such as in-vehicle time, waiting time, and service reliability will be used to quantify equity (Kaplan et al., 2014). Other well-known metrics, such as Gini coefficients (De Maio, 2007), will also be considered to express the overall degree of inequality of transit provision. To assess the vulnerability of populations due to lack of access to health care and essential services this task will develop spatial analytical models of demographic characteristics such as prevalence of obesity and heart disease in a population. In particular, a geographically weighted regression (GWR) model will be employed to quantify the spatial distribution of the key demographic variables at various geographic scales (tract, block group) and its relation to the access to transportation facilities (Nicholson et al., 2019). To quantify the temporal relation between COVID-19 infection counts on these demographic variables and understand the drivers of population vulnerability related to transportation access a hierarchical/multilevel regression model (Gelman and Hill, 2006) will be built.

Task 3 –Integration of Equity in Restoration Planning for Roadway Networks

Efficient operation of a transportation system is particularly important in alleviating the impacts of disruptive events, and the repair and reconstruction of transportation infrastructure consumes tremendous material and human power. In particular, under disruptive disasters, which lead to capacity degradation of transportation infrastructure, it is particularly important to devise an equitable restoration plan that minimizes the aftermath impacts during the recovery period.

This task will focus on equity in the restoration stage of a transportation system to provide effective decision-making methodologies. Equitable task restoration is considered one important aspect of resiliency for transportation systems. In order to ensure the equitability of restoration, the proposed research will use a two-stage optimization framework. The first stage of optimization takes the total travel time as the objective function to solve the decision on which road sections of the network will be repaired after the event given a limited budget. In the second stage, the objective function is the unmet demand and the optimization solution for the decision is made to determine if increased capacity is needed on any link. Unmet demand has been proposed as one measure of resilience for freight transportation, but it has not been used for equitable transportation systems. To determine the unmet demand, we will incorporate the vulnerability profiles developed in Task 1. The temporal vulnerability profiles will be used as weights in the connectivity network to formulate the restoration planning optimization. For example, the sub-populations with a large proportion of disabilities will receive higher priority to restore public transportation links, while the sub-regions with chronic diseases such as obesity and heart disease will receive higher priority to restore links to urgent care and hospital facilities. The Bureau of Public Roads function will be adopted as the travel time function in this work (Maerivoet and De Moor, 2000) when data is not available.

Task 4 – Multisector Stakeholder Collaboration and Engagement in Restoration Planning

Multisector stakeholders, including government agencies, private sectors, nongovernmental organizations, academic institutions, and community residents, will be involved in the process of transportation network recovery planning. The social structure of the network and the positions of the stakeholders will be described by the network centrality measure, including degree centrality, eigenvector centrality, and betweenness centrality. This tool will help facilitate more effective and collaborative transportation network restoration planning to provide risk- and resilience-informed decisions.

In this task, social network analysis (SNA) would be used to analyze how multisector stakeholders collaborate and contribute to Bridge and Road Infrastructure Networks Restoration planning. SNA investigates the patterns of social relationships and interactions among actors in a bounded social system, and it is used to address the following research questions:

1. Which sector of stakeholders is the most influential (or the least influential) in Bridge and Road Infrastructure Networks Restoration planning processes?
2. Are there significant differences across different stakeholder sectors in contributing to Bridge and Road Infrastructure Networks Restoration planning?
3. Is the multisector stakeholder collaboration system centralized or decentralized in Bridge and Road Infrastructure Networks Restoration planning?
4. What forms of stakeholder collaboration are more dominant in Bridge and Road Infrastructure Networks Restoration planning?

Task 5 – Final Report

A final report will be prepared meeting the RITA requirements for UTC funded projects. The content of the report will contain a detailed summary of the results from the preceding tasks and a recommendation for future phases of the project, if necessary. The task involves creating the Final Report, and corresponding documentation. The final report will document the research outcomes, including the pilot study results, the software for the proposed framework, and its user manual. All principal investigators and students involved in the project will contribute to producing the final report and deliverables. Additionally, the framework will be made open source, enabling continuous improvement and development by the scientific community.

1.3. Research Advisory Panel

The project work and the developed survey were done in collaboration with the Research Advisory Panel (RAP). The following people participated in the RAP:

a) Edith Wong, State Arterial Management Engineer, Traffic Engineering and Operations Office, Florida Department of Transportation.
b) Javier Rodriguez, P.E., TSM&O Program Engineer, Florida Department of Transportation.
c) Doralice Pupo, FMS/AMS Specialist, Florida Department of Transportation.

1.4. Report Overview

The report will develop equitable restoration strategies for bridge and road infrastructure networks in coastal communities following hurricanes. Research activities will focus on understanding the impact of hurricanes on infrastructure networks, identifying vulnerable communities, developing restoration plans that prioritize equity and accessibility for all community members, and collaborating with local stakeholders to implement these plans, as shown in Figure 1. The project aims to address issues related to the disproportionate impact of natural disasters on marginalized communities and ensure that infrastructure restoration efforts are inclusive and sustainable.

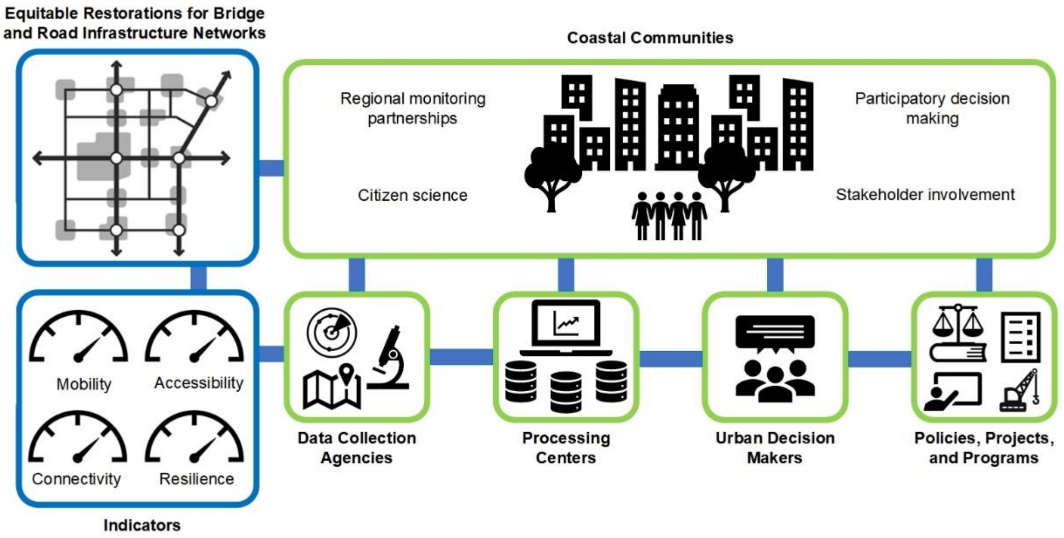


Figure 1. Multisector Stakeholder Collaborations and Engagements

CHAPTER 2. LITERATURE REVIEW

2.1. Methods for Literature Review

Hurricanes, as formidable meteorological phenomena, exert profound impacts on coastal communities worldwide. The consequences of these natural disasters encompass a spectrum of social, economic, and environmental dimensions, triggering extensive research efforts to comprehend their influence and devise effective strategies for mitigation and resilience. In the first task, we aim to develop a 2D Flooding Map for Bridges and Roadway Networks. The initial step in employing the literature review method involves defining the scope and purpose of the review. In the following, we outline the bibliographic databases and keywords used in our literature search. The databases include Science Direct, Transport Research International Documentation (TRID), Ei Compendex, ProQuest Dissertations & Theses, Google Scholar, Scopus, Web of Science, China Science and Technology Journal Database, and cairn.info for sources in Chinese (Mandarin), English, French, German, Polish, Portuguese, Russian and Spanish. In addition to peer-reviewed journals and conference papers, publicly available reports from transit agencies, regional, state, and federal planning organizations, and popular press articles that can be found through Google searches are also included in the review. The search keywords consist of combinations such as resilience paired with either transportation system, transportation network, road and bridge, or road network, alongside one of restoration strategy, recovery, or responsiveness.

Figure 2. Literature search database

With the chosen databases and keywords, the following procedure is used to ensure a systematic literature search. First, we searched in each of the databases mentioned above, such as Google Scholar, with a combination of keywords such as “resilience of transportation system,” “restoration strategy,” and “real-time estimation.” Second, for each relevant study yielded by the database in the first step, we examined its references and included the new studies not identified in the first step; we further used Google Scholar to scan the relevant studies that referenced a paper from the first step. Third, we repeated the above steps until the identified studies through the literature review converged.

Several different journals that published works related to restoration and resilience in a transportation system were included in our literature review. Table 1 lists top 10 journals that contribute the most (e.g. more than two articles) in this literature review. Most of these papers were published on two categories of journals. One category is transportation related journals, among which Transportation Research Record is the most significant source, followed by Transportation research part A. Several mathematical modeling works were published on Computers & Operations Research. The other category is safety science related journals, including Reliability Engineering & System Safety, Safety Science, and Risk Analysis. There are 11 journals which contribute more than two papers in the core set, as listed in Table 1. Among them, Transportation Research Record is the most significant source of articles related to the research on transportation resilience, contributing seven articles alone. Reliability Engineering and Systems Safety, Risk Analysis, Transportation Research-Part A, Transportation Research-Part E, and European Physical Journal B are the followers. Other applications of resilience in transportation are mainly published in Transportation Research-Part B, IEEE Systems Journal, Transport Policy, and Maritime Policy and Management. Theses journals together account for more than half of the reviewed articles. It can be seen from Table 1 that most of these journals have a strong background in research of transportation or risk/safety disciplines.

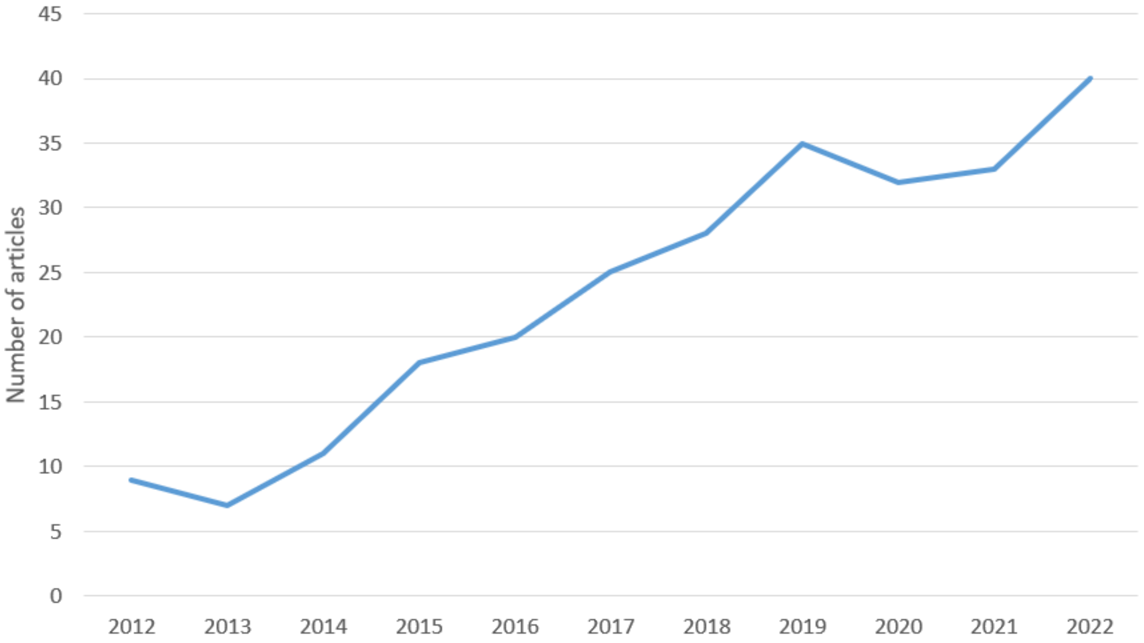


Figure 3. Number of publications per year from 2012-2022

Table 1. Top journal sources of resilience in the transportation field.

No.	Journal title	Articles
1	Transportation Research Record	35
2	Transportation Research-Part A	32
3	Reliability Engineering and Systems Safety	25

4	Risk Analysis	12
5	Transportation Research-Part C	20
6	Transportation Research-Part E	18
7	IEEE Transactions on Intelligent Transportation Systems	16
8	European Physical Journal B	15
9	Transportation Research-Part B	12
10	IEEE Systems Journal	10
11	Transport Policy	8
12	Maritime Policy and Management	7
13	Journal of Infrastructure Systems	7
14	Computer & Operation Research	6
15	Networks & Spatial Economics	5

2.2. Review of Relevant Studies

2.2.1. The influence of hurricanes in coastal communities

The influence of hurricanes on coastal communities has been a subject of extensive research due to the significant impact these natural disasters have on various aspects of social, economic, and environmental systems. This literature review examines key findings and trends in understanding the effects of hurricanes on coastal areas, highlighting their implications for community resilience, disaster preparedness, and policy development. Hurricanes, as powerful meteorological events, bring about destructive winds, heavy rainfall, storm surges, and flooding that can result in extensive damage to infrastructure and housing, loss of lives, disruption of essential services, and long-term socio-economic consequences. Studies consistently emphasize the vulnerability of coastal communities to these impacts, particularly those located in low-lying areas and regions with inadequate infrastructure. Cutter et al. (2003) provides a comprehensive framework for assessing the vulnerability of coastal communities to hurricanes. Their study integrates socio-economic, demographic, and physical factors to create vulnerability indices, revealing the intricate web of factors that shape communities' susceptibility to hurricane impacts. This underscores the need for holistic disaster management approaches that address the interconnected vulnerabilities. In the aftermath of hurricanes, the social fabric of coastal communities undergoes intricate changes. Risk (1994) delve into the social dynamics, highlighting the disproportionate impacts on marginalized groups. They emphasize that vulnerable populations, such as low-income residents and minority communities, face greater challenges in accessing resources and recovering from the aftermath. This insight directs attention to the imperative of equity-driven disaster response strategies. Policy considerations are a critical aspect of managing the influence of hurricanes on coastal communities. Cutter (2006) examines the policy responses following Hurricane Katrina in coastal Mississippi. The study underscores the significance of proactive planning and policy adjustments in minimizing vulnerability and enhancing resilience. Furthermore, Kelman (2011) sheds light on the complex interplay between disasters and politics, illustrating the importance of governance frameworks in disaster management. Advancements in technology have reshaped the landscape of hurricane research. As rising sea surface temperatures potentially amplify hurricane intensity, Mendelsohn et al. (2011) explores the economic consequences of increased hurricane risks. Their research quantifies the potential damages and underscores the need for adaptive strategies that consider climate change implications. In conclusion, the influence of hurricanes in coastal communities encompasses multifaceted dimensions that demand interdisciplinary exploration. The studies discussed here offer a glimpse into the intricate interplay of vulnerability, resilience, policy, and environmental changes in the face of hurricanes. As hurricanes continue to pose significant threats, ongoing research remains essential in devising effective strategies to mitigate their impacts and enhance the resilience of coastal communities. In conclusion, the influence of hurricanes on coastal communities is a complex and multidimensional issue that demands interdisciplinary research and holistic approaches. While significant progress has been made in understanding the impacts and implications, ongoing studies continue to provide insights into effective mitigation and adaptation strategies, community resilience-building efforts, and policy recommendations to reduce the vulnerabilities of coastal communities to hurricanes and other extreme events.

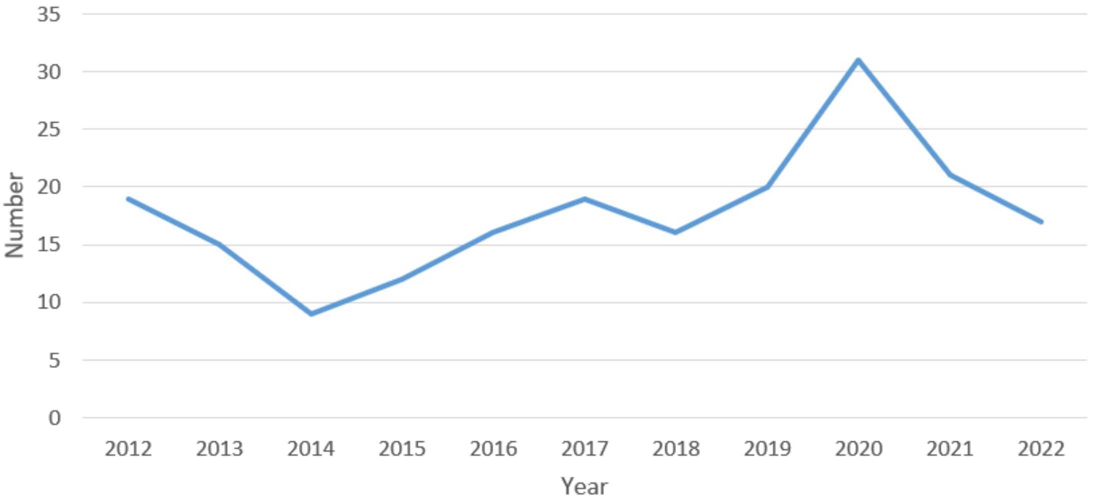


Figure 4. The number of hurricanes from the North Atlantic

2.2.2. Transportation infrastructure/network resilience in hurricane

Hurricanes pose a significant threat to transportation networks, disrupting critical infrastructure and causing substantial economic losses. In recent years, researchers and practitioners have intensified their efforts to enhance the resilience of transportation networks to withstand hurricane impacts (Miller-Hooks et al., 2012). A well-accepted definition of infrastructure system resilience is presented in Bruneau et al. (2003), then it is newly developed by the authors with reference to Enjalbert et al. (2011), Dorbritz (2011), Baroud et al. (2014a), and Shafieezadeh and Ivey Burden

(2014). as illustrated in Figure 6. Faturechi1 and Miller-Hooks (2015) summarized five terms to describe the resilience and its characteristics including: reliability, robustness, flexibility, survivability and vulnerability, which is shown in Figure 5.

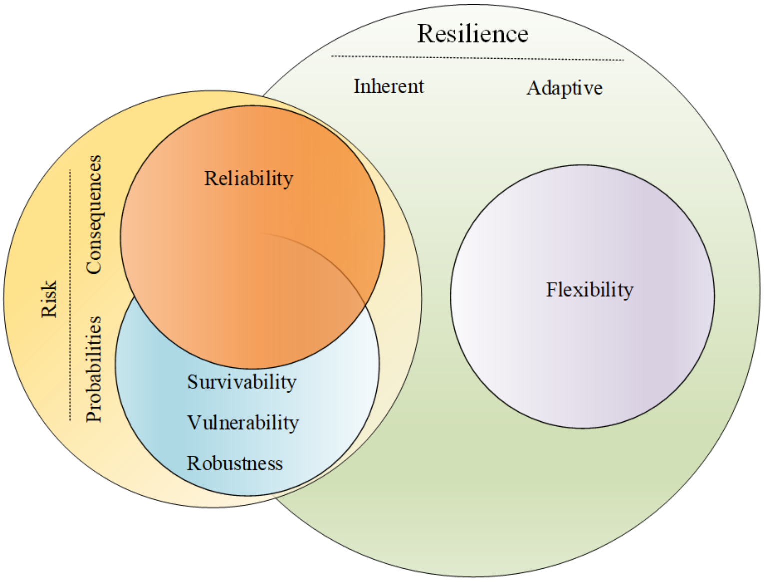


Figure 5. The terms of transportation resilience

2.2.2.1. Reliability

It is generally defined as the probability that a network remains operative given the occurrence of a disruption event (Chen and Miller-Hooks, 2012). It can be either a pre- or post-disruption metric for measuring system performance. The availability of vast amounts of transportation data has led to the development of data-driven approaches for reliability analysis. Machine learning techniques, including deep neural networks, have been applied to predict the vulnerability of transportation infrastructure elements to hurricane-induced hazards, enabling proactive measures to be taken. Enhancing the reliability of transportation networks in hurricane-prone regions involves the implementation of various strategies. These strategies encompass both physical and operational measures. Reinforcing critical infrastructure, such as bridges and roads, to withstand wind and flood forces is a common physical strategy. Additionally, the development of real-time monitoring systems and adaptive traffic management protocols has improved operational resilience. Resilience efforts often focus on the intermodal connectivity of transportation networks. Seamless coordination between different modes of transportation, such as highways, ports, and railways, is essential for maintaining reliable freight and passenger movement during hurricanes. Recognizing the increasing frequency and intensity of hurricanes due to climate change, researchers emphasize the importance of climate adaptation and mitigation strategies. These include floodplain management, coastal protection measures, and sustainable transportation planning to reduce the vulnerability of transportation networks.

