FLORIDA STATE
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Equitable Restoration Strategies for Bridge and Road Infrastructure Networks after Hurricanes in Coastal Communities

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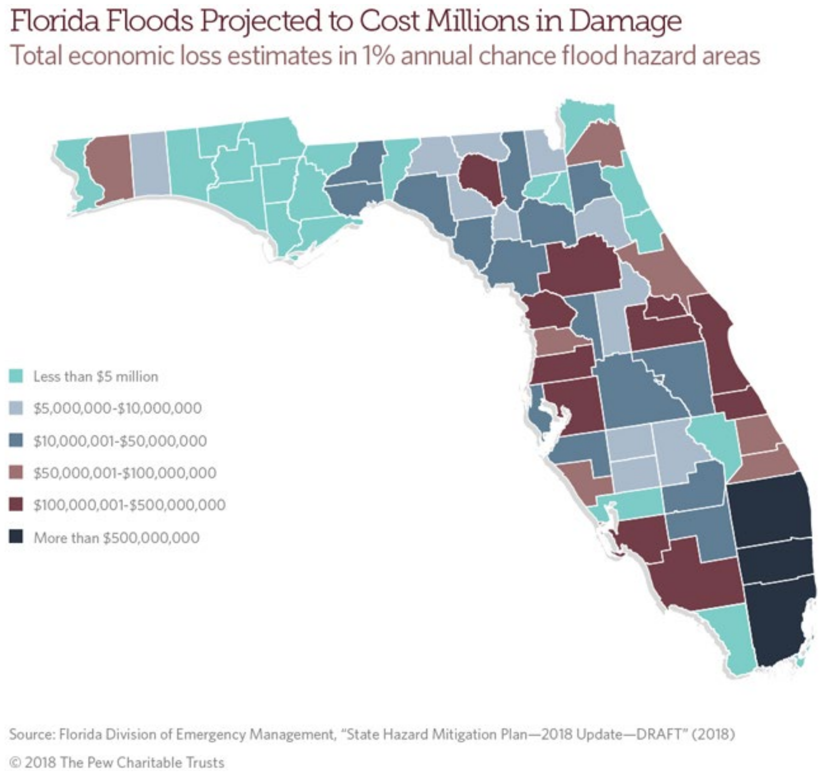
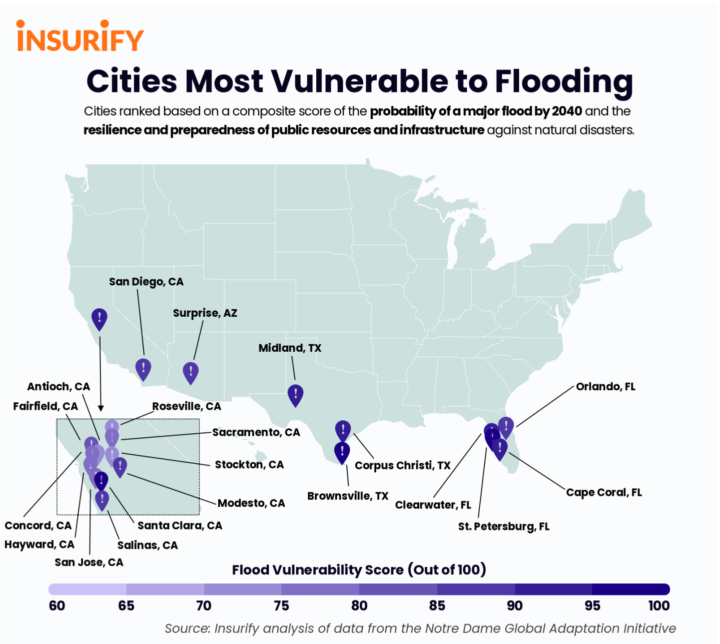
Outline

- Background
- Literature Review
- Development of the 2D Flooding Map
- Quantification of Accessibility
- Equitable Restoration Plan
- Multisector Stakeholder Collaboration and Engagement for Transportation Resilience
- Conclusion and Future Study

Background

- 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

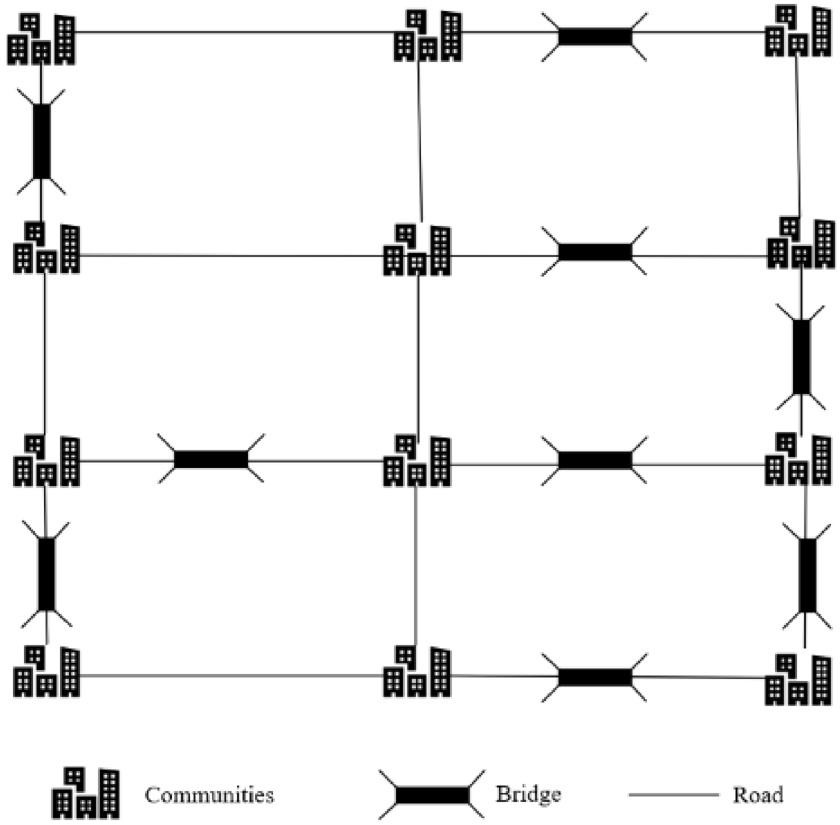




Background

- Bridge and road network play a vital role in ensuring the economic and social well-being of a after hurricane.