2.2.2.2. Robustness

It is the property of being strong, healthy, and hardy. Thus, it is generally defined as the ability to withstand or absorb disturbances and remain intact when exposed to disruptions. One approach to enhancing network robustness is through redundancy and diversification. This involves creating alternative routes and modes of transportation to mitigate the effects of disruptions. Introducing redundancy into critical infrastructure elements, such as bridges and tunnels, can significantly improve network resilience. Robust transportation networks rely on adaptive traffic management systems. These systems use real-time data and predictive analytics to optimize traffic flow during hurricanes. Adaptive traffic signal control, dynamic route guidance, and incident management strategies contribute to efficient and resilient network operations. Robustness is closely linked to intermodal integration. Effective coordination between different transportation modes, such as highways, railways, and ports, ensures the smooth movement of goods and passengers during hurricane events. Integrated planning and investments in intermodal infrastructure facilitate rapid response and recovery. Climate-resilient transportation planning is essential for building robust networks. This involves considering future climate scenarios, sea-level rise, and extreme weather events in infrastructure design and maintenance. Coastal protection measures and sustainable transportation practices contribute to long-term robustness.

2.2.2.3. Flexibility

Flexibility in the context of transportation network resilience refers to the capacity to adapt, reconfigure, and maintain functionality during and after hurricanes. It is the ability of a system to respond to shocks and adjust itself to changes through contingency planning after disruptions. It is also referred to as an ability to reconfigure resources as well as to cope with uncertainties. As such, connotations of flexibility are opposite to that of robustness which emphasizes the ability to endure these changes rather than to adapt to them. Flexibility begins with the design of adaptive infrastructure. Transportation networks can be made more flexible by incorporating features such as modular components, movable barriers, and adaptable roadways. Flexibility is closely linked to intermodal integration, enabling seamless coordination between different transportation modes. Intermodal transportation hubs facilitate the transfer of goods and passengers, allowing for diversions and alternate routes during hurricane events. Investments in intermodal connectivity enhance network flexibility. The integration of real-time decision support systems contributes significantly to flexibility. These systems utilize advanced analytics and modeling to provide decision-makers with timely information for optimizing transportation operations during hurricanes. Dynamic routing, traffic signal control, and evacuation planning benefit from such systems. The flexibility of transportation networks is critical for supply chain resilience. Businesses and logistics providers increasingly rely on agile transportation systems capable of rerouting shipments and adjusting delivery schedules in response to disruptions.

2.2.2.4. Survivability

It is generally defined as the ability to withstand sudden disturbances while meeting original demands. Survivability techniques have been considered as an access to mitigating the vulnerability of a network or system. Building survivable transportation networks begins with designing disaster-resilient infrastructure. This includes constructing bridges, roads, and tunnels with materials and construction techniques that can withstand hurricane forces (Faturechi et al., 2014 and Levenberg et al., 2017). Survivability relies on well-crafted disaster recovery plans. Transportation agencies and authorities must develop comprehensive strategies that outline response procedures, resource allocation, and coordination efforts. Effective planning ensures rapid response and minimizes disruptions to critical infrastructure. Survivability is closely tied to resilient communication systems. Reliable and redundant communication infrastructure, including data networks and emergency alert systems, plays a crucial role in coordinating emergency response efforts during hurricanes. These systems facilitate timely information sharing and decision-making. Survivability extends to multi-modal transportation resilience. Coordinating different transportation modes, including highways, railways, and ports, ensures the continued movement of goods and passengers during hurricane events. Integrated planning and investments in multi-modal connectivity enhance network survivability.

2.2.2.5. Vulnerability

It is defined as the susceptibility to damage or perturbation, especially where small damage or perturbation leads to disproportionate consequences. It is also regarded as the property of a transportation system which may weaken or constrain its ability to endure, handle, and survive threats and disruptive events that originated both within and outside the system boundaries. Researchers have proposed a range of vulnerability indicators, including infrastructure exposure, population density in vulnerable zones, and evacuation capacity, to evaluate network susceptibility to hurricanes, which help prioritize mitigation efforts. Addressing vulnerability begins with the development of climate-resilient infrastructure. Transportation networks can be made less vulnerable to hurricanes through the use of robust materials, improved construction techniques, and fortified structures. Innovations like elevated roadways, flood-resistant barriers, and strengthened bridges enhance resilience. Mitigating vulnerability requires comprehensive risk reduction strategies. Transportation agencies and authorities must adopt measures such as early warning systems, evacuation planning, and improved drainage to reduce the impacts of hurricanes. Risk reduction efforts aim to minimize damage and protect critical transportation assets. Vulnerability extends beyond physical infrastructure to include social and community factors. Engaging communities in disaster preparedness, awareness, and response plans is essential. Effective communication, education, and outreach initiatives empower residents and enhance resilience. Vulnerability considerations must be integrated into transportation planning. Resilience-oriented planning involves evaluating and prioritizing projects that reduce vulnerability, enhance evacuation routes, and ensure rapid recovery. Investment in resilient transportation infrastructure is critical.

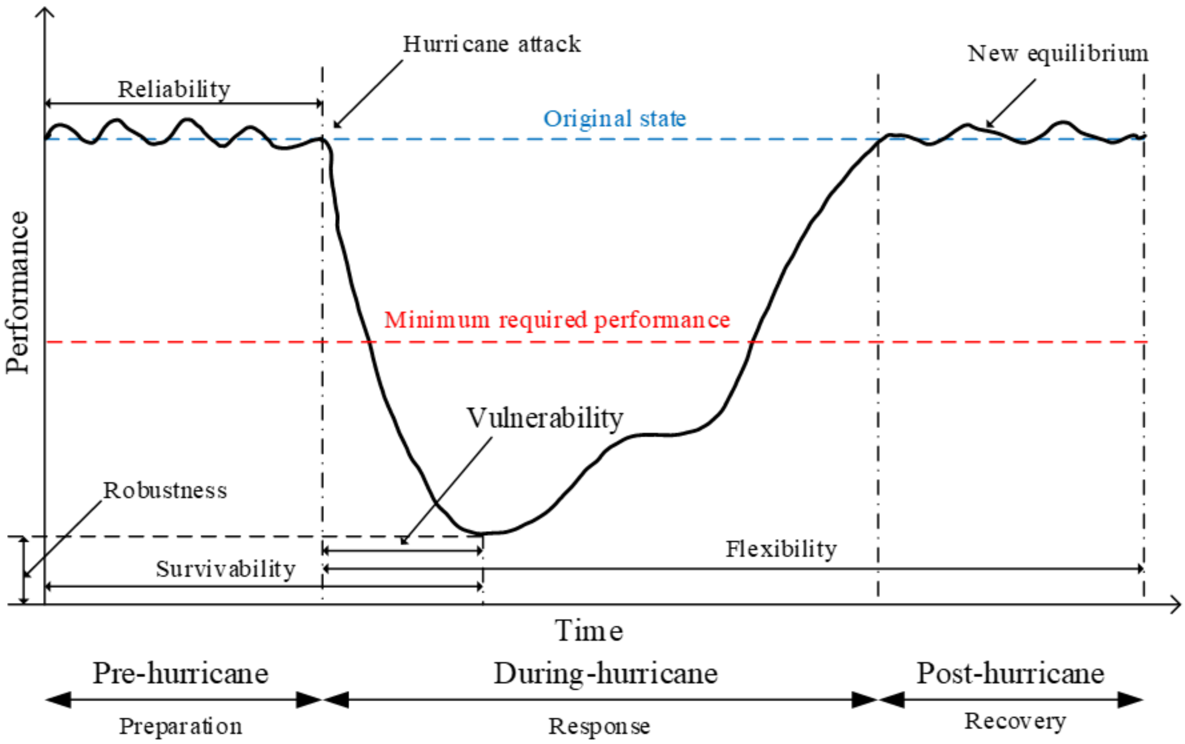


Figure 6. Conceptual definition of resilience of transportation

2.2.3. Transportation network restoration strategy after hurricanes

Transportation networks are among the most critical infrastructures that require particular attention after extreme events which is shown Figure 7. The quality of emergency response, evacuation process, and restoration of other lifelines are directly affected by the functionality of transportation networks. The damage of transportation networks is predominately concentrated on the bridges, as they are the most vulnerable components of these networks. Transportation networks play a vital role in ensuring the economic and social well-being of a community and the condition of such networks following the occurrence of an extreme hazard (e.g. earthquake, extreme windstorms, flood, terrorism, etc.) has a significant impact on the recovery of the community. Highway bridges are vulnerable components in road transportation system, and robustness and recovery of the transportation network as a whole highly depends on their performance.

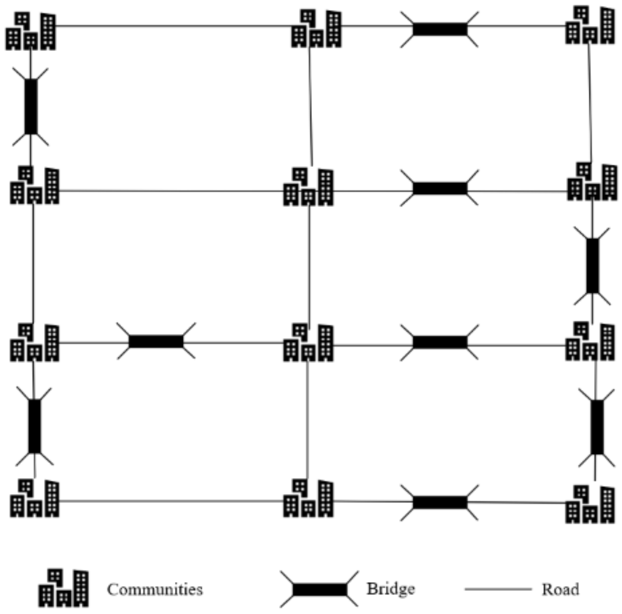


Figure 7. Layout of transportation network

Large-scale hazards can simultaneously damage numerous bridges within transportation systems, leading to both direct and indirect economic losses. Direct losses stem from structural damage, while indirect losses arise from network downtime before full recovery (Bruneau et al., 2003). Shinozuka and Chang (2004) examine restoration schedules for bridge-road transportation networks aimed at minimizing recovery time and optimizing recovery trajectories to reduce indirect economic losses. Various researchers have contributed to exploring transportation network resilience and bridge recovery strategies post-extreme events. Their work includes assessing road network performance (Cimellaro et al., 2011 and Bocchini and Frangopol, 2012a), evaluating seismic resilience (Deco et al., 2013), developing optimal retrofit strategies (Chang et al., 2012), and proposing techniques for intervention scheduling (Bocchini and Frangopol, 2012b). Analyses of hurricane impacts underscore the importance of rapid assessment and prioritization of damaged infrastructure, highlighting collaboration between government agencies and stakeholders (Franchin et al., 2006). Their research emphasizes the significance of transit service restoration in maintaining mobility for residents. The study highlights the need for flexible scheduling and coordination among transit agencies. In conclusion, the restoration of transportation networks after hurricanes is a multidimensional challenge that demands innovative strategies. The studies highlighted in this review provide insights into prioritization, technology integration, policy considerations, and adaptive approaches to restoration. As hurricanes continue to impact communities, ongoing research in this realm is pivotal for bolstering network resilience and ensuring swift recovery.

CHAPTER 3. DEVELOPMENT OF A 2D FLOODING MAP

This chapter provides an overview of Miami-Dade County's geographical location, situated on the southeastern coast of Florida, highlighting its susceptibility to flooding and other natural hazards due to its proximity to the Atlantic Ocean. It examines the county's diverse landscape, encompassing coastal plains and urban areas, and discusses the implications of its geography on infrastructure resilience. Additionally, the chapter presents flooding data sourced from the Federal Emergency Management Agency (FEMA), offering insights into historical flood patterns and vulnerability hotspots within the county. Furthermore, the chapter outlines the methodology for utilizing Geographic Information Systems (GIS) to assess flooding risk and its impact on the transportation network. Through spatial analysis techniques, including elevation mapping, proximity analysis, and floodplain modeling, GIS enables the identification of vulnerable transportation infrastructure segments and informs decision-making processes for mitigation and emergency response planning. The chapter also discusses the integration of GIS data with transportation network modeling to enhance resilience and adaptability to flooding events. Lastly, demographic data and figures related to Miami-Dade County's population characteristics, socioeconomic factors, and accessibility metrics will be addressed in Chapter 4, Socioeconomic Characteristics and Accessibility Quantifications, providing a comprehensive examination of the social and economic dimensions of transportation infrastructure resilience.

3.1. Miami-Dade County Flood Risk

Miami-Dade County, located on the southeastern coast of Florida, encompasses a diverse landscape ranging from coastal plains to urban areas in Figure 8. Its proximity to the Atlantic Ocean makes it vulnerable to the impacts of hurricanes and flooding events. According to data from the Federal Emergency Management Agency (FEMA), the county has experienced recurrent flooding, particularly in low-lying areas and along its extensive network of roads and bridges. Utilizing Geographic Information Systems (GIS), flooding risk can be accurately assessed and assigned to specific segments of the transportation network. By integrating data on elevation, proximity to water bodies, and historical flood patterns, GIS enables the identification of vulnerable areas and the visualization of potential impacts on transportation infrastructure. This spatial analysis facilitates informed decision-making regarding infrastructure resilience and emergency response planning.

Figure 8. Coastal zone of Miami-Dade County

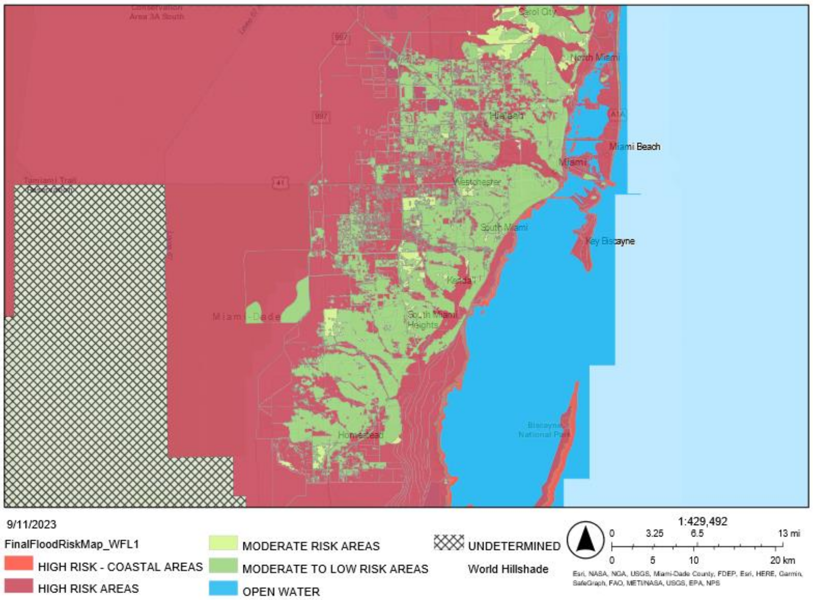


Figure 9. Flood risk of Miami-Dade County

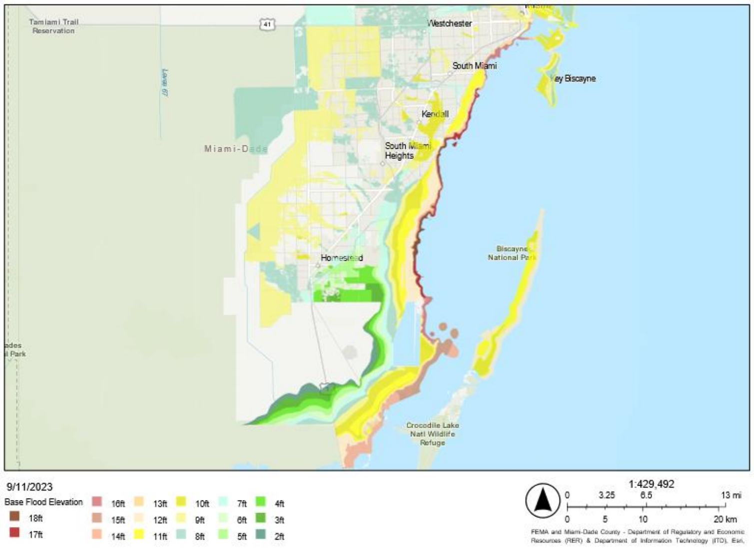


Figure 10. Flood elevation of Miami-Dade County

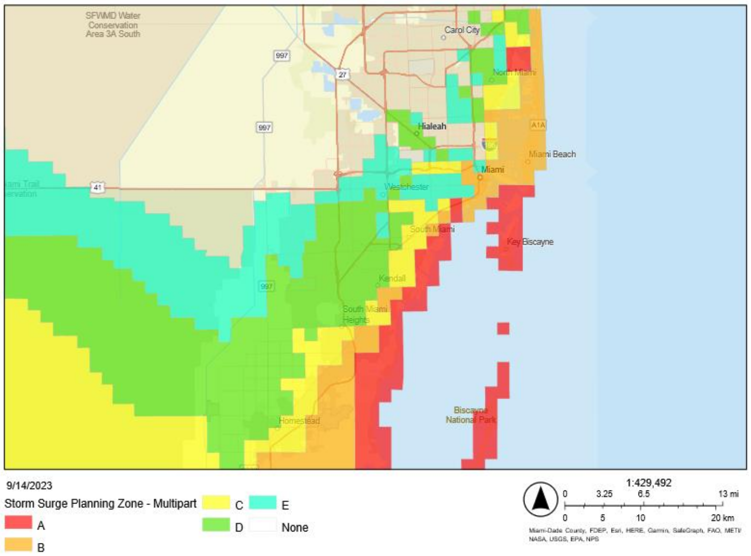


Figure 11. Storm surge zone of Miami-Dade County

3.2. Study Area

To showcase the proposed equitable restoration planning model outlined in Chapter 5, Miami Shores has been chosen as the ideal small-scale study area. This decision is primarily driven by the constraints of computing resources. Miami Shores is situated along the eastern edge of Florida, adjacent to Biscayne Bay. Its proximity to the coast makes it vulnerable to various types of flooding, including coastal and tidal flooding. In the hurricane season, Miami Shores is in a region prone to hurricanes and tropical storms, especially during the hurricane season from June to November. These weather events can bring heavy rainfall, storm surges, and high winds, leading to coastal and inland flooding. The combination of heavy rain and storm surge can result in significant flooding in low-lying areas of the community. Miami Shores, like many coastal areas in Florida, faces the long-term threat of sea-level rise due to climate change. Rising sea levels can exacerbate the impacts of coastal flooding, making the area more susceptible to high-tide flooding, even during non-storm periods. The community's ability to manage stormwater drainage is essential in preventing flooding. Inadequate drainage systems or clogged stormwater infrastructure can lead to localized flooding, especially during heavy rain events. Flooding can have economic consequences for Miami Shores. Businesses may experience disruptions, and property values can decline in flood-prone areas. Additionally, flood-related repairs and infrastructure improvements can be costly for local governments. Miami Shores, like many coastal communities, has taken steps to enhance its resilience to flooding. This may include improved stormwater management, elevation of structures, and infrastructure upgrades to better withstand flooding events. In summary, flooding is a significant concern for Miami Shores due to its coastal location, vulnerability to hurricanes, and the ongoing challenge of sea-level rise. Mitigation and adaptation efforts are crucial to minimizing the impact of flooding on the community and ensuring its long-term resilience.

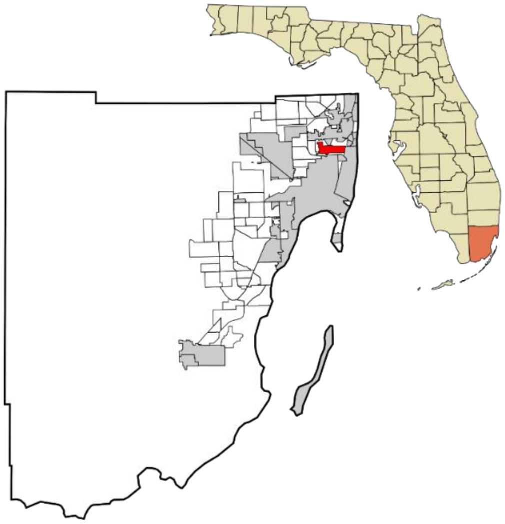


Figure 12. The location of Miami Shores

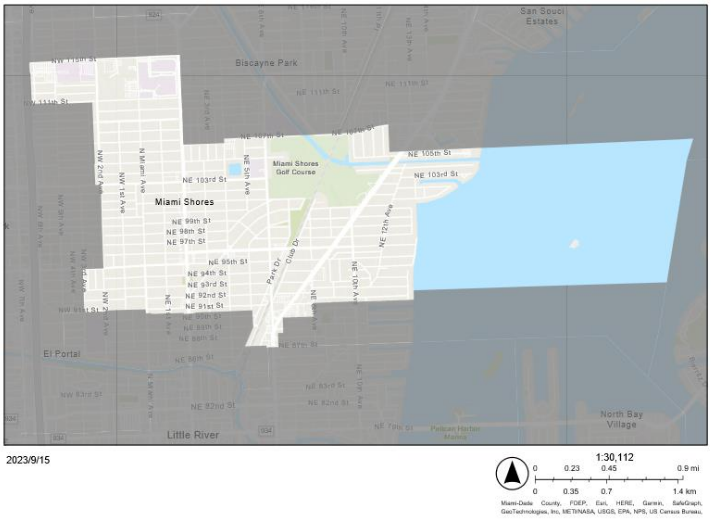


Figure 13. The area of Miami shores

3.3. Transportation Network Data

Transportation Network Data in Miami-Dade County incorporates the Federal Functional Classification System (FUNCLASS) to categorize and analyze the road network within the county. FUNCLASS assigns roads into different classes based on their functional roles and importance in the transportation system. This classification system helps in understanding the hierarchy and characteristics of roads, including their design, capacity, and traffic volume. In Miami-Dade, the transportation network data enriched with FUNCLASS classifications provides valuable insights into the county's road infrastructure. It allows transportation planners and policymakers to assess the distribution of road types, identify primary corridors such as Interstates, arterials, collectors, and local streets, and understand their respective functions. This information is crucial for optimizing transportation planning, prioritizing infrastructure investments, and improving overall mobility and accessibility within the county.

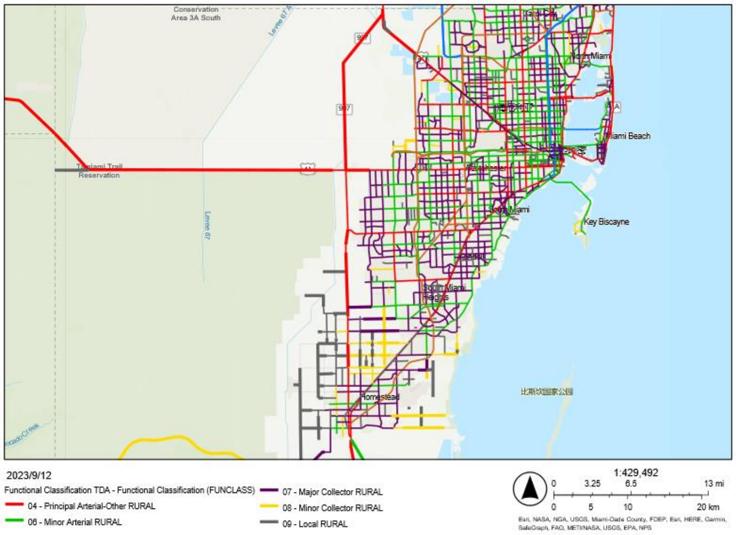


Figure 14. Transportation network of Miami-Dade County

The Miami-Dade Annual Average Daily Traffic (AADT) data provides valuable insights into the volume of traffic on roads within Miami-Dade County on an average day throughout the year, which shown in Figure 15. This dataset offers detailed information about the number of vehicles that traverse various road segments, including highways, arterial roads, and local streets, over a span of 24 hours. By analyzing the AADT data, transportation planners, engineers, and policymakers gain a comprehensive understanding of traffic patterns, congestion levels, and usage trends within Miami-Dade County. This information is essential for infrastructure planning, road maintenance scheduling, traffic management strategies, and safety improvement initiatives. Additionally, the Miami-Dade AADT dataset serves as a critical input for transportation modeling, urban development planning, and investment prioritization in transportation projects. Overall, the AADT data for Miami-Dade County is a valuable resource that supports informed decision-making and facilitates the development of efficient, safe, and sustainable transportation systems within the region.

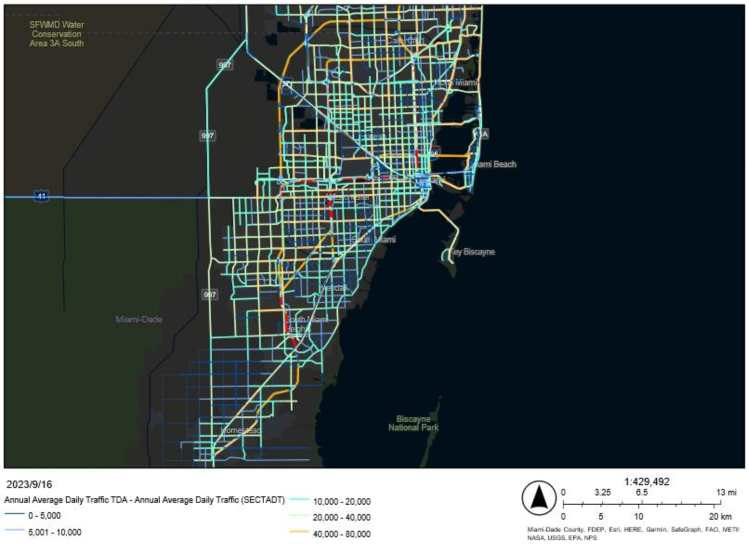


Figure 15. AADT of Miami

This major north-south highway runs through Miami Shores and provides easy access to downtown Miami and other nearby areas. A key north-south road in Miami Shores, it connects the community to neighboring areas and offers access to local businesses and residences. Another important north-south road that provides access to Miami Shores and nearby communities. This east-west road is a major thoroughfare in the area and connects Miami Shores to the nearby city of North Miami. Although not within Miami Shores itself, I-95 is a major interstate highway that runs nearby and provides convenient access to the rest of Miami-Dade County and beyond.

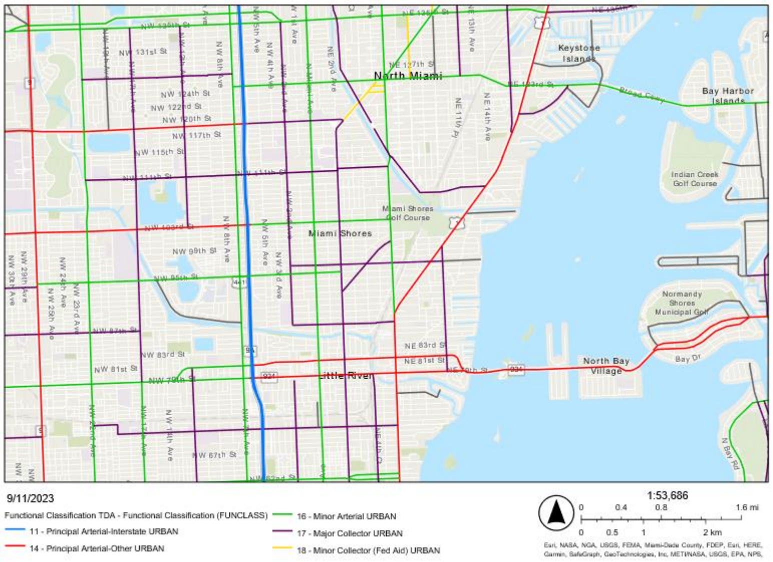


Figure 16. The transportation network of Miami Shores

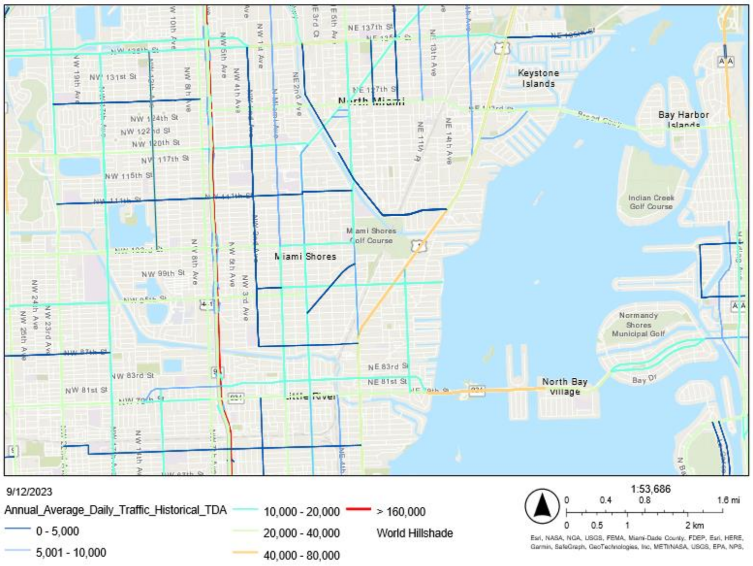


Figure 17. AADT of Miami Shores

3.4. FEMA Historical Data

The Federal Emergency Management Agency (FEMA) periodically updates flood maps, including those for Miami-Dade County. The flood zone designations in Miami-Dade County's Digital Flood Insurance Rate Maps (DFIRMs) are crucial for understanding flood risk levels and informing insurance requirements and mitigation efforts.

a) ZONE AE (Moderate to High Flooding Risk): This zone corresponds to flood depths greater than three feet and mandates the purchase of flood insurance. It signifies areas with a moderate to high risk of flooding.
b) ZONE AH (Moderate to High Flooding Risk): These areas have a 1% annual chance of shallow flooding with an average depth ranging from 1 to 3 feet. Base flood elevations are

provided at selected intervals within these zones, and flood insurance purchase is mandatory.

c) ZONE AO (Sheet Flow): This zone indicates areas with a 1% or greater chance of shallow flooding, typically from sheet flow, with an average depth ranging from 1 to 3 feet. Mandatory flood insurance purchase requirements apply.
d) ZONE VE (High Flooding Risk): This zone corresponds to coastal areas with additional hazards associated with storm waves. There is at least a one-in-four chance of flooding during a 30-year mortgage, and flood insurance requirements are mandatory.
e) Zone A (unnumbered) (High Flooding Risk): Detailed flood hazard analyses are not conducted for these areas, but there is at least a one-in-four chance of flooding during a 30-year mortgage. Mandatory flood insurance requirements also apply.
f) Zone D: These areas have possible but undetermined flood hazards, with no flood hazard analysis conducted. Flood insurance rates are adjusted according to the uncertainty of flood risk.

In Miami-Dade County, most Zone D areas are within Everglades National Park. Moderate-to-low-risk areas, labeled with the letter X (or a shaded X) on flood maps, have reduced but not eliminated flood risk. While flood insurance isn't federally required in these areas, it's recommended for all property owners and renters to mitigate potential financial losses from flooding events. These flood zone designations play a critical role in risk management and resilience planning efforts within the county.

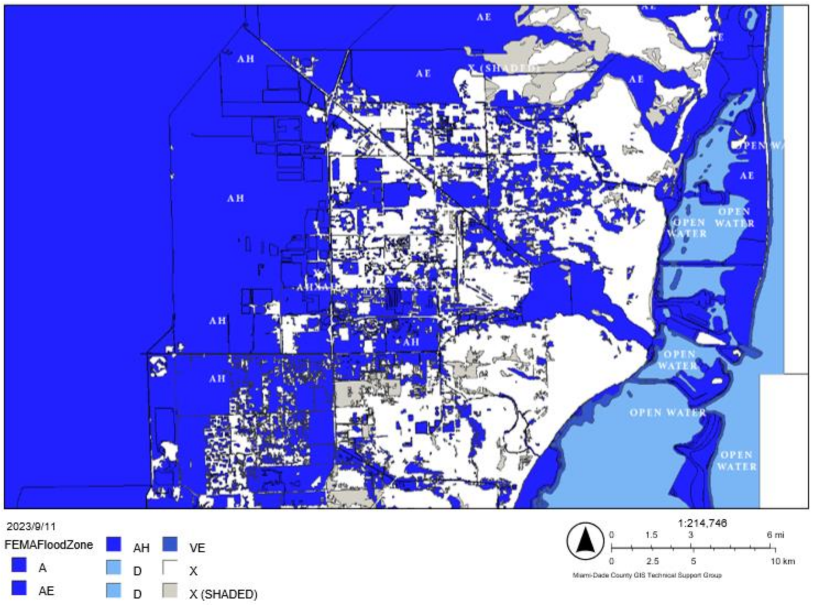


Figure 18. FEMA flood zone in Miami

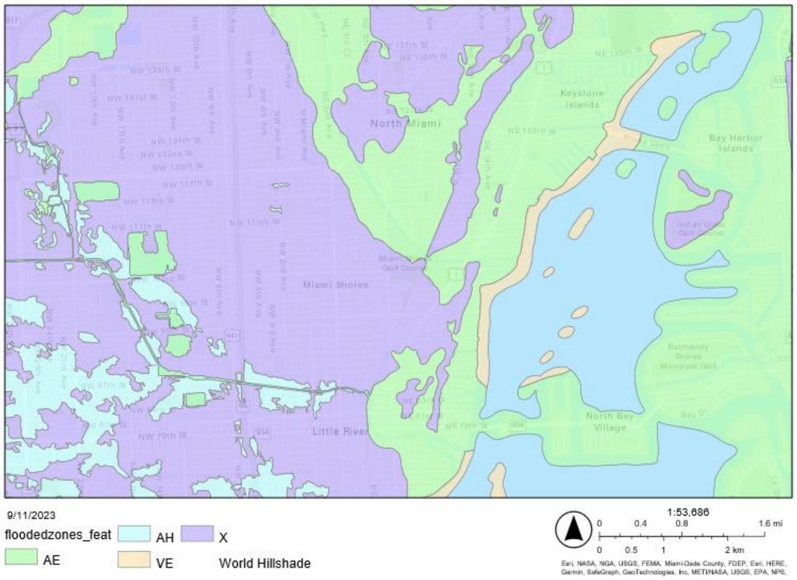
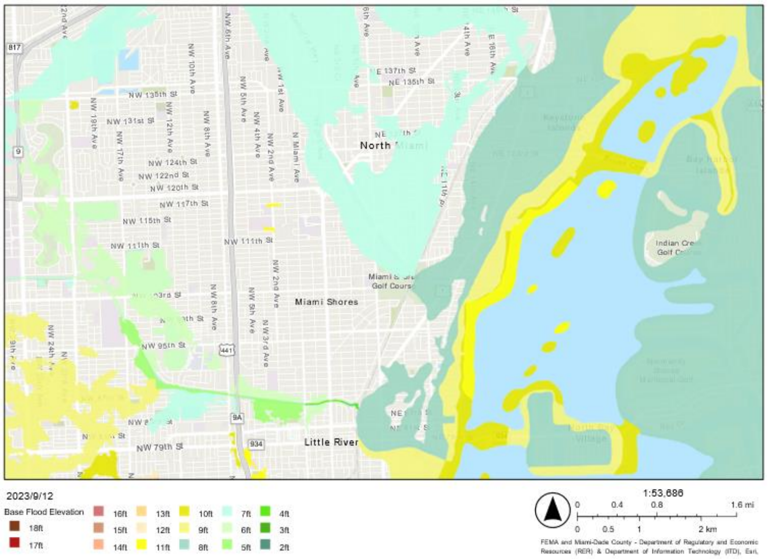


Figure 19. FEMA flood zone in Miami Shores

These zones are used by the Federal Emergency Management Agency (FEMA) to designate the Special Flood Hazard Area (SFHA) and for insurance rating purposes. These data are the flood hazard areas that are or will be depicted on the Flood Insurance Rate Map (FIRM). There is one polygon for each contiguous flood zone designated. This information is required for all draft Digital Flood Insurance Rate Maps. The Digital Flood Insurance Rate Map (DFIRM) Database depicts flood risk information and supporting data used to develop the risk data. The primary risk classifications used are the 1-percent-annual-chance flood event (100 year), the 0.2-percent-annual-chance flood event (500 year), and areas of minimal flood risk. The DFIRM Database is derived from Flood Insurance Studies (FISs), previously published Flood Insurance Rate Maps (FIRMs), flood hazard analyses performed in support of the FISs and FIRMs, and new mapping data, where available. The FISs and FIRMs are published by FEMA.

3.5. GIS Layers

The FEMA is a reputable and reliable source for obtaining flood maps and related data. FEMA's flood maps, available through the National Flood Hazard Layer (NFHL) and the FEMA Flood Map Service Center (MSC), are considered one of the most authoritative and comprehensive sources of flood hazard information in the United States. Therefore, the FEMA historical data will be used to generate 2D flooding maps to determine the roadway segments that may flood by; and how high floodwaters may get.



FEMA and Miami-Dade County - Department of Regulatory and Economic Resources (RER) & Department of Information Technology (ITD), Esri,

Figure 20. The flood depth in Miami Shores

3.6. Flooding Map

In our analysis, we utilized the comprehensive historical flood data provided by FEMA to create detailed 2D flooding maps. These maps serve as invaluable tools for identifying vulnerable sections of both the bridge and road network within Miami-Dade County. By integrating the spatial data of the Miami-Dade County road network with the FEMA flood zone data, we conducted a thorough analysis using the spatial join tool in ArcGIS Pro. This powerful tool allowed us to overlay and intersect the two datasets, enabling us to precisely delineate the road network segments that fall within different flood risk zones. The process involved categorizing the flood risk into three distinct levels: high impact, medium impact, and low impact. This categorization was based on the severity of flooding anticipated in each zone, taking into account factors such as historical flood patterns, elevation data, and proximity to water bodies. By categorizing the flood risk in this manner, we were able to effectively prioritize areas for mitigation and response efforts, allocating resources where they are most urgently needed. The resulting flooding maps provide a comprehensive visual representation of the areas susceptible to flooding within Miami-Dade County. They highlight which road segments are at risk of inundation during flood events, as well as the potential extent of floodwaters in each zone. This information is invaluable for emergency planners, infrastructure managers, and policymakers, as it allows them to make informed decisions regarding flood preparedness, evacuation routes, and infrastructure investments. The development of these flooding maps represents a significant step forward in understanding and mitigating the impact of flooding within Miami-Dade County. By identifying vulnerable road network segments and assessing flood risk levels, we can better protect our communities, enhance resilience to natural hazards, and ensure the safety and well-being of residents and infrastructure assets.

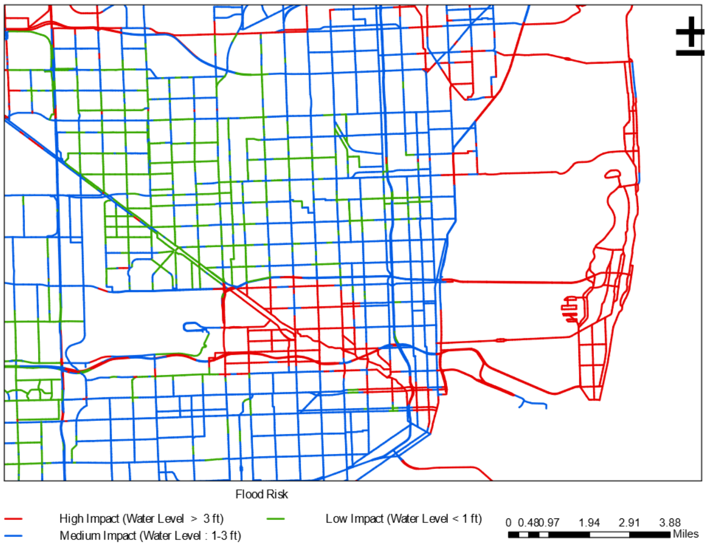


Figure 21. The vulnerable transportation network

3.7. Summary

This chapter focuses on the development of a 2D flooding map, providing an in-depth exploration of Miami-Dade County’s geographical characteristics and its vulnerability to flooding and natural hazards. It discusses the diverse landscape of the county, emphasizing its susceptibility to flooding due to its coastal location. The chapter examines flooding data sourced from FEMA, highlighting historical flood patterns and vulnerability hotspots within the county. Additionally, it outlines the methodology for utilizing Geographic Information Systems (GIS) to assess flooding risk and its impact on the transportation network. By integrating FEMA historical data with GIS technology, the chapter facilitates the generation of 2D flooding maps, enabling the identification of vulnerable road network segments and informing flood risk categorization. Through a case study on Miami Shores, the chapter underscores the ongoing challenges posed by sea-level rise and storm events, emphasizing the importance of data-driven approaches for enhancing community resilience to natural hazards.

CHAPTER 4. QUANTIFICATION OF ACCESSIBILITY

This chapter focuses on the topic of accessibility to essential services in Miami, in particular critical facilities such as hospitals, grocery stores, and hurricane shelters. It explores the roles these facilities play during emergencies, particularly hurricanes, and analyzes their spatial distribution across the city. Using advanced geospatial analysis techniques with ArcGIS Pro, the chapter examines accessibility patterns and presents findings on the correlation between service facility quantity and accessibility, spatial imbalances, and the impact of natural disasters on accessibility. Through detailed descriptions and visual representations like isochrone maps, the chapter offers insights into residents' access to essential services within specific time intervals and highlights areas with varying levels of accessibility. Ultimately, the chapter underscores the significance of these findings for urban planning, emergency management, and infrastructure development in Miami, emphasizing the importance of equitable access to essential services for community resilience and emergency preparedness.