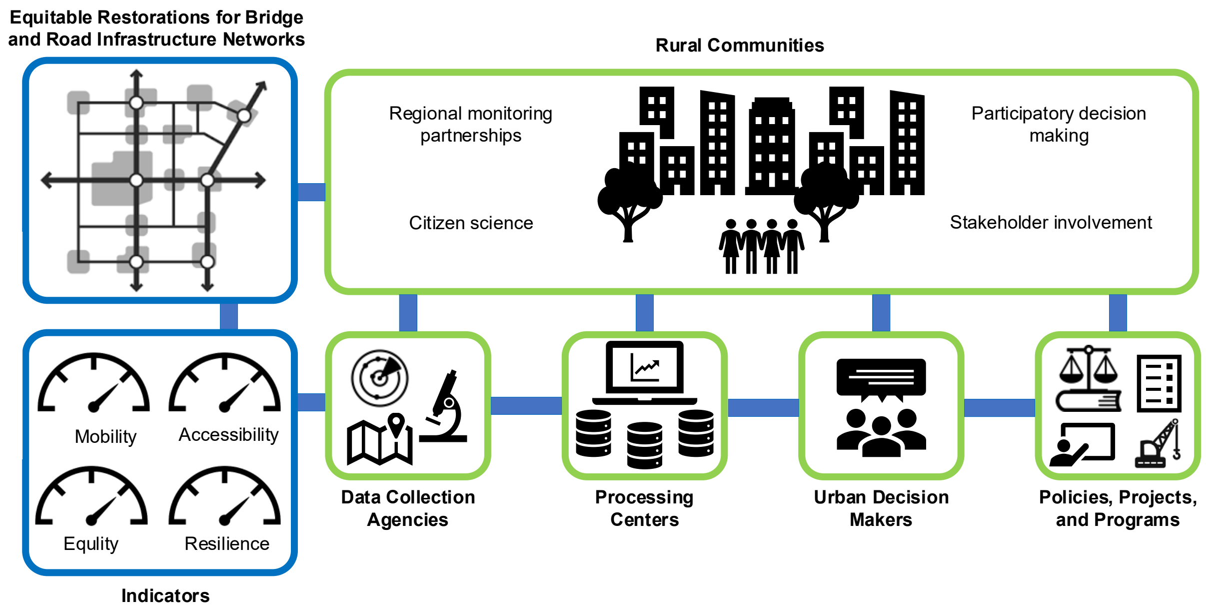
- Repair and reconstruction of Bridge and road network in rural area consumes tremendous material and labor resources.



Background

- In rural area, a nearly equal network cost to different destinations for different people indicates an equitable level of spatial distribution.

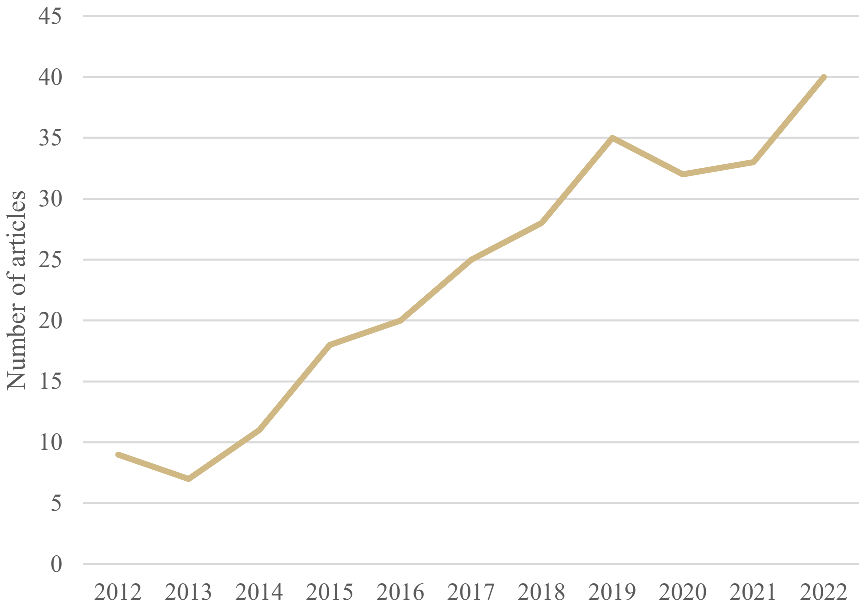
- Transportation practitioners in the United States, for example, have been advised to avoid disproportionate adverse impacts on minority and low-income groups and to mitigate such impacts when possible.



Equitable restoration in rural area

Literature Review

- The keywords used in the search include resilience + one of (transportation system, transportation network, road and bridge, road network) + one of (restoration strategy, recovery and responsive).



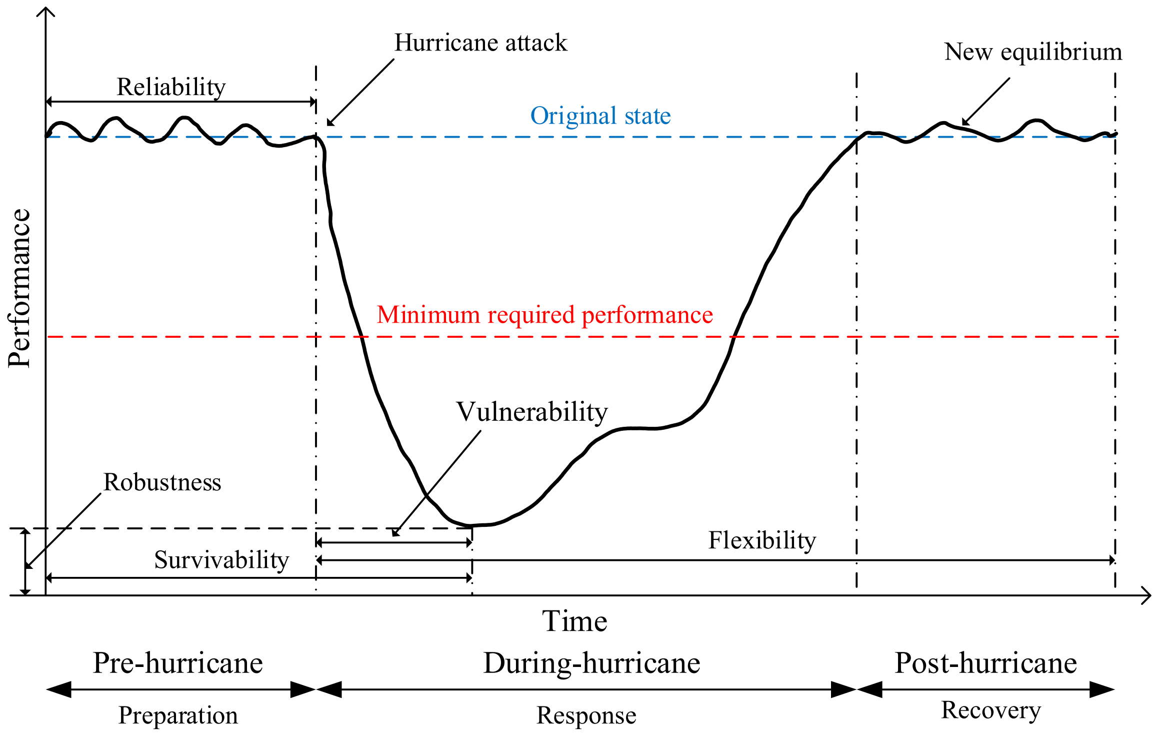
No.	Journal title	Articles
1	Transportation Research Record	35
2	Transportation Research-Part A	32
3	Reliability Engineering and Systems Safety	25
4	Risk Analysis	12
5	Transportation Research-Part C	20
6	Transportation Research-Part E	18
7	IEEE Transactions on Intelligent Transportation Systems	16
8	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

Literature Review

Bridge and road infrastructure network resilience in hurricane

- A well-accepted definition of infrastructure system resilience is presented in Bruneau et al. (2003).