4.1. Demographic Data in Miami-Dade County

The demographic data in Miami-Dade County are shown in Figure 22-29. In Miami-Dade County, areas with a higher concentration of persons over 65 years old may face unique challenges related to accessibility to essential services such as healthcare facilities, senior centers, and transportation options. Understanding the distribution of the elderly population helps identify areas where targeted services and infrastructure improvements may be needed to support the aging population's needs effectively. High poverty population density areas in Miami-Dade County often experience limited accessibility to essential services such as healthcare, education, and employment opportunities. These communities may require interventions such as affordable housing programs, food assistance initiatives, and job training programs to improve residents' quality of life and socio-economic well-being. Variations in white population density across Miami-Dade County can influence the accessibility and availability of essential services in different neighborhoods. Areas with higher white population density may have better access to amenities such as grocery stores, schools, and recreational facilities compared to areas with lower density. Addressing disparities in service provision is essential for promoting equitable access to resources and opportunities for all residents. The distribution of black population density in Miami-Dade County can impact the accessibility of essential services for African American communities. Historically marginalized neighborhoods with higher black population density may face barriers to accessing quality healthcare, educational resources, and economic opportunities. Efforts to improve accessibility must prioritize addressing systemic inequalities and promoting community development initiatives that uplift underserved populations. Areas with higher Asian population density in Miami-Dade County may benefit from cultural competency initiatives and language-accessible services to enhance accessibility to essential resources. Community centers, language interpretation services, and culturally sensitive healthcare facilities can help meet the diverse needs of Asian residents and foster a more inclusive and supportive environment. While American Indian and Alaska Native populations may be smaller in Miami-Dade County, ensuring their accessibility to essential services is crucial for promoting equity and social inclusion. Collaborative efforts between tribal organizations, local governments, and community stakeholders can help identify and address barriers to accessing healthcare, education, and cultural resources for Indigenous communities. Understanding the intersection of demographic characteristics and accessibility to essential services is essential for promoting equitable development and improving residents' overall well-being in Miami-Dade County. By identifying areas with disparities in service provision and implementing targeted interventions, policymakers and community leaders can work towards creating more inclusive and resilient communities for all residents.

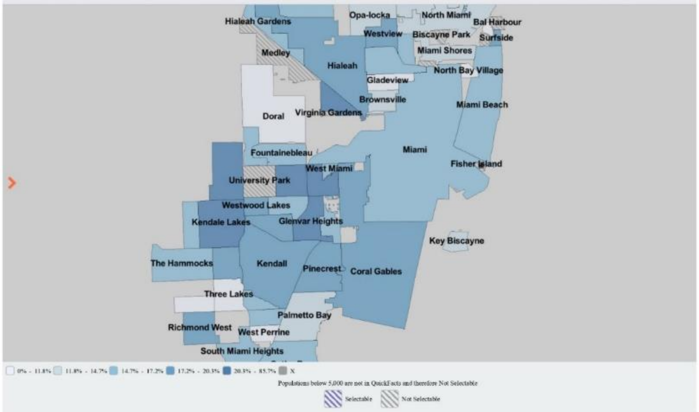


Figure 22. Persons over aged 65 years and older in Miami-Dade County

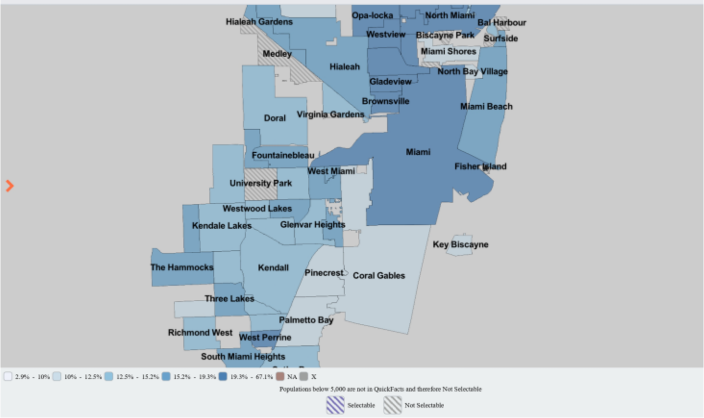


Figure 23. Poverty population density in Miami-Dade County

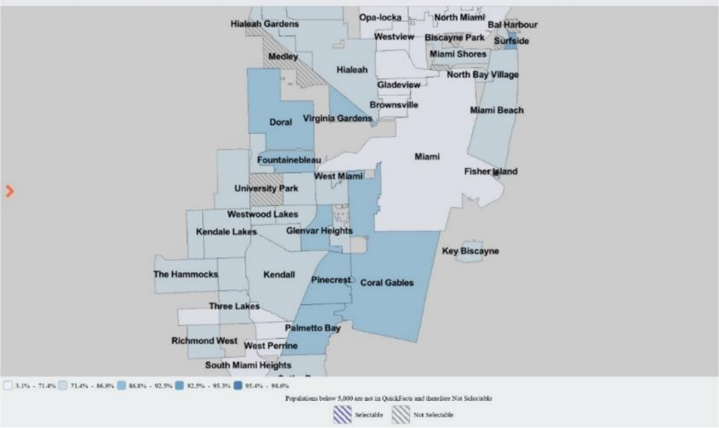


Figure 24. White population density in Miami-Dade County

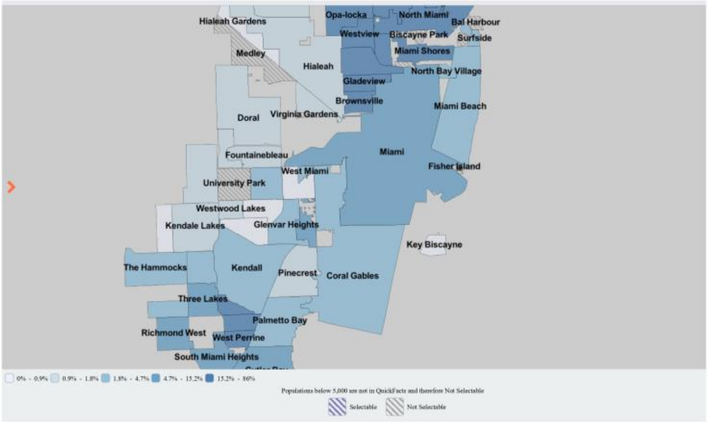


Figure 25. Black population density in Miami-Dade County

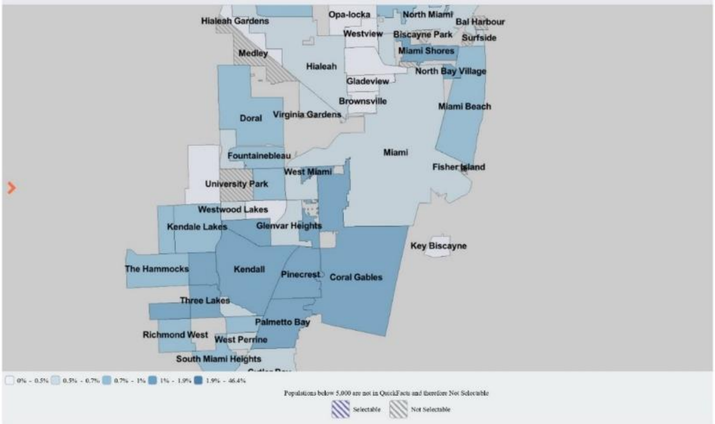


Figure 26. Asian population density in Miami-Dade County

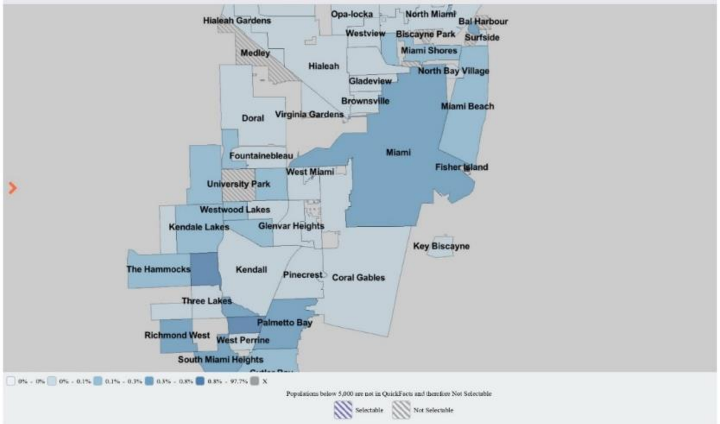


Figure 27. American Indian and Alaska native density in Miami-Dade County

4.2. Definition of Essential Service

Hospitals and medical facilities play a vital role during hurricanes, offering essential medical treatment, surgeries, and emergency care to individuals affected by injuries or illnesses. Equipped with specialized equipment and staff, they can handle surges in patients and address various health needs that arise during disasters. Alongside, police stations and law enforcement agencies ensure public safety, enforce laws, and respond to emergencies, including managing evacuation routes and maintaining order. Additionally, hurricane shelters provide refuge and protection from severe weather, offering basic amenities for evacuees. Together, these organizations form a critical network of support, safeguarding communities during and after hurricanes. The purpose of this map is to provide useful geolocation information to the citizens of Miami-Dade County in case of natural disasters such as hurricane and flood. This map indicates the primary evacuation routes, the locations of hurricane shelters and the locations of evacuation bus pickup points to these shelters. Locations and contact information of hospitals and police stations are provided for emergency support.

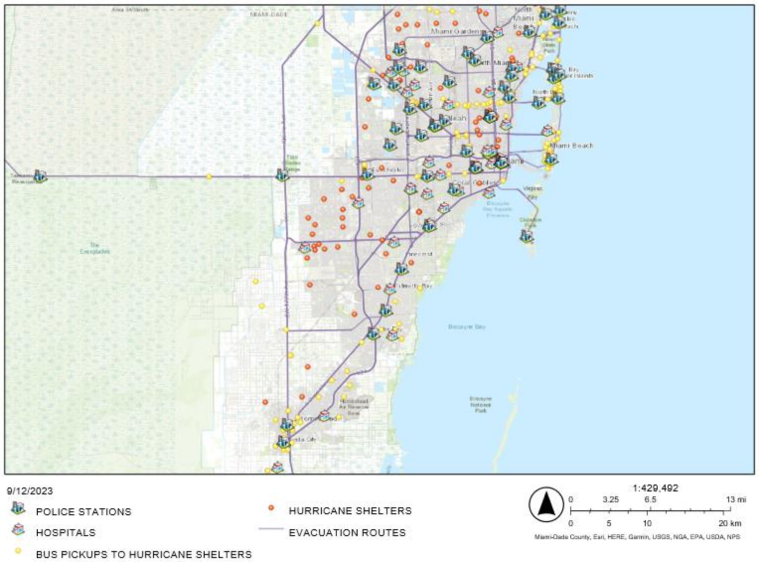


Figure 28. Hurricane shelter in Miami-Dade County

Gas stations are crucial facilities during hurricanes, dispensing gasoline, diesel, and other fuels for vehicles, generators, and machinery. They play a vital role in refueling emergency vehicles, transporting supplies, and powering generators to maintain critical services like electricity and transportation. Fire stations, on the other hand, serve as hubs for firefighters, equipment, and vehicles used to respond to fires, emergencies, and other incidents. During hurricanes, they provide essential rescue services, extinguish fires, conduct search and rescue operations, and assist with medical emergencies. Additionally, grocery and drug stores are indispensable retail establishments selling food, beverages, household goods, and other essential items. They ensure access to vital supplies like non-perishable food, bottled water, batteries, and first aid kits for residents preparing for the storm or needing emergency provisions during and after the disaster. Together, these facilities and services form the backbone of resilience and recovery efforts in communities affected by hurricanes.

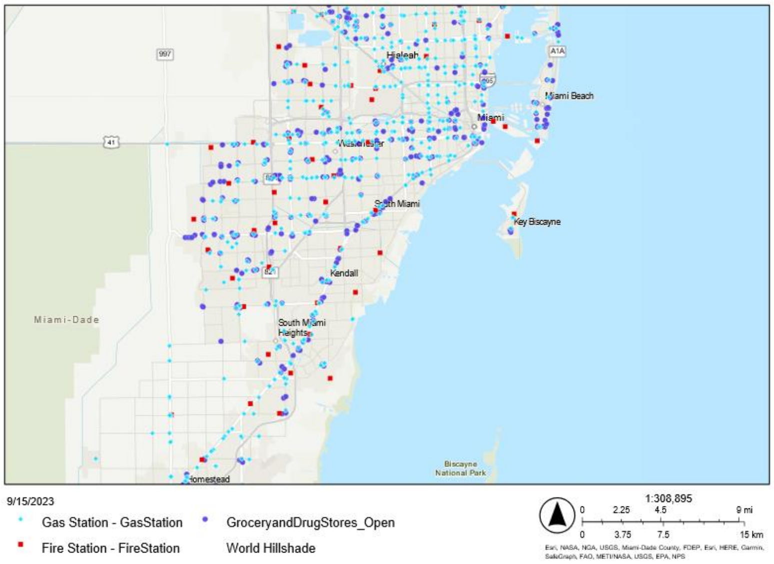


Figure 29. Grocery, gas, fire stations in Miami-Dade County

This map demonstrates the population living in different areas at Miami. It shows the vulnerability of different social communities facing the hurricanes.

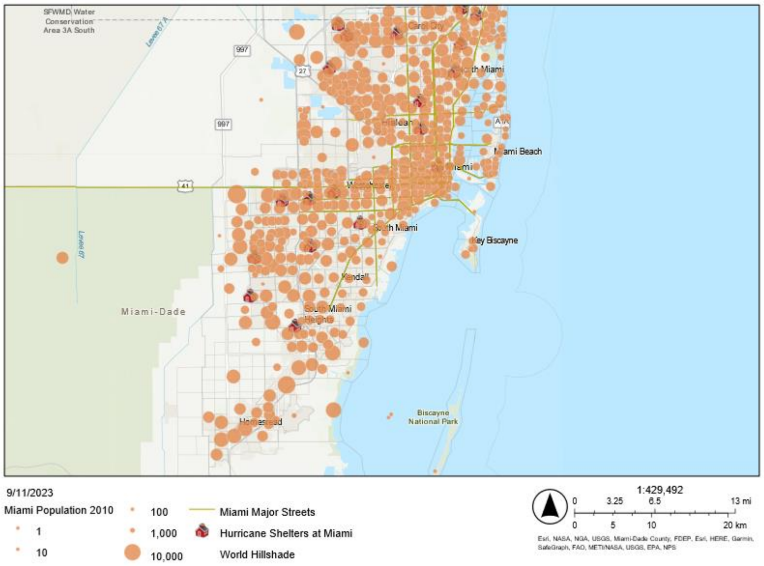


Figure 30. The population density and hurricane shelters

4.3. Quantification Methods of Accessibility

The process of Service Area Calculation in ArcGIS Pro involves several key stages, starting with the definition of analysis parameters such as origin locations, impedance type, and cutoff values. Once parameters are set, the network dataset containing road network topology and attributes is prepared, ensuring proper configuration and connectivity. Next, service areas are computed using algorithms like Dijkstra's algorithm, accumulating costs from origin locations until reaching the defined impedance cutoff. Generated isochrones represent areas reachable within specified time or distance intervals, visualized on the map along with other spatial datasets for context. Interpretation of analysis results helps understand spatial accessibility patterns and identify areas within specified service radius or travel parameters. These insights inform decision-making processes, such as site selection or emergency response planning, with the option for iterative refinement of parameters or dataset configurations based on feedback or changing requirements. This iterative approach allows for exploring different scenarios and addressing specific questions effectively.

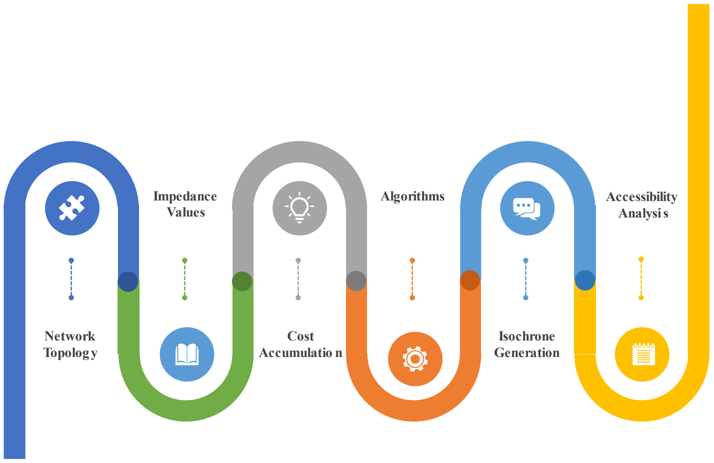
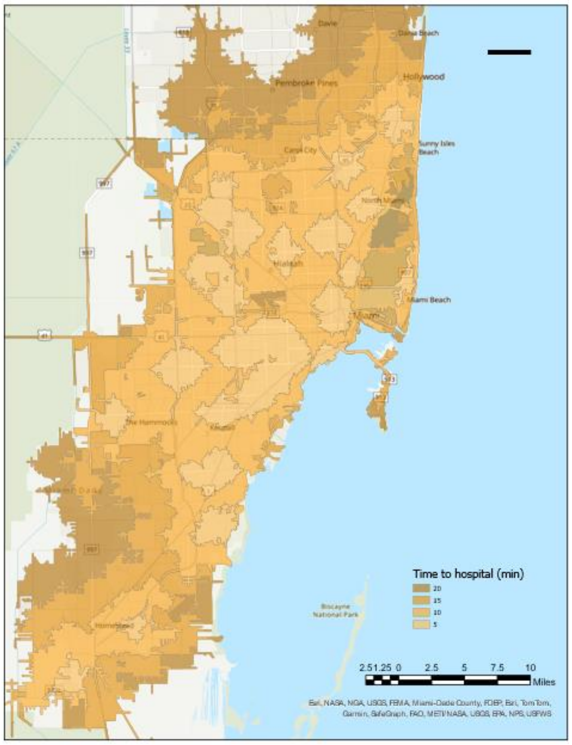


Figure 31. Framework of quantification methods of accessibility

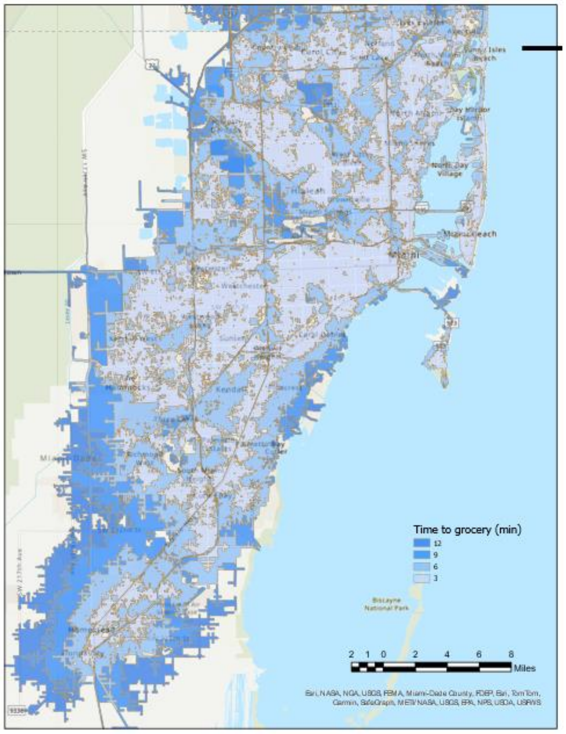
4.4. Accessibility to Essential Service in Miami

We currently possess three isochrone maps depicting accessibility to hospital, grocery and hurricane shelter in Miami. Each map illustrates concentric rings representing the time intervals required to reach these facilities from various locations within the city. Starting with the hospital isochrone map, it showcases accessibility within intervals of 5, 10, 15, and 20 minutes. The shortest interval of 5-minute highlights immediate access to emergency medical care, critical for addressing urgent health needs during emergencies. As the time intervals increase, the coverage area expands, indicating areas where residents can reach hospitals within the specified time frames, essential for timely medical assistance and treatment. Moving to the grocery store isochrone map, it presents accessibility within intervals of 3, 6, 9, and 12 minutes. The shorter intervals signify proximity to grocery stores, ensuring residents can access essential food and supplies within a short travel time. As the intervals increase, the coverage area expands, indicating areas where residents may need to travel slightly farther to reach grocery stores but still within a reasonable time frame. Lastly, the hurricane shelter isochrone map delineates accessibility within intervals of 5, 10, 15, and 20 minutes. These shelters are crucial for providing refuge and protection during hurricanes or other disasters. The shorter intervals indicate areas where residents can quickly access shelters, ensuring they have a safe haven within close proximity during emergencies. As the intervals increase, the coverage area expands, highlighting areas where residents may need to travel farther to reach designated hurricane shelters. Together, these isochrone maps offer valuable insights into the spatial distribution of essential services in Miami and help identify areas with varying levels of accessibility, aiding in emergency preparedness, urban planning, and decision-making processes.



Esri, NASA, NGA, USGS, FEMA, Miami-Dade County, FDEP, Esri, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, USFWS

Figure 32. Accessibility to hospitals



Esri, NASA, NGA, USGS, FEMA, Miami-Dade County, FDEP, Esri, TomTom, Garmin, SafeGraph, METI/NASA, USGS, EPA, NPS, USDA, USFWS

Figure 33. Accessibility to grocery

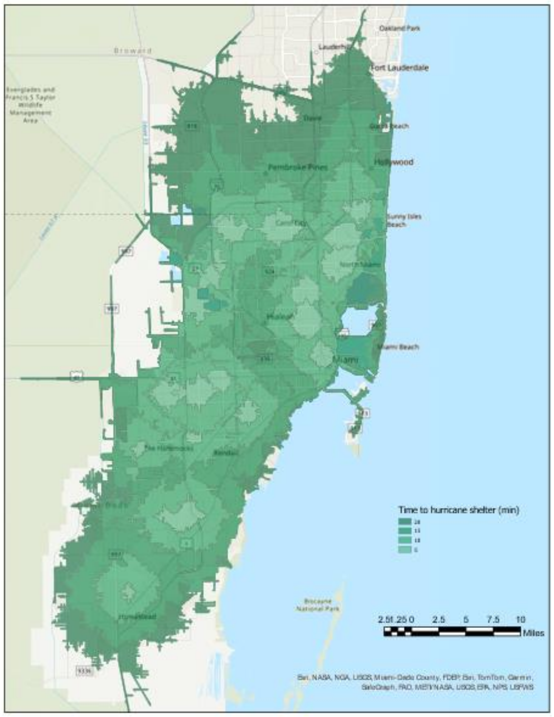


Figure 34. Accessibility to hurricane shelters

4.5. Findings

From the accessibility data, we can derive several important findings. Firstly, we observe a high correlation between accessibility and the quantity of essential service facilities, indicating that the distribution of service facilities is crucial for residents' accessibility. In the Miami area, we also note a significant spatial imbalance in accessibility, with some areas potentially enjoying better coverage of service facilities while others may face lower accessibility. This uneven distribution could lead to underserved communities, especially during emergencies. Another significant finding is that accessibility may rapidly decrease during natural disasters such as hurricanes and floods. This is due to factors such as damage to the road network, road closures, or traffic congestion. Therefore, restoring the road network is essential for recovering accessibility post-disaster. Timely repair and reconstruction of damaged roads and bridges, clearing blocked roads, and implementing traffic management measures can quickly restore road capacity, thus improving residents' accessibility and ensuring timely access to emergency rescue, medical services, and other basic needs. In conclusion, these findings from accessibility data are crucial for urban planning, emergency management, and infrastructure investment. By better understanding and utilizing this data, we can formulate more effective policies and measures to improve the distribution of service facilities, enhance community resilience, and ensure residents have access to necessary support and resources during emergencies.

4.6. Summary

This chapter provides a comprehensive overview of accessibility to essential services in Miami, focusing on hospitals, grocery stores, and hurricane shelters. It begins by highlighting the critical roles of these facilities during hurricanes and other emergencies, emphasizing their significance in providing medical care, essential supplies, and refuge to residents. The chapter includes descriptions of various maps and analyses conducted using ArcGIS Pro, such as isochrone maps illustrating accessibility to hospitals, grocery stores, and hurricane shelters within specific time intervals. Each isochrone map presents concentric rings representing travel time intervals, allowing for a visual understanding of accessibility patterns across the city. Detailed descriptions accompany the maps, explaining the significance of different time intervals and their implications for residents' access to essential services. Additionally, the chapter discusses the findings derived from the accessibility data, including the correlation between service facility quantity and accessibility, spatial imbalances in accessibility, and the impact of natural disasters on accessibility. The chapter concludes by emphasizing the importance of these findings for urban planning, emergency management, and infrastructure investment. It underscores the need for informed decision-making processes to address spatial disparities in accessibility, enhance community resilience, and ensure equitable access to essential services during emergencies. Overall, the chapter provides valuable insights into the accessibility landscape of Miami and offers recommendations for improving service distribution and emergency preparedness in the city.

CHAPTER 5. EQUITABLE RESTORATION OPTIMIZATION PROBLEM

5.1. Research Background

The restoration and enhancement of transportation networks take on paramount importance in the aftermath of hurricanes and similar disasters, as coastal communities strive to recover and rebuild. Despite this urgency, discussions surrounding the resilience of transportation infrastructure often neglect the crucial aspect of social equity. Compounding this challenge is the absence of a universally accepted definition for equity, making it difficult to quantify its significance in the context of post-hurricane restoration efforts.

In response to these challenges, a considerable body of research has emerged focusing on post-disaster transportation network performance modeling and restoration planning. Scholars have endeavored to construct comprehensive frameworks that evaluate the effectiveness of restoration plans in light of budgetary limitations. For example, Wu et al. (2021) introduced a novel system resilience index encompassing both traffic efficiency and safety, acknowledging the importance of ensuring smooth vehicular flow while prioritizing commuter safety. Besides, Feng and Zhang (2014) explored various accessibility-based equity measures within transportation networks, emphasizing the need for fair distribution of resources and infrastructure post-disaster.

Despite these advancements, existing literature tends to concentrate on singular aspects of restoration, often prioritizing either mobility improvement or equity considerations. However, the practical reality necessitates a more nuanced approach, one that integrates multiple dimensions of resilience. It is crucial not only to optimize traffic efficiency but also to guarantee equitable access to transportation resources, thereby addressing the diverse needs and vulnerabilities of different communities.

Acknowledging the importance of adopting a holistic perspective in post-disaster restoration endeavors, the primary aim of this chapter is to propose an innovative model that simultaneously considers mobility and social equity as key resilience metrics in the aftermath of hurricanes. Our proposed resilience measure is envisioned as a weighted average of mobility and equity metrics, synthesizing these interrelated dimensions into a unified framework. By elucidating the Pareto-optimal solutions of link capacity, our model provides stakeholders with invaluable guidance, enabling them to tailor restoration strategies in accordance with their prioritized objectives and preferences. This approach offers a systematic method for defining and assessing equity metrics within the realm of transportation resilience.

In essence, this research endeavor seeks to transcend conventional paradigms of post-disaster transportation network restoration by advocating for a more inclusive approach, one that harmonizes the imperatives of both mobility enhancement and equity consideration. By synthesizing these complementary dimensions, our proposed model aims to cultivate resilient and equitable post-disaster transportation systems that cater to the diverse needs and vulnerabilities of affected communities. Additionally, a pilot study conducted in Miami Shores quantifies the combined impact of mobility and equity considerations on transportation resilience outcomes. The experimental results offer insights into planning post-hurricane transport network recovery, integrating social equity considerations alongside mobility factors, within the constraints of limited budgets.

5.2. Resilience Measure Considering Mobility and Equity

5.2.1. Notation

For the road network, we denote $r \in N$ as a node where N is the set of nodes. $a \in A$ denotes a link, linking two nodes, where A is the set of links. P_{rs} denotes a feasible path from r to s, consisting of multiple links connected from the starting node r to the end node s. If there are K_{rs} feasible paths from node r to s, the kth path is denoted as $P_{rs}^{k}, k = 1,2, \cdots, K_{rs}$. For the kth path P_{rs}^{k}, it consists of links connecting from r to s. An example of a simple road network is shown below.

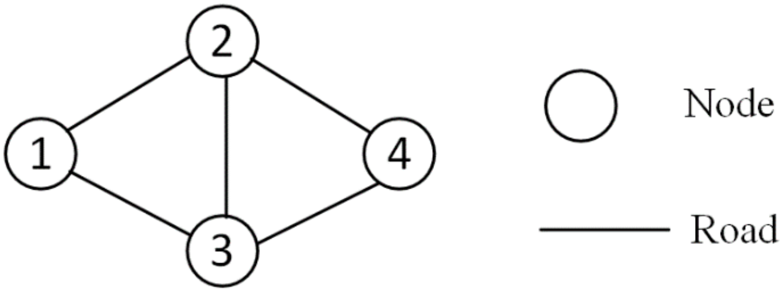


Figure 35. A simple example of road network

There are 4 nodes $N = \{1, 2, 3, 4\}$ and 10 links $A = \{1 \rightarrow 2, 1 \rightarrow 3, 2 \rightarrow 1, 2 \rightarrow 3, 2 \rightarrow 4, 3 \rightarrow 1, 3 \rightarrow 2, 3 \rightarrow 4, 4 \rightarrow 2, 4 \rightarrow 3\}$. A path refers to a sequence of nodes in the network where each adjacent pair of nodes is connected by a link. A key characteristic of a feasible path in the road network is that it does not contain any cycles, meaning that no node is repeated along the way. The feasible paths from node r to s is shown in the following table. The number of paths from the origin to the destination is the simple example is mostly 3, but there are 4 feasible paths from node 1 to node 4 (and from node 4 to node 1). The more complex the road network becomes, the more feasible paths it may contain from one node to another.

Table 2. Feasible paths of the example road network

(r, s)	K_{rs}	P_{rs}
$(1, 2)$	3	$P_{12}^{1} = \{1 \rightarrow 2\}, P_{12}^{2} = \{1 \rightarrow 3 \rightarrow 2\}, P_{12}^{3} = \{1 \rightarrow 3 \rightarrow 4 \rightarrow 2\}$
$(1, 3)$	3	$P_{13}^{1} = \{1 \rightarrow 3\}, P_{13}^{2} = \{1 \rightarrow 2 \rightarrow 3\}, P_{13}^{3} = \{1 \rightarrow 2 \rightarrow 4 \rightarrow 3\}$
$(1, 4)$	4	$P_{14}^{1} = \{1 \rightarrow 2 \rightarrow 4\}, P_{14}^{2} = \{1 \rightarrow 3 \rightarrow 4\}, P_{14}^{3} = \{1 \rightarrow 2 \rightarrow 3 \rightarrow 4\}, P_{14}^{4} = \{1 \rightarrow 3 \rightarrow 2 \rightarrow 4\}$
$(2, 1)$	3	$P_{21}^{1} = \{2 \rightarrow 1\}, P_{21}^{2} = \{2 \rightarrow 3 \rightarrow 1\}, P_{21}^{3} = \{2 \rightarrow 4 \rightarrow 3 \rightarrow 1\}$
$(2, 3)$	3	$P_{23}^{1} = \{2 \rightarrow 3\}, P_{23}^{2} = \{2 \rightarrow 1 \rightarrow 3\}, P_{23}^{3} = \{2 \rightarrow 4 \rightarrow 3\}$
$(2, 4)$	3	$P_{24}^{1} = \{2 \rightarrow 4\}, P_{24}^{2} = \{2 \rightarrow 3 \rightarrow 4\}, P_{24}^{3} = \{2 \rightarrow 1 \rightarrow 3 \rightarrow 4\}$
$(3, 1)$	3	$P_{31}^{1} = \{3 \rightarrow 1\}, P_{31}^{2} = \{3 \rightarrow 2 \rightarrow 1\}, P_{31}^{3} = \{3 \rightarrow 4 \rightarrow 2 \rightarrow 1\}$

$(3,2)$	3	$P_{32}^{1} = \{3 \to 2\}, P_{32}^{2} = \{3 \to 1 \to 2\}, P_{32}^{3} = \{3 \to 4 \to 2\}$
$(3,4)$	3	$P_{34}^{1} = \{3 \to 4\}, P_{34}^{2} = \{3 \to 2 \to 4\}, P_{34}^{3} = \{3 \to 1 \to 2 \to 4\}$
$(4,1)$	4	$P_{41}^{1} = \{4 \to 2 \to 1\}, P_{41}^{2} = \{4 \to 3 \to 1\}, P_{41}^{3} = \{4 \to 3 \to 2 \to 1\}, P_{41}^{4} = \{4 \to 2 \to 3 \to 1\}$
$(4,2)$	3	$P_{42}^{1} = \{4 \to 2\}, P_{42}^{2} = \{4 \to 3 \to 2\}, P_{42}^{3} = \{4 \to 3 \to 1 \to 2\}$
$(4,3)$	3	$P_{43}^{1} = \{4 \to 3\}, P_{43}^{2} = \{4 \to 2 \to 3\}, P_{43}^{3} = \{4 \to 2 \to 1 \to 3\}$

5.2.2. Mobility measure: Recovery deficiency index

We use the total system travel time to reflect the mobility efficiency of transportation network. Before hurricane-induced hazards happen, the total system travel time is expressed by following:

$$TSTT_0 = \sum_{a \in A} x_a \cdot t_a(x_a, c_a), \tag{1}$$

where x_a is the traffic flow on link a, $a \in A$; $t_a(x_a, c_a)$ is the travel time on link a, and c_a is the capacity of link a before hurricane-induced hazards.

The travel time can by defined by the Bureau of Public Roads (BPR) function (Manual, T. A. (1964)):

$$t_a(x_a, c_a) = t_0 \left(1 + \alpha \left(\frac{x_a}{c_a}\right)^{\beta}\right), \tag{2}$$

where α, β are constants.

After hurricane-induced hazards, the total system travel time can be expressed by following:

$$TSTT = \sum_{a \in A} x_a \cdot t_a(x_a, c_a^0 + c_a^1), \tag{3}$$

where c_a^0 is the capacity of link a after hurricane-induced hazards. c_a^1 defines the capacity improvement for link a. It satisfies that $0 \leq c_a^1 \leq c_a - c_a^0$. If $c_a^1 = 0$, then no recovery is done for link a; if $c_a^1 = c_a - c_a^0$, then the link a is recovered to its before hurricane-induced hazards level.

The travel time on link a after the capacity improvement can be calculated by the following:

$$t_a(x_a, c_a^0 + c_a^1) = t_0 \left(1 + \alpha \left(\frac{x_a}{c_a^0 + c_a^1}\right)^{\beta}\right), \tag{4}$$

Assuming that the demand stays same after hurricane happens, we define an index to denote the performance of restoration plan for transportation network. The recovery deficiency index is expressed by following:

$$D = \frac{TSTT - TSTT_0}{TSTT}, \tag{5}$$

where $TSTT_0$ and $TSTT$ are the total system travel time before the hurricane happens and after the restoration plan is adopted respectively. A similar index, named efficiency indicator, is defined by $R_i = TSTT_0 / TSTT$ (Wu et al. (2021)). The two indices are summed up to 1, i.e., $D + R_i = 1$.

The proposed recovery deficiency index measures how deficient the restoration plan is. If $TSTT = TSTT_0$, then the road network has been recovered to its original state, so the recovery deficiency index equals to 0. The closer $TSTT$ gets to $TSTT_0$, the smaller the recovery deficiency index D becomes, indicating that the network is more effectively recovered.

5.2.3. *Equity measure: GINI coefficient*

In this study, we adopt the conventional location-based accessibility measure. Such type of accessibility has been popularly applied in node-based travel demand analysis based on gravity-type trip distribution models. Hence, without loss of generality, we define the node-accessibility as following (Feng and Zhang (2014)):

$$W_s = \sum_{r \neq s} \left[\frac{P_r}{\bar{t}_{rs}{}^{\theta}} \right], \forall r, s \in N, \tag{6}$$

where P_r is the node population, $\bar{t}_{rs}$ is the average travel time from node r to node s, N is the set of nodes, and θ is a constant.

The average travel time of different paths from node r to node s can be obtained by taking the average of travel times of all feasible paths:

$$\bar{t}_{rs} = \frac{\sum_{k \in P_{rs}} t_{rs}^k}{K_{rs}}, \tag{7}$$

where P_{rs} is the set of the paths connecting node r and node s, K_{rs} is the number of candidate paths from node r to node s, $K_{rs} = |P_{rs}|$, t_{rs}^k is travel time on path k connecting node r and node s. Considering the user equilibrium network flow assignment problem, for all possible routes with positive path flows, the travel time should be the same. Therefore, in our model, theoretically, $t_{rs}^k = \bar{t}_{rs}, \forall k \in K_{rs}$.

When focusing on spatial equity, there is a need to measure equity by reflecting the distributional extent of policy impacts. Regarding the practical popularity in different fields, we adopt GINI coefficient measures that are formulated on the basis of node accessibility, as shown in the following equation.

$$E = \frac{1}{2N^2 \bar{W}} \sum_{r \in N} \sum_{s \in N} |W_r - W_s|, \tag{8}$$

where E is the GINI coefficient, N is the number of nodes, $\bar{W}$ is the average node accessibility across the whole network.

$$\bar{W} = \frac{\sum_r W_r}{N}, \tag{9}$$

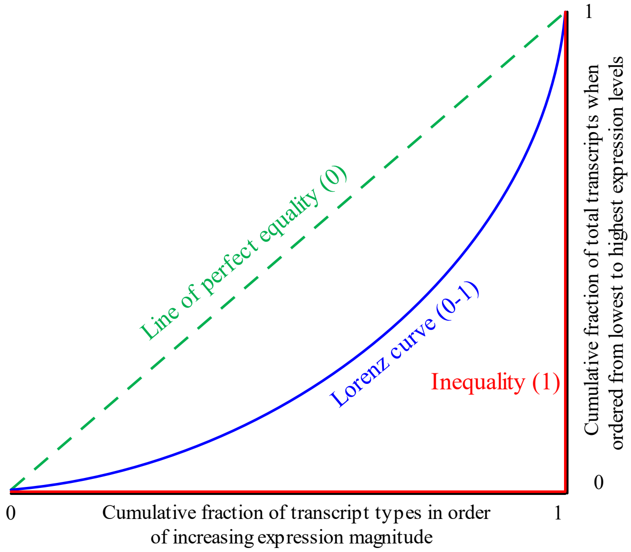


Figure 36. GINI coefficient

Besides GINI coefficient, there are other equity measures that are also proposed and applied in the literature. Feng and Zhang (2014) summarized the equity measures in the following table:

Table 3. Equity measures

Equity measure	Abbr.	Formula
GINI coefficient	GINI	$E_{gini} = \frac{1}{2N^2\overline{W}} \sum_{r \in N} \sum_{s \in N} \lvert W_r - W_s \rvert$
Theil index	THEIL	$E_{theil} = \frac{1}{N} \sum_{r \in N} \frac{W_r}{\overline{W}} \log\left(\frac{W_r}{\overline{W}}\right)$
Mean log deviation	LEDV	$E_{ledv} = \frac{1}{N} \sum_{r \in N} \lvert \log(\overline{W}) - \log(W_r) \rvert$
Relative mean deviation	RDEV	$E_{rdev} = \frac{1}{N\overline{W}} \sum_{r \in N} \lvert \overline{W} - W_r \rvert$
Coefficient of variation	COV	$E_{cov} = \frac{1}{\overline{W}} \left(\frac{1}{N} \sum_{r \in N} (\overline{W} - W_r)^2 \right)^{\frac{1}{2}}$

Atkinson index	ATK	$E_{atk} = 1 - \frac{1}{\overline{W}}\left(\frac{1}{N}\sum_{r\in N}(W_r)^{1-\epsilon}\right)^{\frac{1}{1-\epsilon}} \quad (\epsilon \neq 1)$

5.2.4. *Resilience measure*

A novel transportation resilience measure combining mobility (travel time) and equity within bridge and road infrastructure network.

$$R = \mu \cdot D + (1-\mu) \cdot E, \tag{10}$$

where μ is a weight parameter between $[0,1]$, which is usually defined by the stakeholders based on the specific scenario and priority.

5.3. Bi-level optimization problem

5.3.1. *Upper-level optimization problem*

The optimization problem is bi-level, with the upper level decides the road enhancements, and the lower level assigns the traffic flow.

The objective of upper level is to minimize the system travel delay and inequity with limited budget, quantified by the proposed resilience measure. City administrators will make decision for the restoration plan. However, road users still have the right to choose the route that costs them the least. We use user equilibrium model for traffic flow assignment, which is defined as lower-level problem in the next subsection. Therefore, the formulation of the upper level bi-objective bi-level EROP proposed in this work is illustrated as follows:

$$Min: R = \mu \cdot D + (1-\mu) \cdot E, \tag{11}$$

Subject to:

$$\textstyle\sum_{a\in A} M_a(c_a^1) \leq B, \tag{12}$$

$$c_a^1 \geq 0, \forall\, a \in A, \tag{13}$$

$$c_a^0 + c_a^1 \leq c_a, \forall\, a \in A, \tag{14}$$

where (11) is the objective function. Constraint (12) makes sures that the cost of restoration plan cannot exceed the total budget, where $M_a(c_a^1)$ is the cost for restoring link a with capacity c_a^1, and $M_a(0) = 0, \forall a \in A$. Constraints (13) and (14) ensure that for every candidate link, the capacity recovery size is non-negative, and the recovered capacity cannot exceed the initial capacity before the hurricane.

The lower-level optimization problem is to decide the optimal capacity recovery plan. By solving (11) - (14) we can get the capacity enhancement plan for each link c_a^1.

5.3.2. *Lower-level optimization problem*

For the road network, the User Equilibrium (UE) is based on the assumption that each user wishes to minimize his/her travel time, so travel times on all used paths of each O-D pair are equal, and the travel time on any unused path is equal to or greater than the used travel time. In that case, no user can reduce his/her travel time by unilaterally changing path, so the network has become stationary, i.e. user equilibrium. Therefore, the lower optimization problem is to decide the optimal traffic assignment, which can be expressed by user equilibrium model:

$$Min: \sum_a \int_0^{x_a} t_a(w, c_a^0 + c_a^1) dw, \tag{15}$$

Subject to:

$$t_a(w, c_a^0 + c_a^1) = t_0 \left(1 + \alpha \left(\frac{w}{c_a^0 + c_a^1}\right)^\beta\right), \tag{16}$$

$$x_a = \sum_r \sum_s \sum_k f_{rs}^k \delta_{rs}^{a,k}, \forall\, a \in A, \tag{17}$$

$$\sum_k f_{rs}^k = q_{rs}, \forall r, s \in N, \tag{18}$$

$$f_{rs}^k \geq 0, \forall k \in K_{rs}, r, s \in N, \tag{19}$$

where x_a is the traffic flow on link a; t_a is the travel time on link a; f_{rs}^k is the traffic flow on the path k connecting node r and node s; $\delta_{rs}^{a,k}$ is an indictor variable: $\delta_{rs}^{a,k} = 1$, if link a is part of the path k connecting node r and node s, otherwise $\delta_{rs}^{a,k} = 0$. q_{rs} is the travel demand from r (origin) to s (destination).