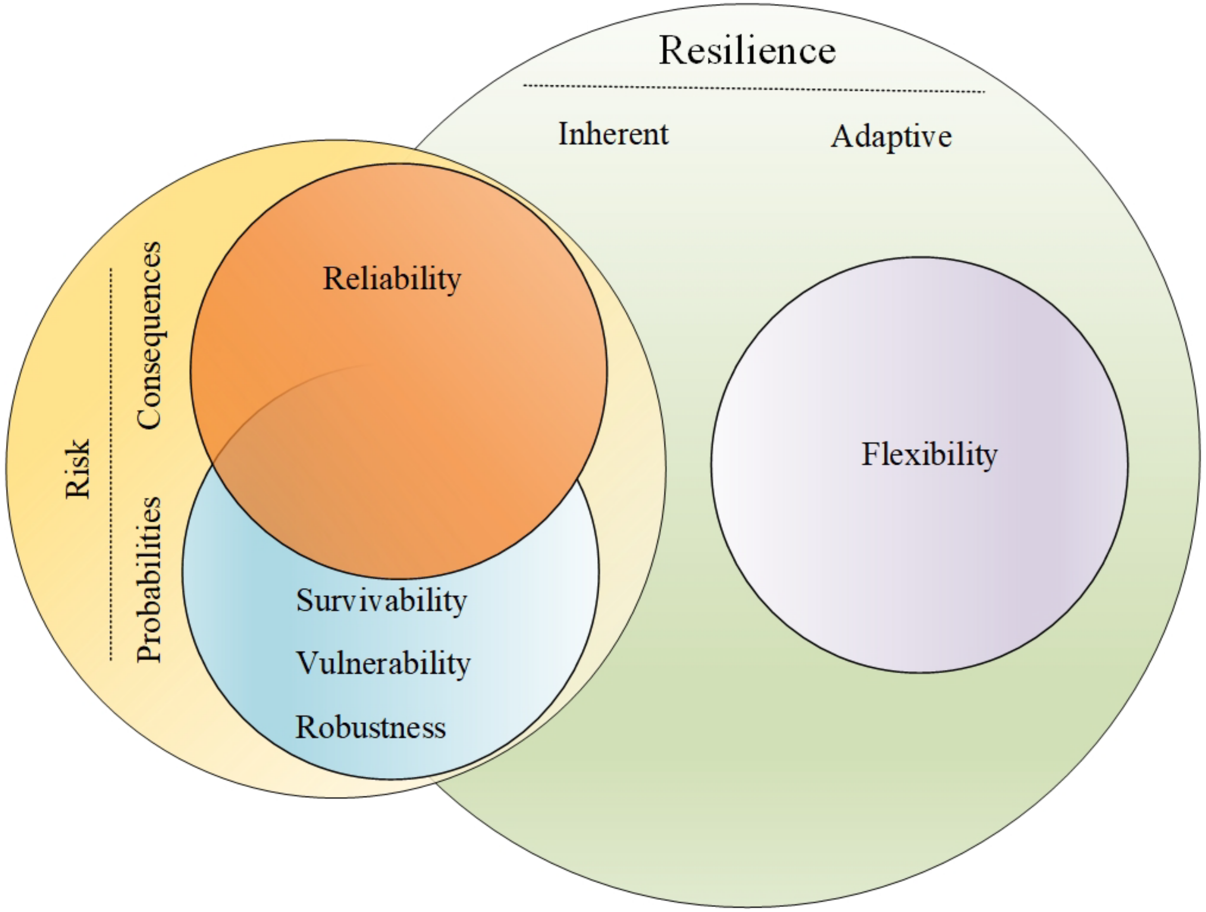
- Then it is newly developed by the authors with reference to Enjalbert et al. (2011), Dorbritz (2011), Baroud et al. (2014a), and Shafieezadeh and Ivey Burden (2014).



Literature Review

Bridge and road infrastructure network resilience in hurricane

- Faturechi and Miller-Hooks (2015) summarized five terms to describe the resilience and its characteristics including: reliability, robustness, flexibility, survivability and vulnerability.



Literature Review

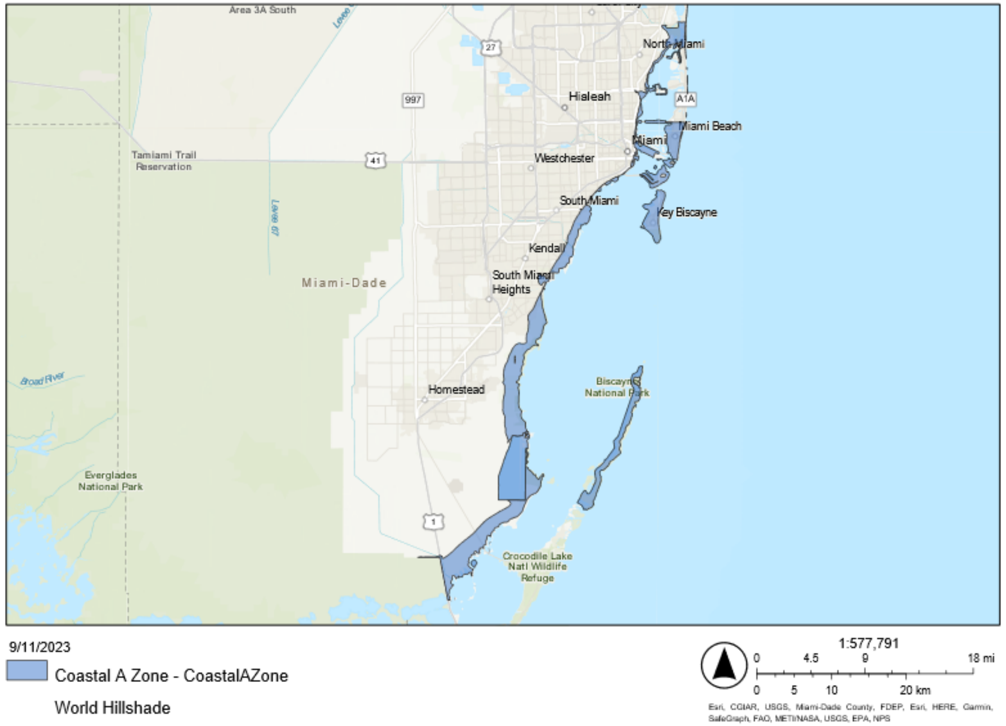
Bridge and Road Infrastructure Network Resilience in Hurricane

Reliability : It is generally defined as the probability that a network remains operative given the occurrence of a disruption event. It can be either a pre-or post-disruption metric for measuring system performance.
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.
Flexibility : . It is the ability of a system to respond to shocks and adjust itself to changes through contingency planning after disruptions.
Survivability : It is generally defined as the ability to withstand sudden disturbances while meeting original demands.
Vulnerability : It is defined as the susceptibility to damage or perturbation – especially where small damage or perturbation leads to disproportionate consequences.

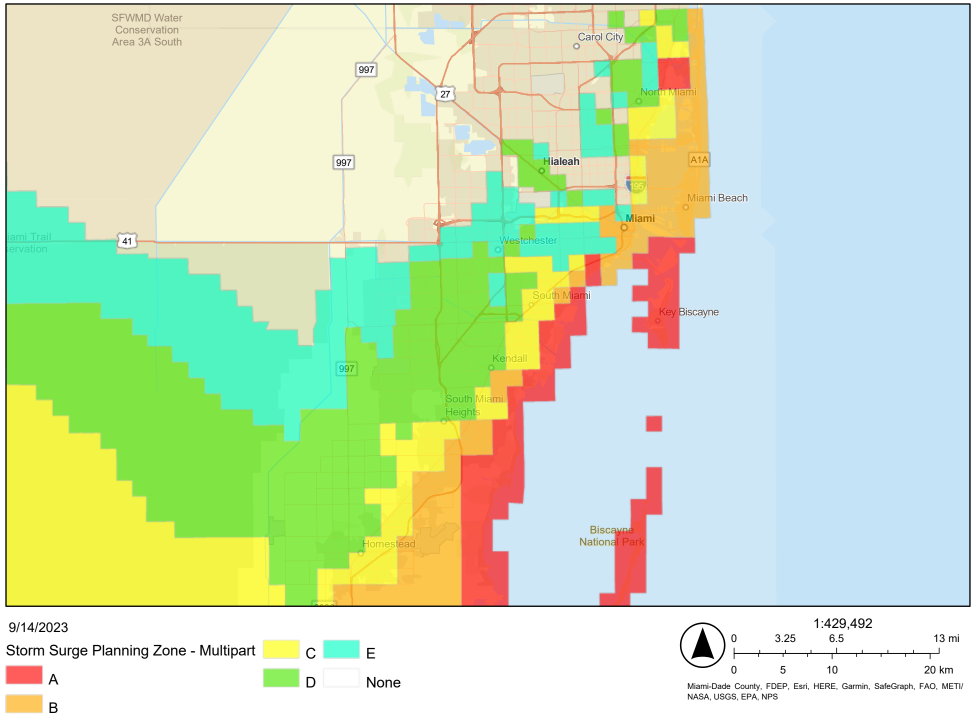
Development of A 2D Flooding Map

Study Area

- Miami is a coastal city situated along the shores of Biscayne Bay and the Atlantic Ocean. As a result, it is highly susceptible to coastal flooding. Storm surges from hurricanes and tropical storms can lead to severe flooding, particularly in low-lying coastal areas.



Coastal zone of Miami

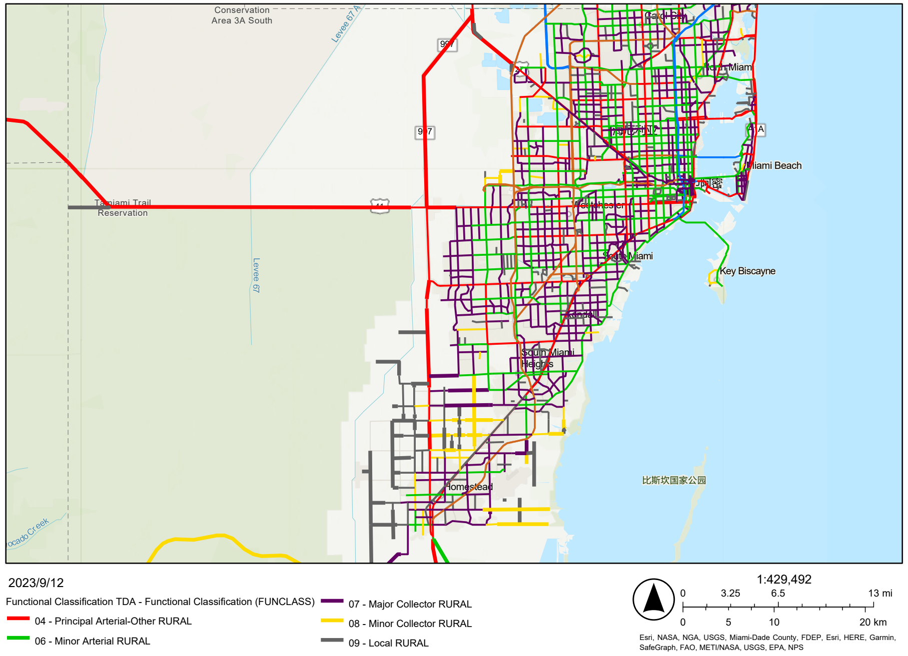


Storm surge zone of Miami Dade County

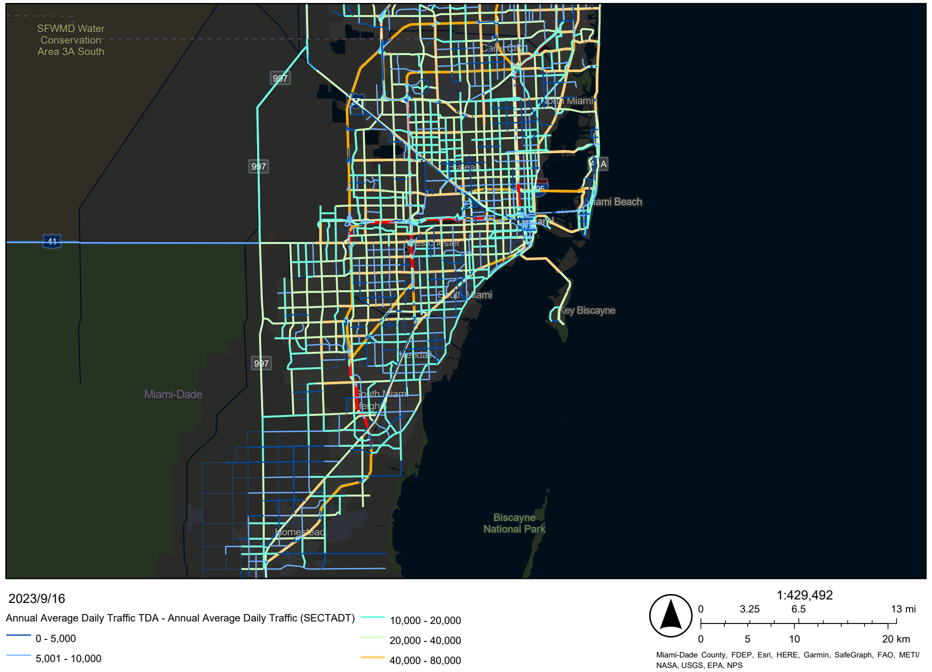
Development of A 2D Flooding Map

Transportation Network Data

- Florida uses the Federal Functional Classification System, which is common to all states.
- 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



Transportation network of Miami Dade County
(https://cosspp.maps.arcgis.com/home/item.html?id=5c629bc81b104fca8d937343cdcefe29)



AADT of Miami Dade County
(https://tdaappsprod.dot.state.fl.us/fto/)

Development of A 2D Flooding Map

FEMA History Data

- The Federal Emergency Management Agency (FEMA) periodically updates those maps for flood zone.

ZONE AE : Flood depths greater than three feet, Mandatory flood insurance purchase requirement.