Eq. (15) is the objective function for the UE model. Equation (16) is the formula to calculate the travel time on link a. Constraint (17) calculates the traffic flow on link a, which is the summation of all path flows that consist of the link a. Constraint (18) satisfies that the summation of path flows from node r to node s equals the demand from node r to node s. Constraint (19) makes sure that the path flow is non-negative.

The lower-level optimization problem is to decide the optimal traffic assignment. By solving (15) - (19) we can get the flow assignment f_{rs}^k. Then by using (17) we can get the flow on each link.

5.3.3. *Bi-level equitable restoration optimization problem*

The formulation of the overall bi-objective bi-level equitable restoration plan optimization problem (EROP) proposed in this work is illustrated as follows.

The upper-level problem is:

$$Min: R = \mu \cdot D + (1 - \mu) \cdot E, \tag{20}$$

Subject to:

$$\sum_{a \in A} M_a(c_a^1) \leq B, \tag{21}$$

$$c_a^1 \geq 0, \forall\, a \in A, \tag{22}$$

$$c_a^0 + c_a^1 \leq c_a, \forall\, a \in A, \tag{23}$$

The lower-level problem is:

$$Min: \sum_a \int_0^{x_a} t_a(w, c_a^0 + c_a^1 y_a^1) dw, \tag{24}$$

Subject to:

$$t_a(w, c_a^0 + c_a^1) = t_0 \left(1 + \alpha \left(\frac{w}{c_a^0 + c_a^1}\right)^\beta\right), \tag{25}$$

$$x_a = \sum_r \sum_s \sum_k f_{rs}^k \delta_{rs}^{a,k}, \forall\, a \in A\,, \tag{26}$$

$$\sum_k f_{rs}^k = q_{rs}, \forall r, s \in N, \tag{27}$$

$$f_{rs}^{k} \geq 0, \forall k \in K_{rs}, r, s \in N, \tag{28}$$

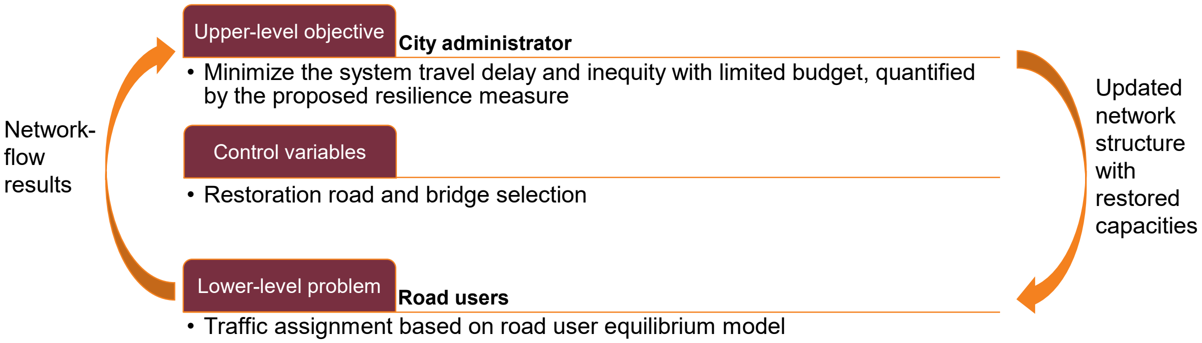


Figure 37. Bi-level equitable restoration optimization problem

5.4. Pilot Study

5.4.1. Data Source

In this chapter, Miami Shores is chosen as the pilot area, building upon the discussions of its flooding map and transportation network in Chapter 3. Figure 38 illustrates the fundamental transportation infrastructure, a transportation network modeled based on Miami Shores. Building on our findings from Chapter 2, it's important to note that Miami Shores is susceptible to hurricanes and flooding. With 13 zones represented by the nodes in Figure 38, each node serves as the focal point of a specific area within the community. In our investigation, disruptions to the transportation network are primarily caused by road flooding, with the possibility of partial or full disruption for some links. The parameters listed in Table 5 are established according to the characteristics of each link, while those in Tables 4 are derived from annual average daily traffic data. When juxtaposed with real-world transportation networks, this transportation network resembles that of a small to medium-sized city.

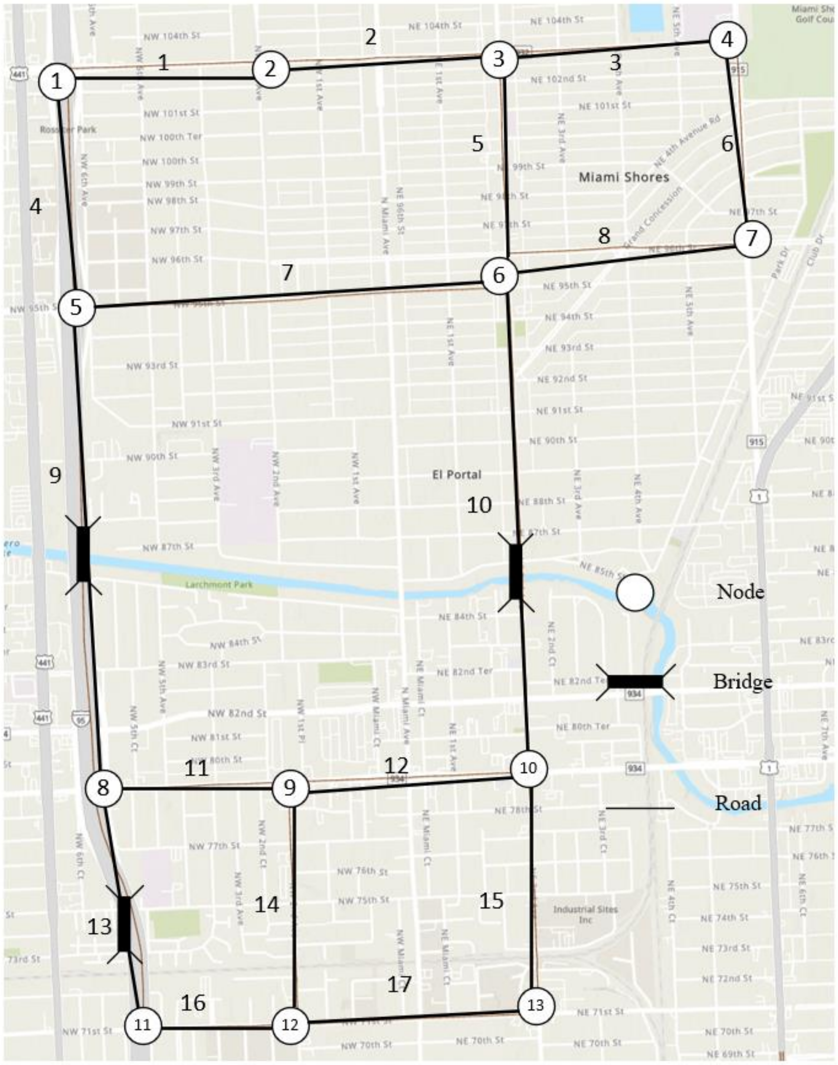


Figure 38. Bridge and roadway network for Miami Shores

The travel demand (origin-destination matrix) with unit of vehicle per hour, is summarized in the following Table 4.

Table 4. Travel demand input for Miami Shores

D O	1	2	3	4	5	6	7	8	9	10	11	12	13
1		1450	780	1256	755	959	1353	984	1601	1891	513	623	560
2	1450		547	1501	744	1531	1375	743	681	670	1756	1261	611
3	780	547		1635	1256	563	1470	1805	1256	1286	1039	1681	770

4	1256	1501	1635		1276	1068	1048	804	1631	1702	925	1515	684
5	755	744	1256	1276		1265	1273	1722	593	1270	811	1126	1274
6	959	1531	563	1068	1265		1287	1572	676	1669	1406	1297	1944
7	1353	1375	1470	1048	1273	1287		767	1986	585	1045	1396	1300
8	984	743	1805	804	1722	1572	767		1255	782	1569	1818	1985
9	1601	681	1256	1631	593	676	1986	1255		1034	797	1854	1570
10	1891	670	1286	1702	1270	1669	585	782	1034		1677	1542	1761
11	513	1756	1039	925	811	1406	1045	1569	797	1677		937	1606
12	623	1261	1681	1515	1126	1297	1396	1818	1854	1542	937		601
13	560	611	770	684	1274	1944	1300	1985	1570	1761	1606	601	

The free-flow travel time, the before-hurricane capacity and after-hurricane capacity for different links are summarized in the following table.

Table 5. Potential damaged links

Road	O-D	Free flow travel time (min)	Capacity before hurricane (10^3 veh/hour)	Capacity after hurricane (10^3 veh/hour)
1	1-2	3.6	13.40	6.02
2	2-3	2.4	9.01	
3	3-4	3.6	54.19	12.02
4	1-5	3.0	15.92	
5	3-6	2.4	69.12	46.81
6	4-7	2.4	34.22	
7	5-6	2.4	59.37	46.81
8	6-7	2.4	61.15	25.82
9	5-8	1.2	55.07	28.25

10	6-10	1.2	46.85	
11	8-9	2.4	23.23	13.86
12	9-10	3.0	10.52	
13	8-11	3.0	9.92	
14	9-12	2.4	9.90	
15	10-13	1.2	21.62	
16	11-12	1.8	32.91	15.68
17	12-13	1.2	62.79	46.81

There are 9 roads (17 links) that are damaged in our experiment. We set the constants in travel time calculations (Eq. (25)) to be $\alpha = 0.15, \beta = 4$, and the constant in the node-accessibility coefficient (Eq. (6)) to be $\theta = 1$. We assume that the cost to recovery 1 unit of capacity is the same over all links. Therefore, the budget constraint Eq. (21) is equivalent to capacity assignment constraint:

$$\sum_{a \in A} c_a^1 \leq C, \tag{29}$$

where C is the maximum capacity recovery size, a proxy of monetary budget.

5.4.2. Algorithm

Due to the complexity of the bi-level optimization problem, the theoretical global optimum cannot be guaranteed. In practice, one of the solutions is genetic algorithm (GA) (Lambora et al. (2019)). Genetic algorithm is a computational technique inspired by the principles of natural selection and genetics. It's used to solve optimization and search problems by mimicking the process of evolution. The algorithm starts with a population of potential solutions represented as individuals. These individuals undergo a process of selection, crossover, and mutation to produce new offspring that inherit characteristics from their parent solutions. Through successive generations, the population evolves towards better solutions based on a predefined fitness function that evaluates the quality of each individual. Selection mechanisms like roulette wheel selection or tournament selection choose individuals for reproduction based on their fitness, while crossover and mutation introduce variation into the population. Over time, the genetic algorithm tends to converge towards optimal or near-optimal solutions, making it a powerful tool for tackling complex optimization problems across various domains. The algorithm iterates through generations, applying selection, crossover, and mutation operators until a termination condition is met, such as reaching a maximum number of generations or achieving a satisfactory solution (Mitchell 1998).

The pseudo code and the flowchart for the optimization problem are summarized below.

```
Genetic Algorithm (GA):
    Initialize population (capacity enhancement $c_a^1, \forall a \in A$);
    Evaluate fitness (resilience measure $R$) of each individual in the population;
    Repeat until termination condition is met:
        Select parents for reproduction;
        Create offspring through crossover and mutation;
        Evaluate fitness of new offspring;
        Select individuals for the next generation;
        Replace the current population with the selected individuals;
    Terminate when a stopping criterion is satisfied.
```

Figure 39. Pseudo code for EROP

Figure 40. Flowchart of the genetic algorithm

When evaluating fitness, we need to solve the lower-level problem to get the link flow as well as the path flow first, given the individual (capacity enhancement plan). The lower-level problem of the network flow assignment for the user equilibrium model is solved by the Frank-Wolfe algorithm. The Frank-Wolfe algorithm is an iterative optimization technique utilized for solving convex optimization problems with linear constraints. It is particularly effective for problems where the objective function can be expressed as a linear combination of a large number of components. The algorithm iteratively minimizes the linear approximation of the objective function by finding the optimal step size along the negative gradient direction at each iteration. However, instead of moving all the way to the minimum, it takes a step towards the minimizer within the feasible region, governed by a step size parameter. This process continues until convergence to an optimal or near-optimal solution is achieved.

We apply the Frank-Wolfe algorithm to solve the lower-level traffic flow assignment problem. The goal is to determine the optimal allocation of traffic flow across the road network considering the user equilibrium condition as well as satisfying demand and capacity constraints. The algorithm proceeds by iteratively updating the traffic flow distribution along the road network based on the current gradient of the objective function. At each iteration, it computes the gradient of the objective function with respect to the traffic flow variables and identifies the direction that yields the most significant decrease in the objective function value. This direction is determined by solving a linear approximation of the optimization problem, often referred to as a linear subproblem or linearization step. The algorithm then computes the optimal step size along this direction, ensuring that the resulting traffic flow remains feasible within the network constraints. This process repeats until convergence, where the traffic flow assignment stabilizes, and further iterations yield negligible improvements in the objective function value. Through this iterative procedure, the Frank-Wolfe algorithm provides an efficient and scalable approach to optimizing traffic flow assignment in large road networks.

5.4.3. Experimental Results

We set the total recovery capacity to be 50. For different value of μ in the resilience measure, we set $\mu = 0.2, 0.5, 0.8$. $\mu = 0.5$ means that the mobility measure D and the equity measure E are with equal weights. A smaller μ means that the higher weights are add to E, while a larger μ means that the higher weights are added to D. The experiment results are summarized below.

Table 6. Experiment results for recovery capacity for different μ

Road	Link	Maximum recovery capacity	$\mu = 0.2$	$\mu = 0.5$	$\mu = 0.8$
1	1 → 2	7.38	7.38	6.26	4.67
	2 → 1	7.38	0.18	4.80	4.73
3	3 → 4	42.17	13.85	16.17	15.65
	4 → 3	42.17	3.96	0	15.38
5	3 → 6	22.31	6.00	10.40	0.42
	6 → 3	22.31	0.42	0.21	0
7	5 → 6	12.56	5.58	3.52	2.02
	6 → 5	12.56	0.69	0.29	0
8	6 → 7	35.33	0.08	2.45	1.12
	7 → 6	35.33	0.93	1.04	0.13
9	5 → 8	26.82	10.92	1.46	3.6
	8 → 5	26.82	0	1.51	0.01
11	8 → 9	9.37	0	0.81	1.06
	9 → 8	9.37	0.02	0	0
16	11 → 12	17.23	0	0.25	0.01
	12 → 11	17.23	0	0	0.65
17	12 → 13	15.98	0	0.09	0
	13 → 12	15.98	0	0.74	0.54

Sum	50	50	50

Although the genetic algorithm cannot guarantee the global optimal solution, the solution after several iterations and evolutions can provide us with valuable insights. Several key findings are summarized below.

Firstly, different directions of a road are given different weights in the restoration process. For example, when $\mu = 0.2$ or $\mu = 0.5$, the link $1 \rightarrow 2$ are given more recovery capacity than the link $2 \rightarrow 1$. This is determined by the demand from the origin-destination matrix, as well as the different travel time on different links.

Secondly, for different values of μ, the recovery strategies are different. A larger μ gives more priority to link $4 \rightarrow 3$, but less priority to link $3 \rightarrow 6$. This reflects the stakeholders' different preferences on mobility and equity. For mobility considerations, link $4 \rightarrow 3$ is more important, while for equity considerations, link $3 \rightarrow 6$ is more important. The decision of recovery plan should be carefully designed based on different objectives.

Thirdly, no matter what μ value is, some links are always given higher priority while others are not. For example, link $1 \rightarrow 2$ and link $3 \rightarrow 4$ should always be recovered to a higher capacity. These roads are typically playing an important role and they link multiple communities, which should always be paid more attention to during the recovery process. In contrast, road 11, 16 and 17 are not given a higher capacity recovery quote.

Moreover, it is imperative to acknowledge that the solution above is based on road capacity, free flow travel time, the damage of the hurricane to roads, and many other factors. A different level of damage to different roads may yield different solution. Nevertheless, our experiments provide valuable insights on designing the recovery plan as well as measuring the importance of different roads considering mobility and equity measures. It also helps to understand the features of different communities and travel path choices in the city.

5.5. Conclusion

In this section, we proposed a novel resilience measure in post-hurricane bridge and roadway infrastructure network recovery that considers both mobility and equity, which has not been extensively addressed but has a discernible impact on planning and decision making. We designed a bi-level optimization model, with the upper-level deciding the optimal recovery plan and the lower-level deciding the network flow assignment. To solve this problem, we adopt the genetic algorithm, which can yield a satisfactory solution given the complexity of the problem.

We did the pilot study based on the Miami Shores. We varied weights μ assigned to equity quantification and mobility. The results show that different weights lead to alterations in recovery planning. Under an investment budged constraint, differences arise between equity quantification and mobility considerations in recovery planning.

We acknowledge that the recovery planning is a complex process. Which link should be given higher priority is based on multiple factors, including the demand of the whole network, the initial capacity and the post-hurricane capacity, the network structure, weights assigned to mobility and equity, and other hyperparameters. Our theoretical model as well as the experimental results provide valuable insight into recovery planning.

5.6. Future Study

There are several avenues for extending the scope of this study. Firstly, forthcoming research endeavors could broaden the current approach by delving into the dynamic quantification of restoration within the realm of recovering planning. This could entail exploring various levels of uncertainty inherent in the model, such as uncertainties surrounding demand fluctuations and the capacities of roads and bridges.

Secondly, the development of more efficient algorithms stands as a promising direction for expediting the solving process. Additionally, delving into the optimization model to provide theoretical guarantees for approximate solutions in comparison to optimal ones could significantly enhance the robustness of the approach.

Thirdly, there exists potential for enriching the model by incorporating additional factors beyond its current scope. Factors such as age, gender, race, and income, among others, could provide valuable insights into the dynamics of the system under study.

Lastly, expanding the experimental framework to encompass a variety of networks and parameters would serve to validate the proposed model comprehensively. This would involve conducting experiments across diverse contexts to assess the generalizability and applicability of the model across different scenarios and settings.

CHAPTER 6. MULTISECTOR STAKEHOLDER COLLABORATION AND ENGAGEMENT FOR TRANSPORTATION RESILIENCE

6.1. Multisector Stakeholder Collaborations and Engagements

Multisector stakeholder collaboration and engagement refer to the process of bringing together individuals, organizations, and groups from diverse sectors to collectively address complex challenges, pursue common goals, or promote social change. This approach recognizes that many issues faced by society are interconnected and cannot be effectively addressed by any single sector alone. Instead, it emphasizes the importance of collaboration and cooperation across different fields, including government, non-profit organizations, businesses, academia, and communities. At its core, multisector stakeholder collaboration involves creating partnerships and networks that leverage the unique strengths, resources, and expertise of each sector. By working together, stakeholders can pool their knowledge, share best practices, and coordinate efforts to achieve shared objectives. This collaborative approach enables stakeholders to tackle issues from multiple angles, leading to more holistic and sustainable solutions.

Engagement is a critical component of multisector collaboration, as it involves actively involving stakeholders in the decision-making process and ensuring that their voices are heard and valued. Effective engagement strategies seek to foster open communication, build trust, and promote inclusivity among all participants. This may involve holding meetings, workshops, or forums where stakeholders can exchange ideas, provide input, and contribute to the development and implementation of initiatives. Multisector stakeholder collaboration and engagement can take many forms, ranging from informal partnerships to more structured alliances or coalitions. Regardless of the specific model, successful collaboration requires strong leadership, clear communication, and a shared vision for change. It also requires a commitment to equity, diversity, and inclusion, ensuring that the benefits of collaboration are accessible to all stakeholders, especially those who may be marginalized or underrepresented. Overall, multisector stakeholder collaboration and engagement are essential for addressing complex societal challenges, promoting innovation, and driving positive social impact. By working together across sectors, stakeholders can harness the collective power of their expertise and resources to create meaningful change and build a more sustainable and resilient future.

6.2. Application in Transportation Resilience

Transportation systems play a critical role in ensuring the mobility, accessibility, and connectivity of communities, businesses, and supply chains. However, these systems are vulnerable to various disruptions, including natural disasters, extreme weather events, technological failures, and social unrest. Enhancing the resilience of transportation infrastructure requires coordinated efforts across multiple sectors, including government agencies, transportation authorities, emergency responders, businesses, non-profit organizations, and community groups. This literature review examines the application of multisector stakeholder collaboration and engagement in building transportation resilience, highlighting key themes, challenges, and best practices identified in the literature.

6.2.1. Area and theme

6.2.1.1. Interagency coordination

Effective transportation resilience requires collaboration among multiple government agencies responsible for transportation planning, infrastructure management, emergency response, and public safety. Interagency coordination facilitates the sharing of information, resources, and expertise to enhance preparedness, response, and recovery efforts. Studies emphasize the importance of establishing formalized coordination mechanisms, such as joint task forces, interagency agreements, and mutual aid agreements, to facilitate seamless collaboration during crises.

6.2.1.2. Public-Private Partnerships

Public-private partnerships (PPPs) play a crucial role in enhancing transportation resilience by leveraging the resources, expertise, and innovation of both sectors. PPPs facilitate the development, operation, and maintenance of resilient transportation infrastructure, such as roads, bridges, ports, airports, and public transit systems. Examples of PPP initiatives include infrastructure financing, risk sharing, asset management, and technology deployment. However, ensuring transparency, accountability, and alignment of interests between public and private partners is essential for the success of PPPs in transportation resilience.

6.2.1.3. Community Engagement

Meaningful engagement with communities and stakeholders is essential for building transportation resilience that meets the needs and priorities of local residents. Community members possess valuable knowledge about transportation vulnerabilities, access challenges, and mobility needs, making them key stakeholders in resilience planning and decision-making. Engaging communities through participatory processes, public meetings, workshops, and outreach campaigns fosters trust, builds social capital, and enhances the legitimacy and effectiveness of transportation resilience initiatives.

6.2.1.4. Cross-Sector Collaborations

Building transportation resilience requires collaboration across diverse sectors, including transportation, urban planning, public health, environmental sustainability, and economic development. Cross-sector collaboration enables stakeholders to address the interconnected nature of transportation challenges and identify synergies between resilience-building efforts in different domains. Studies highlight the importance of breaking down silos, promoting interdisciplinary approaches, and fostering shared ownership and accountability among stakeholders from various sectors.

6.2.2. Challenges

Limited funding, staffing, and technical capacity pose significant challenges to multisector collaboration in transportation resilience. Securing financial resources, building institutional capacity, and investing in workforce development and training are essential for overcoming resource constraints and sustaining collaborative resilience efforts over the long term.

Access to timely, accurate, and actionable data is critical for effective transportation resilience planning and decision-making. However, challenges related to data sharing, interoperability, privacy, and security hinder collaboration among stakeholders and impede the integration of data-driven approaches into resilience initiatives. Overcoming these challenges requires establishing data governance frameworks, standardizing data formats, and addressing legal and regulatory barriers to data sharing.

Complex governance structures, fragmented decision-making processes, and competing interests among stakeholders can hinder collaboration and slow down the implementation of resilience measures. Strengthening governance mechanisms, enhancing coordination, and clarifying roles and responsibilities are essential for streamlining decision-making and accelerating progress toward transportation resilience goals.

6.2.3. Practices

Adopting integrated planning approaches that consider transportation resilience in conjunction with other urban development goals, such as land use, housing, and environmental sustainability, promotes holistic and synergistic solutions. Integrated planning fosters collaboration across sectors, aligns policy objectives, and maximizes co-benefits while minimizing trade-offs between competing priorities. Conducting comprehensive risk assessments and scenario planning exercises enables stakeholders to identify, prioritize, and address transportation vulnerabilities and threats. By analyzing potential hazards, vulnerabilities, and consequences, stakeholders can develop proactive mitigation strategies, adaptive management plans, and contingency measures to enhance transportation resilience. Investing in capacity-building programs, training workshops, and knowledge exchange platforms enhances the technical skills, leadership capabilities, and collaborative competencies of transportation stakeholders. Capacity building fosters a culture of resilience, empowers stakeholders to take proactive measures, and builds networks of support and collaboration across sectors and disciplines.

6.3. Bipartite SNA model

6.3.1. Concept

The Bipartite Social Network Analysis (SNA) model (Hoppe et al., 2016) is a framework used to analyze and understand relationships between two distinct sets of entities in a network. In a bipartite network, nodes are divided into two separate groups, and connections only occur between nodes in different groups, rather than within the same group. This model is particularly useful for examining relationships between two distinct types of entities, such as organizations and individuals, users and products, or actors and events.

A bipartite graph is a mathematical representation of a bipartite network, consisting of two sets of nodes and edges connecting nodes from different sets. In the context of social networks, one set of nodes often represents one type of entity (e.g., organizations), while the other set represents another type of entity (e.g., individuals). Edges between nodes indicate relationships or interactions between entities.

Bipartite networks can be projected onto each set of nodes to create two separate monopartite networks. In a projection, nodes of one set are connected if they share a common neighbor in the other set. For example, in a bipartite network of users and products, a user-user projection would connect users who have interacted with the same products. Similarly, a product-product projection would connect products that have been interacted with by the same users.

The degree distribution of nodes in a bipartite network refers to the distribution of connections or interactions that nodes have with nodes in the other set. Nodes with a high degree in one set may indicate central or influential entities that interact with a diverse range of entities in the other set.

Centrality measures, such as degree centrality, betweenness centrality, and closeness centrality, can be applied to nodes in a bipartite network to identify the most important or influential entities in the network. These measures help to understand which entities play key roles in connecting different parts of the network or facilitating interactions between entities in different sets.

Community detection algorithms can be used to identify clusters or communities of closely connected nodes within each set of a bipartite network. By partitioning the network into cohesive groups, community detection helps to uncover underlying structures and patterns of interactions between entities in the network.

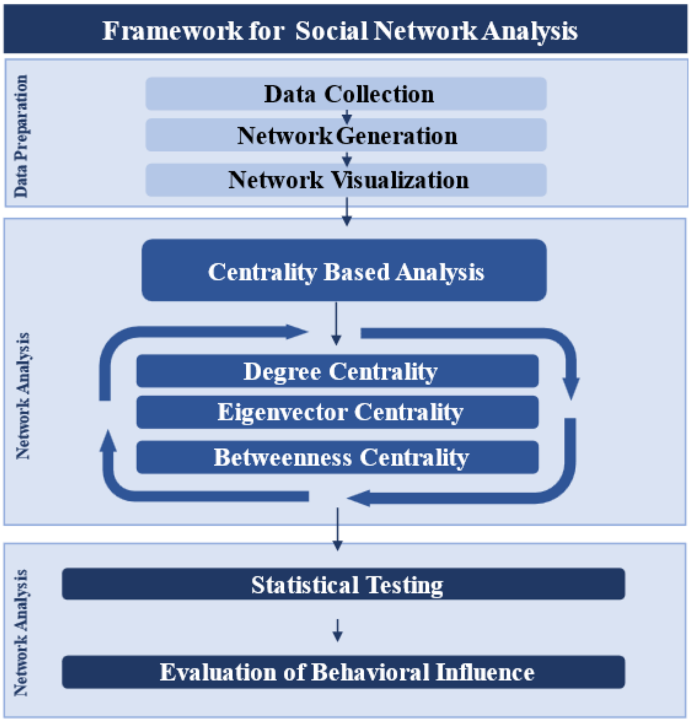


Figure 41. Framework of social network analysis

6.3.2. Data collection

To gather data for the proposed bipartite network, we systematically examined all official documents published on government websites, including those of various offices or departments within the City of Miami, City of Miami Beach, Broward County, and Miami-Dade County. We adhered to three primary inclusion criteria during the systematic review. Initially, the document topics needed to pertain to “transportation” and at least one of “emergency,” “resilience,” or “disaster,” ensuring the relevance of the selected documents. Secondly, the document types were limited to plans, reports, or guidelines, as these typically offer formal strategies or guidance on transportation resilience planning. Thirdly, focusing on recent years, we considered documents published between 2011 and 2024. Employing these inclusion criteria, we included a total of 29 documents in our analysis, with their distribution and word cloud summarized in Figure 42 and 43.

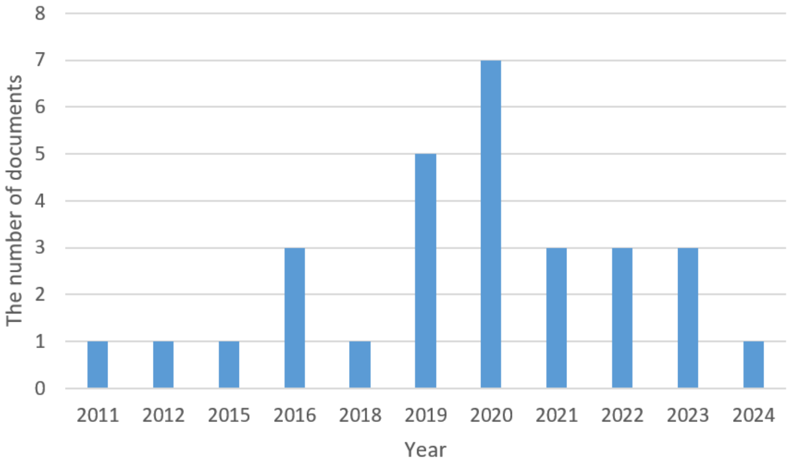


Figure 42. The number of documents in different years

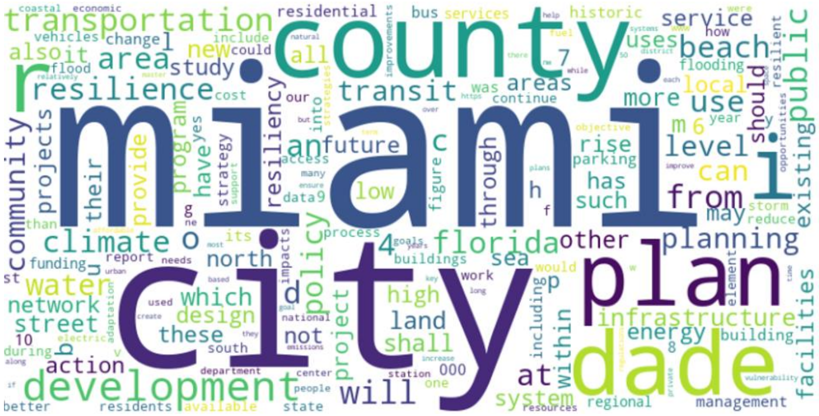


Figure 43. Word cloud of the documents

Following the collection of all transportation resilience planning documents, we coded two sets of nodes for analysis in the SNA model. The first set involved extracting and abbreviating document titles using acronyms, categorized into city level, county level, and regional level based on their planning scope. For the second set, we identified and abbreviated the names of stakeholders contributing to each document. These stakeholders were classified into five categories: public agencies, private industries, NGOs, academia, and community residents, based on a comprehensive literature review. A tie between nodes occurred when a stakeholder contributed to the planning document, creating a bipartite stakeholder-by-document network. Stakeholders were thus indirectly connected through the planning document, with ties representing affiliation relationships between stakeholders and transportation resilience planning documents. In our analysis, we treated the bipartite network as undirected and binary, and visualized it using Gephi version 0.10.1.

6.3.3. Network centrality measure

6.3.3.1. Degree centrality

Degree centrality measures the number of connections that a node has in a network. It quantifies the direct influence or connectivity of a node (Newman, 2008). Nodes with higher average degree centrality are directly connected to more nodes in the network. They play a significant role in the spread of information or influence due to their numerous connections. However, average degree centrality does not consider the quality or importance of the connections. This measure is useful for identifying nodes with many direct connections. However, it may overlook nodes that are indirectly influential or act as bridges between different parts of the network. The degree centrality is obtained by following (Ren et al., 2023):

$$C_d(i) = \sum_{j=1}^{N} x_{ij} \tag{30}$$

where $C_d(i)$ is the degree centrality of the node i; i is one node; j is another node; x_{ij} is the binary adjacency matrix ($x_{ij} = 1$ represents that node i is directly connected to node j; and $x_{ij} = 0$ otherwise.); N is total number of nodes of network.

6.3.3.2. Eigenvector centrality

Eigenvector centrality measures the influence of a node in a network based on the influence of its neighbors (Newman 2008). It considers both the quantity and quality of connections by assigning higher centrality scores to nodes connected to other highly central nodes. Nodes with higher eigenvector centrality scores are not only well-connected but are also connected to other highly central nodes. This measure captures the concept of indirect influence, where a node's importance is amplified by its connections to other influential nodes. Eigenvector centrality is more nuanced than average degree centrality as it considers the global network structure. It identifies nodes that are not only well-connected but also well-connected to other influential nodes, making it suitable for capturing the importance of nodes in complex networks. The eigenvector centrality can be expressed by following (Ren et al 2023):

$$C_{ev}(i) = \frac{1}{\lambda} \sum_{j=1}^{N} x_{ij}\, C_{ev}(j) \tag{31}$$

where $C_{ev}(i)$ and $C_{ev}(j)$ is degree centrality of the node i; x_{ij} is the binary adjacency matrix; N is total number of nodes of network.

6.3.3.3. Betweenness centrality

Betweenness centrality measures the extent to which a node lies on the shortest paths between pairs of other nodes in the network. It quantifies a node's control over the flow of information or resources between other nodes. Nodes with higher betweenness centrality scores act as bridges or bottlenecks in the network. They control the flow of information between different parts of the network and are crucial for maintaining connectivity. This measure captures the importance of nodes in facilitating communication pathways. Betweenness centrality complements average degree and eigenvector centrality by focusing on the node's position in the network rather than the number or quality of its connections. It identifies nodes that serve as critical intermediaries or connectors, playing a vital role in network communication and information flow. Betweenness centrality can be calculated by following (Ren et al 2023):

$$C_b(i) = \sum \frac{g_{jk}(i)}{g_{jk}},\ i \neq j \neq k \tag{32}$$

where $C_{ev}(i)$ is betweenness centrality of the node i; g_{jk} is the number of shortest paths between node j and node k; $g_{jk}(i)$ is the number of those paths that go through node i; the binary adjacency matrix; N is total number of nodes of network.

Degree centrality focuses on direct connections and is useful for identifying nodes with many connections. Eigenvector centrality considers both the quantity and quality of connections, capturing the influence of nodes connected to other influential nodes. Betweenness centrality identifies nodes that act as bridges or bottlenecks in the network, controlling the flow of information between different parts of the network.

6.3.4. Network visualization

The visualization depicted in Figure 44 illustrates a bipartite Social Network Analysis (SNA) model. Circular nodes symbolize transportation resilience planning documents, while nodes of varying shapes represent stakeholders from diverse sectors. The size of each node corresponds to its degree centrality within the network. Overall, the network comprises 176 nodes and 216 connections, with 147 nodes representing stakeholders and 29 nodes representing transportation resilience planning documents. Public agencies, private industries, and non-governmental organizations (NGOs) are prominently represented in the network, with 79 public stakeholders, 33 private stakeholders, and 10 NGO stakeholders. In contrast, academia and community residents have fewer representatives, including only 6 stakeholders from academia and 19 stakeholders from community residents. Examining node sizes based on degree centrality reveals key contributors to transportation resilience planning. Notably, Miami-Dade County, the City of Miami, the City of Miami Beach, the Florida Department of Transportation, and the Department of Transportation & Public Works emerge as significant public stakeholders. Among private stakeholders, Florida Power & Light and the Urban Land Institute exhibit substantial engagement. The NGO "100 Resilient Cities," funded by The Rockefeller Foundation, is prominently involved in transportation resilience initiatives. Academic stakeholders such as Florida International University, the University of Miami, and the University of Florida have made notable contributions, with Florida International University being the most active participant in the network.

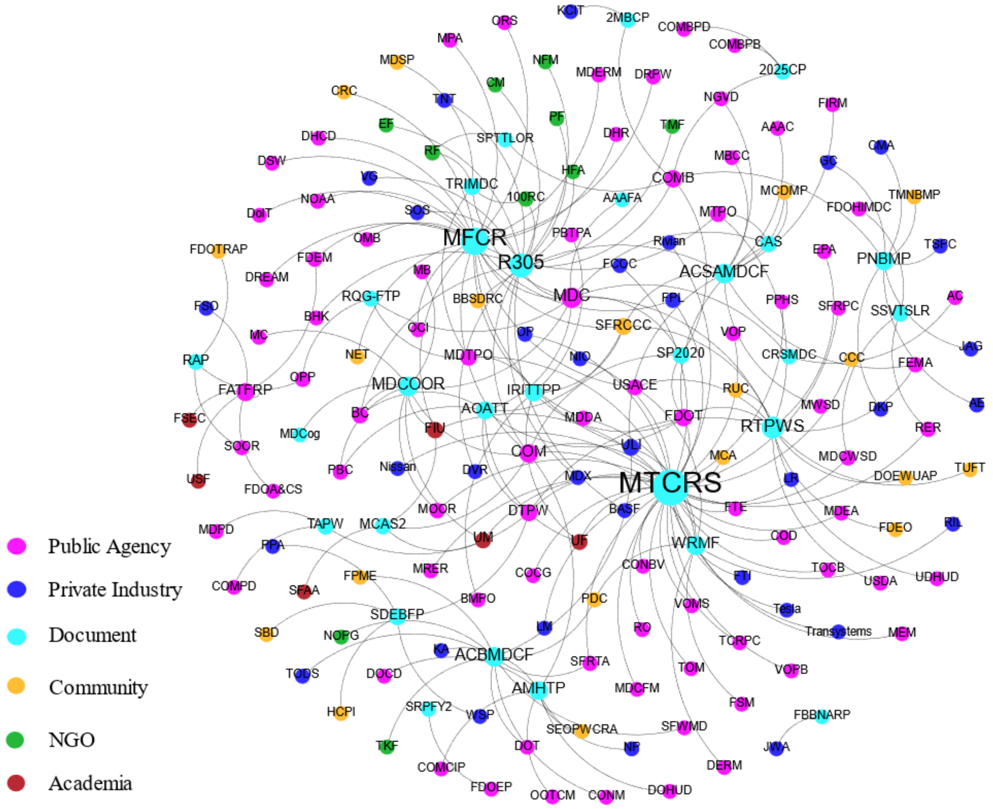


Figure 44. Bipartite network visualization

6.3.5. *Network centrality analysis*

The outcomes from the assessment of network centrality metrics, encompassing average degree, eigenvector, and betweenness centralities among the five stakeholder sectors, are presented in Figure 45-47. Academic and public agencies displayed higher average degree centralities compared to the community and NGO sectors. This suggests greater involvement of academia and public agencies in resilience planning efforts, potentially enhancing their expertise and influence within the network. Conversely, private industry exhibited the lowest average degree centrality, indicating less frequent contributions to transportation resilience planning documents.

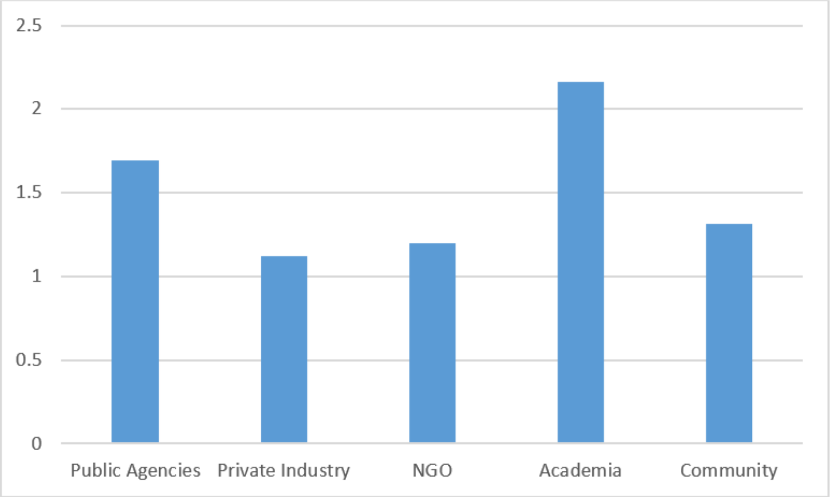


Figure 45. Average degree centralities by stakeholder sector

Substantial disparities were observed in average eigenvector centralities across the stakeholder sectors, with public agencies registering the highest values. Academia also demonstrated relatively higher average eigenvector centralities, underscoring their significance in key transportation planning documents. However, the NGO sector displayed the lowest average eigenvector centrality, indicating limited involvement in critical resilience planning initiatives.