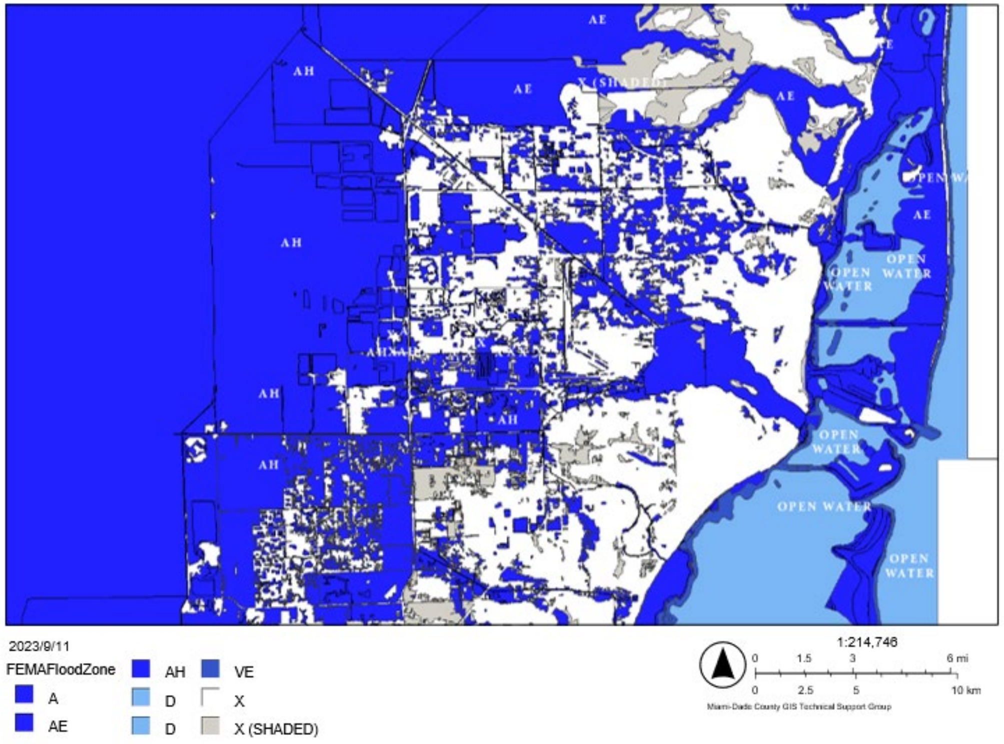
ZONE AH : Areas with a 1% annual chance of shallow flooding, usually ponding with flooding risk less then 1 feet. These areas have a 26% chance of flooding over the life of a 30-year mortgage. Mandatory flood insurance purchase requirements.

ZONE AO : Areas with a 1% or greater chance of shallow flooding, usually sheet flow with an average depth ranging from 1 to 3 feet. Mandatory flood insurance purchase requirements.

ZONE VE : This is the flood insurance rate zone that corresponds to coastal areas that have additional hazards associated with storm waves, which is meet high flooding risk. (greater than three feet)

Zone D : Areas with possible but undetermined flood hazards. No flood hazard analysis has been conducted.

Zone X : This zone is moderate-to-low-risk areas, that flood depth is 1 to 3 feet.



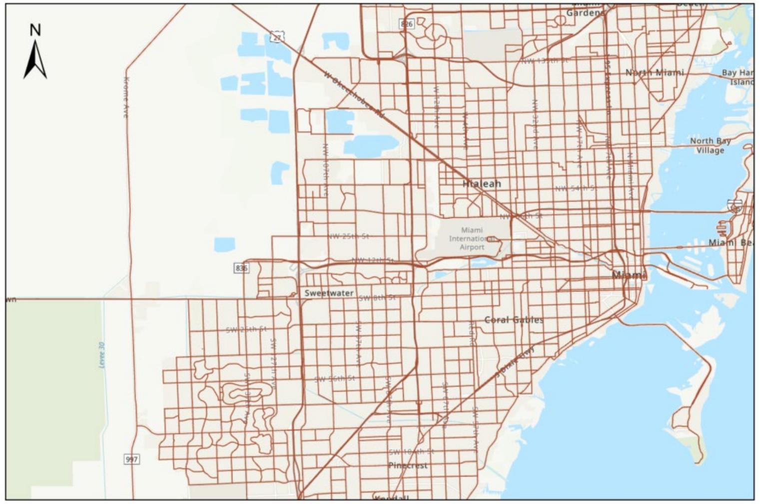
FEMA flood zone in Miami Dade county
(https://www.arcgis.com/home/item.html?id=0e7925d988e24d05aa4a9573fd542529)

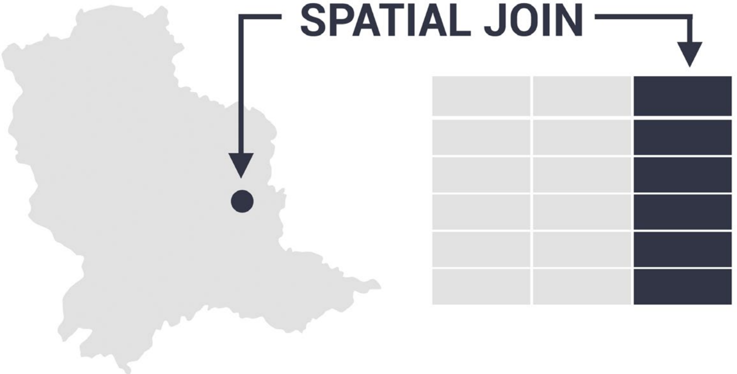
Development of A 2D Flooding Map

FEMA History Data

- The FEMA historical data will be used to generate 2D flooding maps to determine the bridge and road network that may flood by; and how high floodwaters may get.

- Combining the Miami-Dade road network data with the FEMA flood zone data, we were able to identify the road network in different zones by using the spatial join tool of ArcGIS Pro.

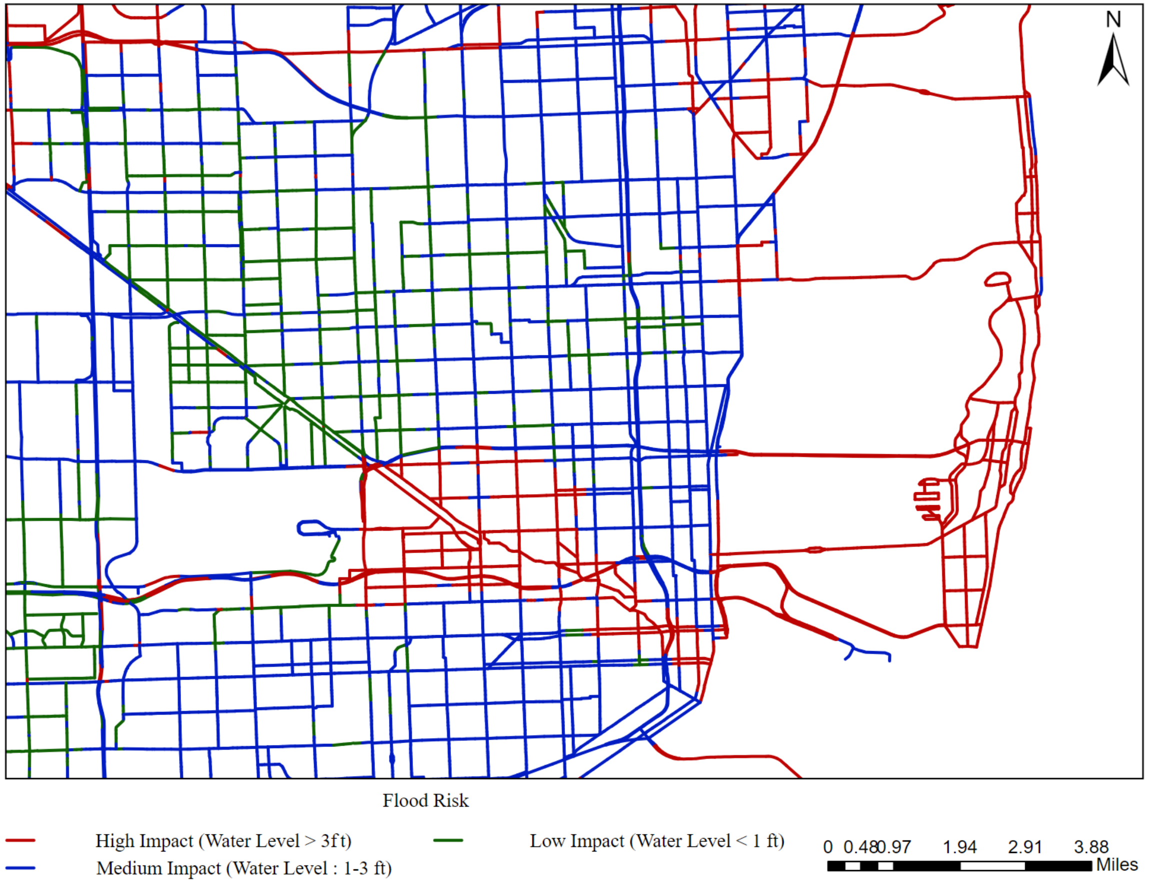




Development of A 2D Flooding Map

2D Flooding Map

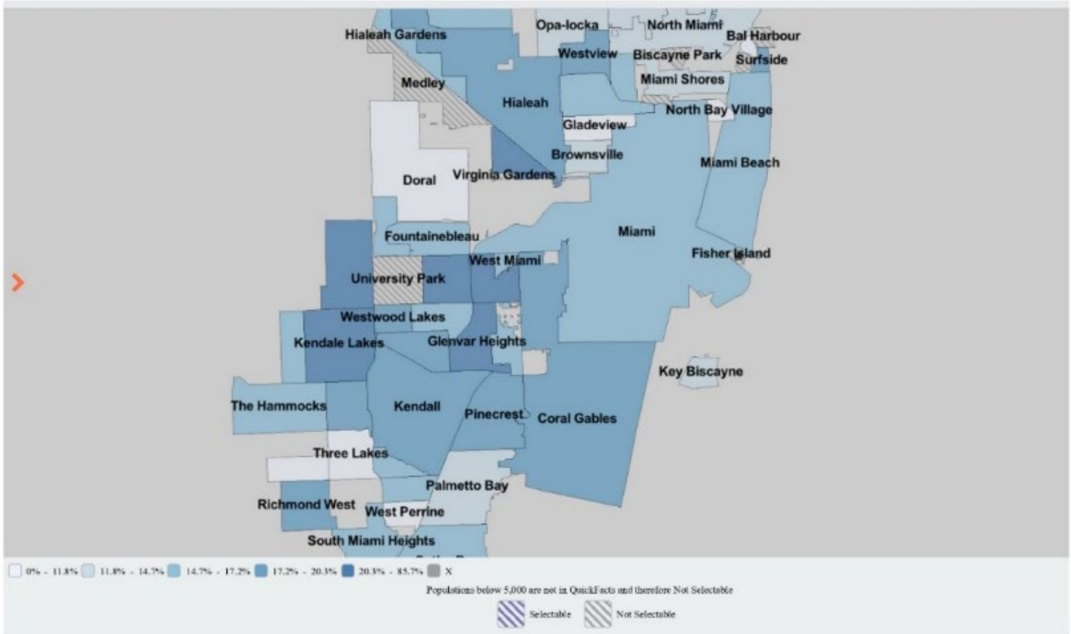
- Based on FEMA flood data, we categorize flood risk into three levels:
  - High Impact : Water level > 3 ft
  - Medium Impact: Water level: 1-3 ft
  - Low Impact: Water level < 1 ft



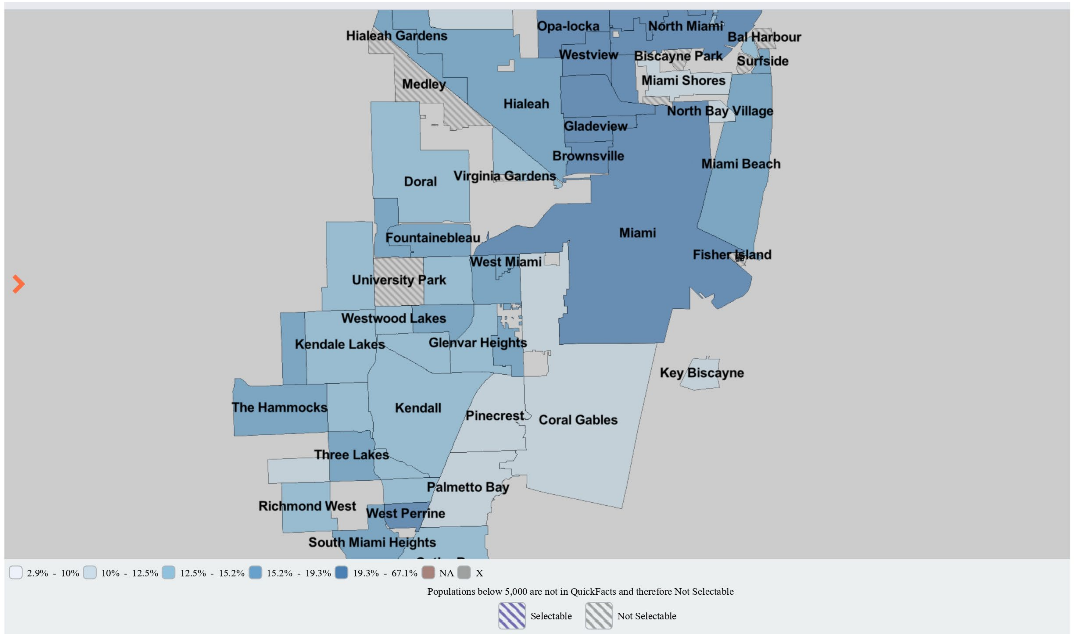
Quantification of Accessibility

Demographic data 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.