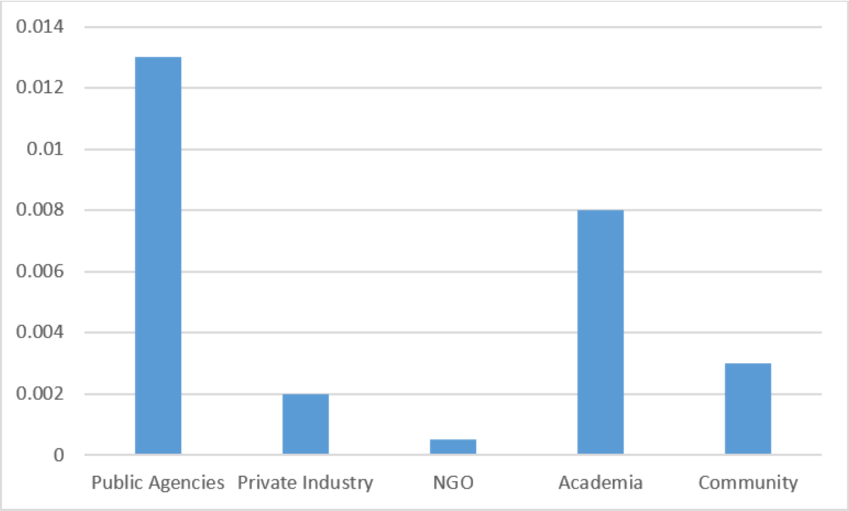


Figure 46. Average eigenvector centralities by stakeholder sector

Academic stakeholders exhibited the highest betweenness centrality among all sectors, signifying their dominant role in facilitating information flow and averting network fragmentation. Public agencies also demonstrated relatively higher betweenness centrality, emphasizing their pivotal role in coordinating information exchange across sectors. Conversely, community, private industry, and NGO sectors exhibited notably lower average betweenness centralities, reflecting their reduced control over information exchange and diminished influence in planning processes.

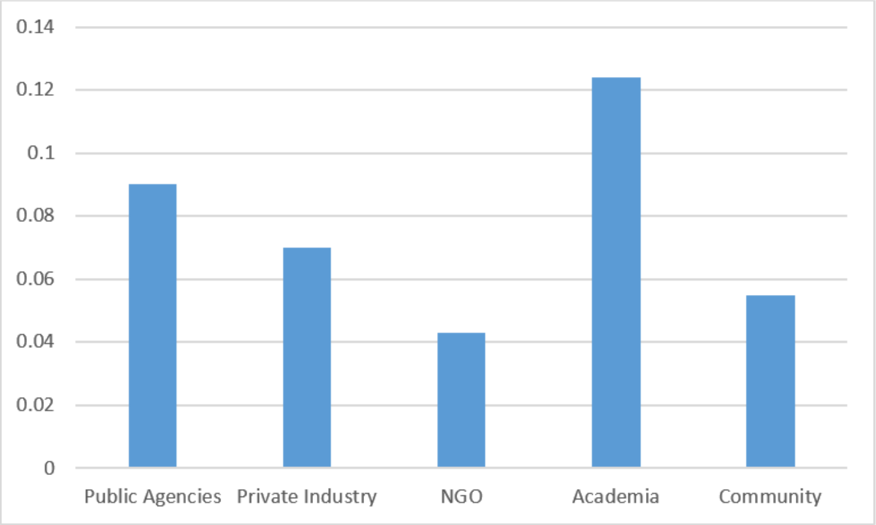


Figure 47. Average betweenness centralities by stakeholder sector

6.4. Discussion

After evaluating the network centrality measures for all stakeholder sectors, Kruskal-Wallis H tests were utilized to assess potential differences among these sectors in each centrality measure. The Kruskal-Wallis H test, a nonparametric method commonly employed for comparing multiple independent samples, was employed for this analysis. The test outcomes were evaluated based on the calculated probability value (p-value). A p-value below 0.05 indicates significant differences among the sectors. Subsequently, post hoc pairwise comparison tests, specifically Mann-Whitney U tests, were conducted to identify significantly distinct pairs of stakeholder groups. The obtained p-values for all three centrality measures were below 0.05, indicating significant differences among the stakeholder sectors in terms of centrality. Post hoc pairwise comparisons were subsequently conducted to identify significantly different pairs of sectors. Table 7 provides a summary of these post hoc comparisons, revealing similar patterns in the p-values across the three network measures. Notably, significant differences were observed between five pairs of stakeholder sectors: public and private stakeholders, public stakeholders and NGOs, public stakeholders and community residents, private stakeholders and NGOs, and private and academic stakeholders.

Table 7. Summary of post hoc pairwise comparisons

Pairwise combinations	Degree centrality	Eigenvector centrality	Betweenness centrality
PA v.s. PI	0.026	0.031	0.017
PA v.s. NGO	0.655	0.570	0.036
PA v.s. AC	0.140	0.260	0.698

PA v.s. CO	0.405	0.389	0.077
PI v.s. NGO	0.219	0.242	0.049
PI v.s. AC	0.003	0.006	0.515
PI v.s. CO	0.26	0.298	0.598
NGO v.s. AC	0.128	0.129	0.167
NGO v.s. CO	0.861	0.972	0.277
AC v.s. CO	0.081	0.081	0.178

The findings from social network analysis consistently highlight the greater involvement of public agencies in transportation resilience planning compared to sectors such as NGOs, private industries, and community. The pivotal role of public agencies in resilience planning processes. This heightened involvement may stem from public agencies' strong sense of societal responsibility in enhancing transportation resilience. Additionally, political leaders often prioritize city resilience to benefit local communities and bolster their own political standing. Furthermore, public agencies are adept at coordinating diverse resources and fostering collaboration among stakeholders, thanks to their organizational capabilities, leadership, and access to various resources such as funding and emergency services.

Their active engagement underscores a collaborative decision-making environment that integrates diverse epistemic perspectives to address complex public challenges. Given the ongoing threat of disasters, there is a critical need for scientific knowledge generation and policy interventions to mitigate disaster risks. Academic stakeholders contribute invaluable expertise and research insights to support resilience efforts, providing evidence-based recommendations and measurable outcomes that inform policy formulation. Their involvement ensures the integration of cutting-edge knowledge and innovations into resilience practices, maximizing the utilization of expertise and fostering knowledge transfer for effective policy implementation. Moreover, academic stakeholders contribute to public education and training throughout resilience planning processes, enhancing public awareness and preparedness for disaster response. In contrast, relatively limited involvement of community residents in transportation compared to other sectors. Upon closer examination of the transportation resilience documents, we observed a lack of formal recognition of community's contributions, with discussions about their involvement being generally ambiguous. Furthermore, our analysis revealed that the representation of community organizations predominantly consisted of homeowner associations, which predominantly represent property owners and may overlook the perspectives of renters or the homeless population. This suggests that a significant segment of the community may have limited opportunities to participate in resilience planning processes, and their voices may not be adequately heard. Despite the potential challenges associated with community engagement, it remains essential for the success of transportation resilience planning initiatives. Community residents, being directly affected by resilience efforts, provide valuable insights into their values and needs, which are integral for designing user-centered resilience strategies. Although various barriers such as financial constraints, cultural diversity, and distrust in government may hinder community engagement, it is imperative to systematically involve community residents in resilience planning. Such engagement facilitates open dialogue and fosters a sense of empowerment among community residents, leading to more inclusive and effective resilience initiatives. Additionally, empowering community residents with knowledge and garnering their support for resilience initiatives can facilitate smoother policy implementation and ultimately enhance the resilience of communities.

6.5. Summary

This chapter provides an in-depth exploration of multisector stakeholder collaborations and their application in enhancing transportation resilience. It begins by defining multisector stakeholder collaboration as the process of bringing together individuals, organizations, and groups from diverse sectors to collectively address complex challenges or promote social change. The chapter emphasizes the interconnected nature of societal issues and the importance of collaboration across government, non-profit organizations, businesses, academia, and communities. Key themes discussed in the chapter include interagency coordination, public-private partnerships, community engagement, and cross-sector collaborations. These themes highlight the necessity of coordinated efforts among multiple sectors to address the vulnerabilities of transportation systems and enhance their resilience against various disruptions.

The chapter also introduces the Bipartite Social Network Analysis (SNA) model as a framework for analyzing relationships between stakeholders involved in transportation resilience planning. It discusses network centrality measures such as degree centrality, eigenvector centrality, and betweenness centrality, and their implications for understanding stakeholder dynamics and influence within the network. Findings from the network analysis reveal the significant involvement of public agencies and academic institutions in transportation resilience planning, while highlighting the limited engagement of private industries and community residents. The chapter concludes with recommendations for fostering more inclusive and effective multisector collaboration in transportation resilience initiatives, emphasizing the importance of community engagement and equitable representation of stakeholders.

CHAPTER 7. CONCLUSION AND FUTURE STUDY

7.1. Conclusion

In the face of the ever-present threat of hurricanes in coastal areas, it is imperative to ramp up research efforts to ensure swift and fair restoration of bridge and roadway networks. This project has yielded a tool designed to assess community resilience in terms of accessing critical services post-hurricanes, accompanied by a decision-making framework to incorporate equity into the restoration process of these networks. Key outcomes include the development of a flooding map pinpointing vulnerable roads and bridges, an optimization model integrating equity considerations into restoration strategies, and the establishment of collaborative networks across various sectors to optimize recovery sequences.

Utilizing FEMA historical data alongside GIS technology, this project has facilitated the creation of 2D flooding maps, crucial for identifying vulnerable segments of the road network and categorizing flood risks.

In analyzing post-hurricane accessibility, a strong correlation between accessibility and the presence of essential service facilities has been observed, emphasizing the pivotal role of facility distribution in ensuring residents' accessibility. However, spatial imbalances in accessibility within the Miami area have been noted, potentially resulting in underserved communities, particularly during emergencies. Furthermore, accessibility may drastically decrease during natural disasters, necessitating prompt restoration of the road network to improve residents' access to emergency services and basic necessities.

The development of a bi-level optimization model, coupled with a genetic algorithm for solution-finding, has enabled the integration of equity considerations into the restoration phase of coastal bridge and roadway networks. Pilot studies conducted in Miami Shores have demonstrated the influence of varying weights assigned to equity quantification and mobility on recovery planning outcomes, shedding light on the complexity of the process. Factors such as network demand, initial capacity, post-hurricane capacity, and other hyperparameters play critical roles in determining priority links for restoration, highlighting the need for a comprehensive approach to recovery planning.

In delving into multisector stakeholder collaborations, the introduction of the Bipartite Social Network Analysis (SNA) model has provided a framework for analyzing relationships between stakeholders involved in transportation resilience planning. Central to this analysis are measures such as degree centrality, eigenvector centrality, and betweenness centrality, offering insights into stakeholder dynamics and influence within the network. Despite significant involvement from public agencies and academic institutions, limited engagement from private industries and community residents has been noted. Recommendations have been made for fostering inclusive and effective multisector collaboration in transportation resilience initiatives, stressing the importance of community engagement and equitable representation of stakeholders.

In conclusion, this project marks a significant step towards enhancing Greater Miami's resilience against hurricane threats. By integrating data-driven approaches, equitable considerations, and collaborative frameworks, the groundwork has been laid for more effective policies and measures aimed at bolstering community resilience and ensuring timely access to essential services during emergencies. Continued research and concerted efforts across sectors will be vital in translating these findings into tangible improvements in transportation resilience and community well-being.

7.2. Future Study

As the threat of hurricanes looms large over coastal cities, urgent research endeavors are imperative to fortify the resilience of bridge and roadway networks, ensuring swift and equitable restoration efforts. Building upon the foundation laid by the project outlined, several key avenues for future investigation emerge:

While our project provided valuable insights through 2D flooding maps, the development of a high-resolution 3D flooding inundation framework is essential. This framework would enable the accurate prediction of flooding levels over time, identifying impassable nodes and links within road networks well in advance of extreme events. By employing forecasted maps updated in real-time, jurisdictions can proactively pinpoint affected areas, facilitating efficient response measures. Integration with Urban Transportation Modelling Systems (UTMS) can further enhance our ability to assess vehicle flow and travel time under various flooding scenarios.

In this project, static accessibility comparisons offer only a partial understanding of post-hurricane conditions. Future research must focus on developing dynamic models capable of accounting for elastic demand, predicting changes in accessibility amidst evolving road conditions and emergency responses. Leveraging machine learning algorithms and crowd-sourced data promises to refine these models, enabling more accurate resource allocation and evacuation planning strategies.

Refinement of optimization models to better incorporate equity considerations is imperative for post-hurricane recovery planning. Conducting sensitivity analyses to gauge the impact of equity weights on recovery strategies and devising tactics to mitigate disparities across communities are essential steps in this endeavor.

Exploring policy interventions and governance structures that prioritize equity, sustainability, and resilience in transportation infrastructure investments is paramount. This may entail advocating for legislative reforms, incentivizing green infrastructure solutions, and fostering intergovernmental collaboration to address multifaceted challenges spanning jurisdictional boundaries.

By pursuing these future research directions, stakeholders can propel the resilience of coastal transportation infrastructure forward, ensuring equitable access to critical services before, during, and after hurricanes. Through collaborative efforts between policymakers, planners, and practitioners, we can build a more resilient and inclusive framework to confront the challenges posed by extreme weather events.

REFERENCES

Baglin, C. NCHRP Synthesis 454: Response to Extreme Weather Impacts on Transportation Systems. TRB, National Research Council, Washington, D.C., 2014. https://nap.nationalacademies.org/download/22376

Baroud, H., Barker, K., Ramirez-Marquez, J. E., & Rocco, C. M. (2014a). Importance measures for inlandwaterway network resilience. *Transportation Research Part E: Logistics and Transportation Review*,62(1), 55–67.

BC096-17, Post-Disaster Dynamic Routing of Emergency Vehicles, 2003, Florida Department of Transportation. Traffic Engineering and Operations.

BD548-05, Framework for Modeling Emergency Evacuation, 2005, Florida Department of Transportation. Traffic Engineering and Operations.

Bocchini, P., & Frangopol, D. M. (2012). Optimal resilience-and cost-based postdisaster intervention prioritization for bridges along a highway segment. *Journal of Bridge Engineering*, *17*(1), 117-129.

Bocchini, P., & Frangopol, D. M. (2012). Restoration of bridge networks after an earthquake: Multicriteria intervention optimization. *Earthquake Spectra*, *28*(2), 427-455.

Boselly, S. E. Roadway Flash Flood Warning Devices Feasibility Study: Final Report for ITS-IDEA Project 79. TRB, National Research Council, Washington, D.C., 2001. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://onlinepubs.trb.org/onlinepubs/sp/its-idea_79.pdf

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., ... & Von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake spectra*, *19*(4), 733-752.

Chen, L., & Miller-Hooks, E. (2012). Resilience: an indicator of recovery capability in intermodal freight transport. *Transportation Science*, *46*(1), 109-123.

Cimellaro, G. P., Renschler, C., Arendt, L., Bruneau, M., & Reinhorn, A. M. (2011, July). Community resilience index for road network systems. In *EURODYN* (Vol. 2011, p. 8th).

Cutter, S. (2006). The geography of social vulnerability: Race, class, and catastrophe. *Understanding Katrina: Perspectives from the social sciences*, 120-122.

Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., & Webb, J. (2008). Community and regional resilience: Perspectives from hazards, disasters, and emergency management. *Geography*, 1(7), 2301-2306.

Dewberry and Venner Consulting. NCHRP Project 20-59/Task 53: FloodCast: A Framework for Enhanced Flood Event Decision Making for Transportation Resilience. Technical Memorandum #1. 2015. Chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/http://floodcast.info/wordpress/wp-content/uploads/2018/07/NCHRP-20-5953Floodcast-Practitioner-Guidebook.compressed.pdf

Dorbritz, R. (2011). Assessing the resilience of transportation systems in case of large-scale disastrousevents. *InProceedings of the 8th International Conference on Environmental Engineering*, 1070–1076.

Emrich, C. T., Aksha, S. K., & Zhou, Y. (2022). Assessing distributive inequities in FEMA's Disaster recovery assistance fund allocation. *International Journal of Disaster Risk Reduction*, 74, 102855.

Enjalbert, S., Vanderhaegen, F., Pichon, M., Ouedraogo, K. A., & Millot, P. (2011). Assessment of trans-portation system resilience. *In Human modelling in assisted transportation*(pp. 335–341). SpringerMilan.496C. WAN ET AL.

Faturechi, R., & Miller-Hooks, E. (2015). Measuring the performance of transportation infrastructure systems in disasters: A comprehensive review. *Journal of infrastructure systems*, 21(1), 04014025.

Faturechi, R., Levenberg, E., & Miller-Hooks, E. (2014). Evaluating and optimizing resilience of airport pavement networks. *Computers & Operations Research*, *43*, 335-348.

Franchin, P., Lupoi, A., & Pinto, P. E. (2006). On the role of road networks in reducing human losses after earthquakes. *Journal of earthquake engineering*, *10*(02), 195-206.

GM&B (Greater Miami and the Beaches). 2019.“Resilient 305 strategy.” Accessed May 20, 2021. https://resilient305.com/wp-content/uploads/2019/05/Full-Strategy-2.pdf.

Hoppe, H. U., Harrer, A., Göhnert, T., & Hecking, T. (2016). Applying network models and network analysis techniques to the study of online communities. *Mass Collaboration and Education*, 347-366.

Iowa DOT: The Iowa DOT has implemented the Iowa Flood Information System (IFIS) (https://ifis.iowafloodcenter.org/ifis/)

Kelman, I. (2011). *Disaster diplomacy: how disasters affect peace and conflict*. Routledge.

Knutson, T. R., Chung, M. V., Vecchi, G., Sun, J., Hsieh, T. L., & Smith, A. J. (2021). Climate change is probably increasing the intensity of tropical cyclones. *Critical Issues in Climate Change Science, Science Brief Review*. https://doi. org/10.5281/zenodo, 4570334(4).

Lambora, A., Gupta, K., & Chopra, K. (2019). Genetic algorithm-A literature review. *In 2019 international conference on machine learning, big data, cloud and parallel computing (COMITCon)* (pp. 380-384). IEEE.

Levenberg, E., Miller-Hooks, E., Asadabadi, A., & Faturechi, R. (2017). Resilience of networked infrastructure with evolving component conditions: Pavement network application. *Journal of Computing in Civil Engineering*, *31*(3), 04016060.

Louisiana DOTD (http://www.dotd.la.gov/Inside_LaDOTD/Divisions/Engineering/Public_Works/NFIP/Misc%20 Documents/Flood%20Risk%20Reports/Amite%20-%20Flood%20Risk%20Report.pdf)

Mendelsohn, R. O., Emanuel, K., & Chonabayashi, S. (2011). The impact of climate change on hurricane damages in the United States. *World Bank Policy Research Working Paper*, (5561).

Miller-Hooks, E., Zhang, X., & Faturechi, R. (2012). Measuring and maximizing resilience of freight transportation networks. *Computers & Operations Research*, *39*(7), 1633-1643.

Minnesota DOT (https://www.dot.state.mn.us/its/projects/2016-2020/systemsengineeringforitsandcav/floodwarningse.pdf)

Mitchell, M. (1998). *An introduction to genetic algorithms*. MIT press.

Newman, M. E. (2008). The mathematics of networks. *The new palgrave encyclopedia of economics*, 2(2008), 1-12.

Nicholson, D., Vanli, O. A., Jung, S., & Ozguven, E. E. (2019). A spatial regression and clustering method for developing place-specific social vulnerability indices using census and social media data. *International Journal of Disaster Risk Reduction*, 38, 101224.

Park, S., Smith, V., & Hyde, A. (2021). Practices for Integrated Flood Prediction and Response Systems (No. NCHRP Project 20-05, Topic 51-10). https://nap.nationalacademies.org/download/26330

Ren, H., Zhang, L., Whetsell, T. A., & Ganapati, N. E. (2023). Analyzing Multisector Stakeholder Collaboration and Engagement in Housing Resilience Planning in Greater Miami and the Beaches through Social Network Analysis. *Natural Hazards Review*, 24(1), 04022036.

Risk, A. (1994). Natural Hazards, People's Vulnerability, and Disasters. *London and New York: Routledge*.

Sadri, A. M., Ukkusuri, S. V., & Gladwin, H. (2017). The role of social networks and information sources on hurricane evacuation decision making. *Natural Hazards Review*, 18(3), 04017005.

Shafieezadeh, A., & Ivey Burden, L. (2014). Scenario-based resilience assessment framework for criti-cal infrastructure systems: Case study for seismic resilience of seaports. *Reliability Engineering &System Safety*,132, 207–219.

Shinozuka, M., & Chang, S. E. (2004). Evaluating the disaster resilience of power networks and grids. *In Modeling spatial and economic impacts of disasters* (pp. 289-310). Berlin, Heidelberg: Springer Berlin Heidelberg.

Testa, A. C., Furtado, M. N., & Alipour, A. (2015). Resilience of coastal transportation networks faced with extreme climatic events. *Transportation Research Record*, 2532(1), 29-36.

Wu, Y., Hou, G., & Chen, S. (2021). Post-earthquake resilience assessment and long-term restoration prioritization of transportation network. *Reliability Engineering & System Safety*, 211, 107612.

Zhang, L., Wen, Y., & Jin, M. (2009). The framework for calculating the measure of resilience for intermodal transportation systems (No. 10-05-09). *National Center for Intermodal Transportation*.

Zhao, T., & Zhang, Y. (2020). Transportation infrastructure restoration optimization considering mobility and accessibility in resilience measures. *Transportation Research Part C: Emerging Technologies*, 117, 102700.