Persons over 65 years and over in Miami Dade County

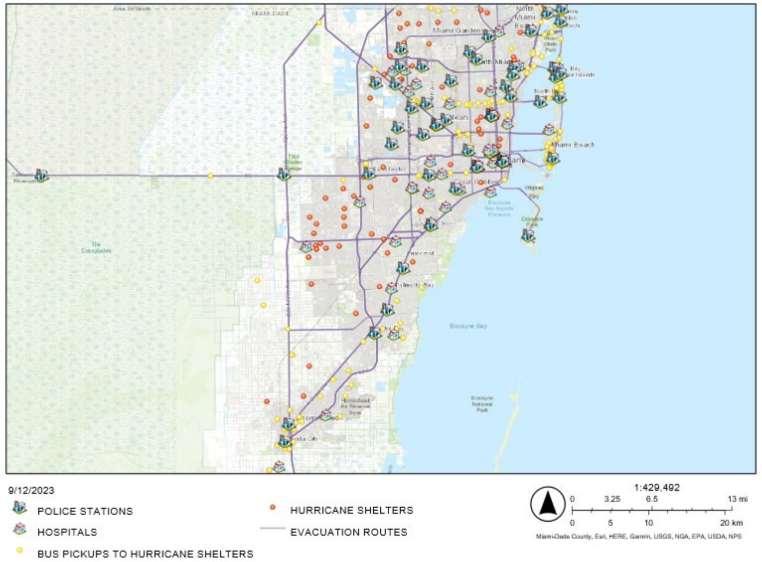


Poverty population density in Miami Dade County

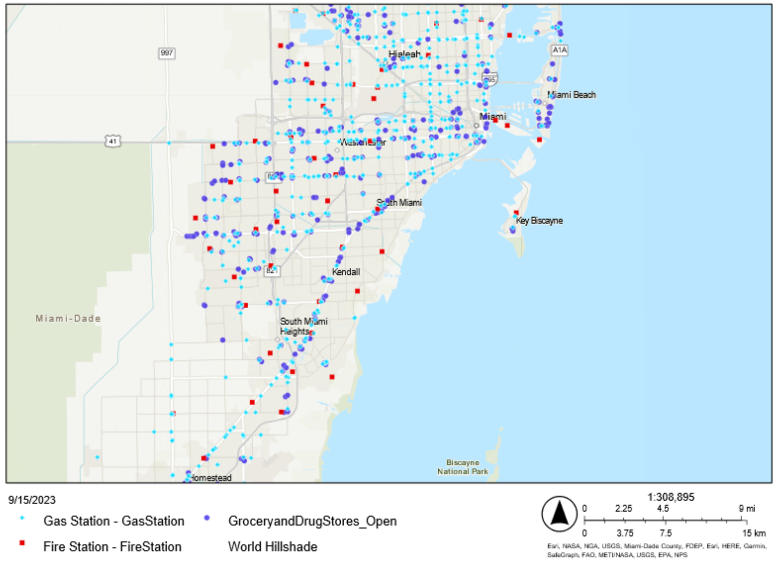
Quantification of Accessibility

Definition of Essential Service

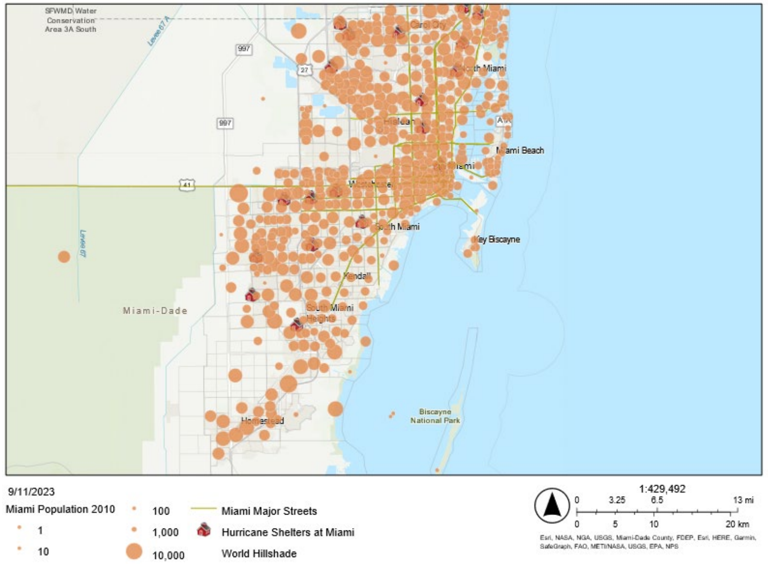
- The accessibility to essential facilities and services form the backbone of resilience and recovery efforts in communities affected by hurricanes.



Hurricane shelter in Miami Dade County



Grocery, gas, fire station in Miami Dade County

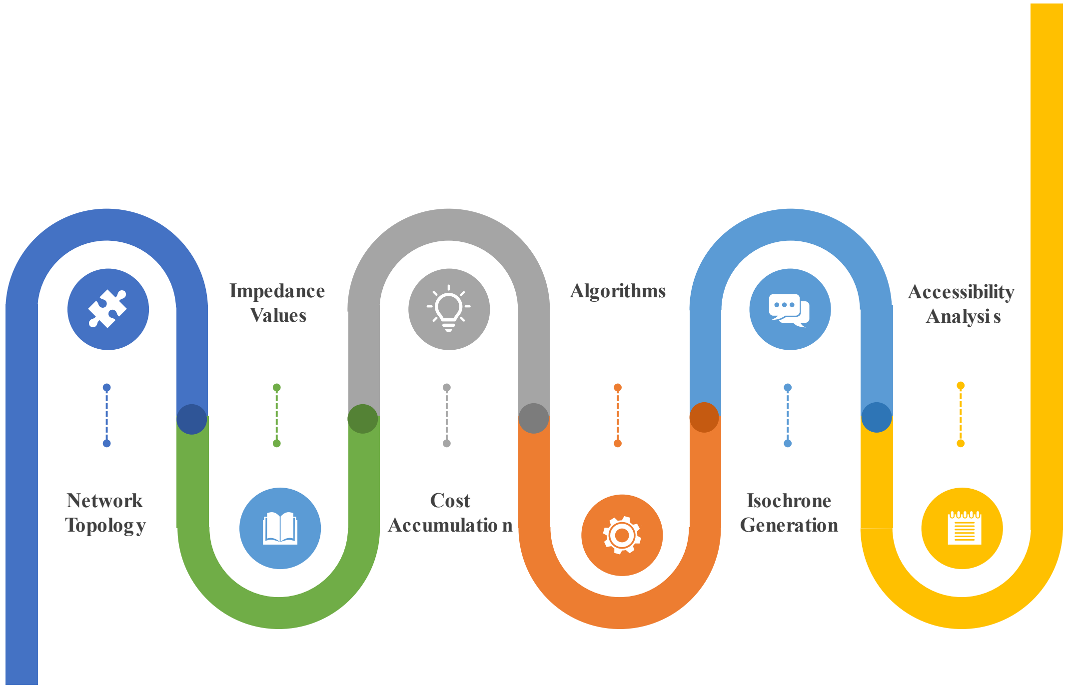


The population density and hurricane shelter

Quantification of Accessibility

Quantification Methods of Accessibility

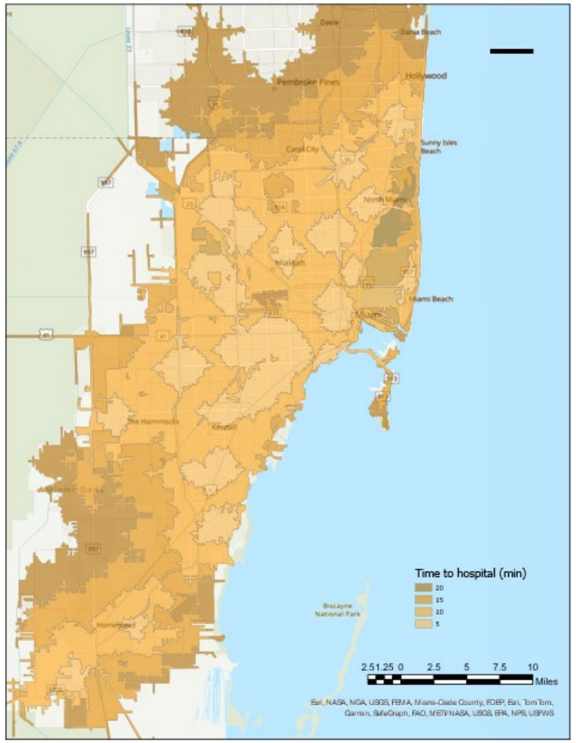
- Network Topology
- Impedance Values
- Cost Accumulation
- Algorithms
- Isochrone Generation
- Accessibility Analysis



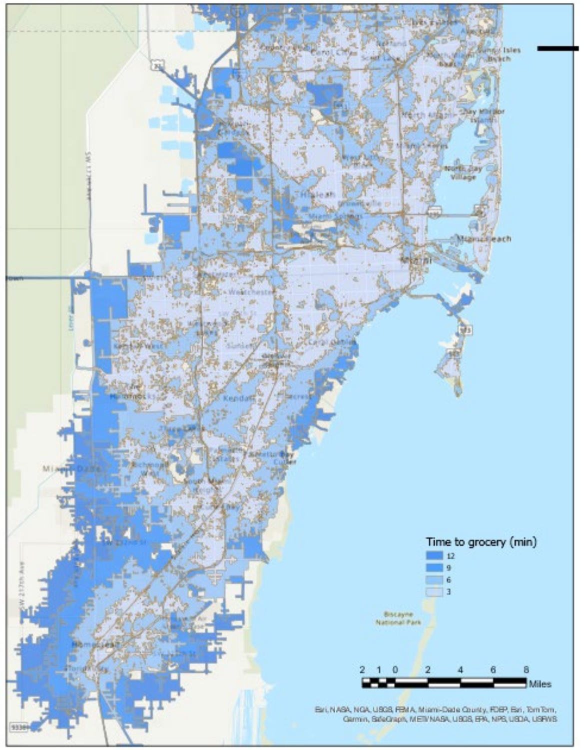
Framework of quantification methods of accessibility

Quantification of Accessibility
Accessibility to Essential Service

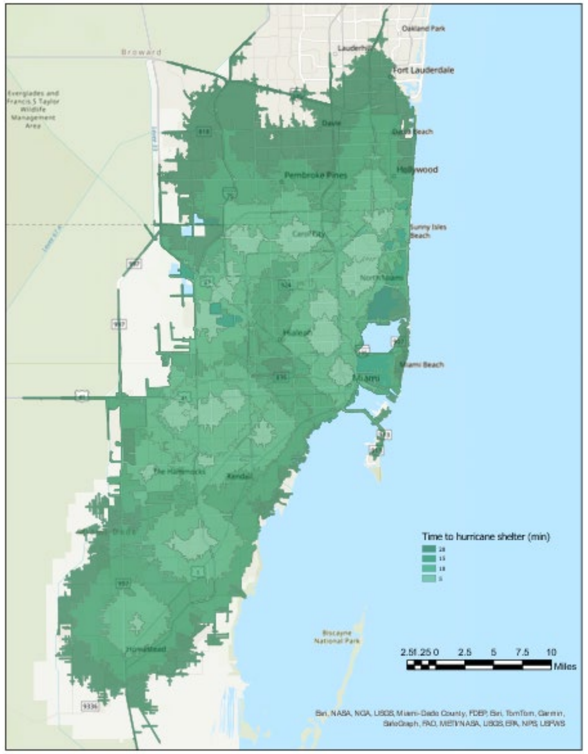
- The isochrone maps depicting accessibility to hospital, grocery and hurricane shelter in Miami. Each map illustrates concentric rings representing the time intervals required to reach these facilities from various locations within the city.



Accessibility to hospital in Miami



Accessibility to grocery in Miami



Accessibility to hurricane shelter in Miami

Equitable Restoration Optimization Problem (EROP)

Problem Description

- Considering mobility efficiency (travel time) and equity in resilience measure

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

$$R = \mu * D + (1 - \mu) * E$$

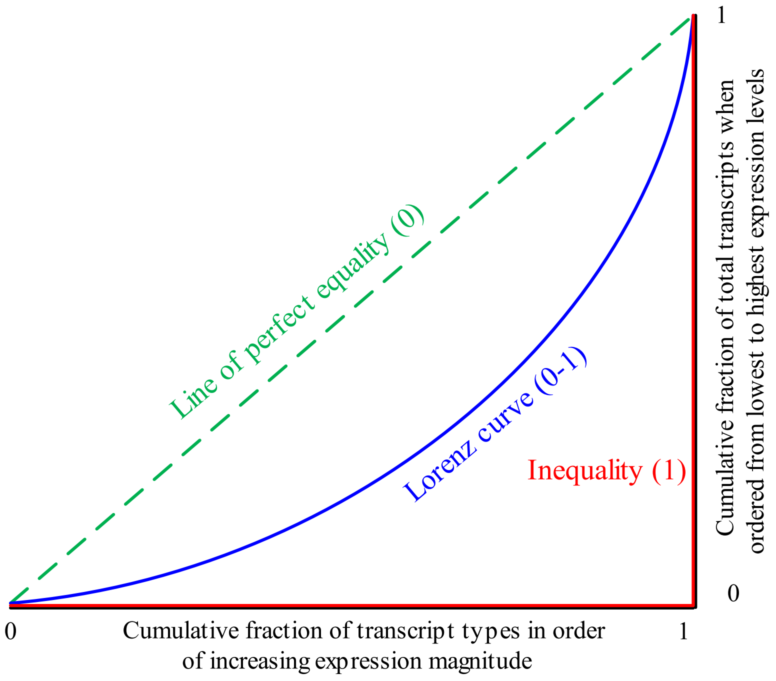
where μ is a weight parameter between [0,1], which is usually defined by the stakeholders based on the specific scenario and priority.

Delay index: $$D = \frac{TSTT - TSTT_0}{TSTT} = \frac{\sum_a x_a * t_a(x_a, c_a^0 + c_a^l y_a^l) - \sum_a x_a^0 * t_a^0(x_a^0)}{\sum_a x_a * t_a(x_a, c_a)}$$

where $TSTT_0$ and $TSTT$ are the total system travel time before the hurricane happens and after the restoration plan is adopted respectively.

Equity index: $$E = \frac{1}{2n^2\overline{W}} \sum_{r \in N} \sum_{s \in N} |W_r - W_s|$$

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



GINI index

Equitable Restoration Optimization Problem (EROP)
Problem Description

- Restoration Strategy Plan Problem Formulation

Restoration plan optimization after hurricane is formulated as a bi-level optimization problem.

Network-flow results

Upper-level objective — **City administrator**

- Minimize the system travel delay and inequity with limited budget, quantified by the proposed resilience measure

Control variables

- Restoration road and bridge selection

Lower-level problem — **Road users**

- Traffic assignment based on road user equilibrium model

Updated network structure with restored capacities

Equitable Restoration Optimization Problem (EROP)

Problem Description

The upper-level problem is:

Input updated traffic flow from lower-level problem

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

Subject to:

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

$$c_a^1 \ge 0, \forall\, a \in A, \quad (22)$$

$$c_a^0 + c_a^1 \le c_a, \forall\, a \in A, \quad (23)$$

The lower-level problem is:

Input updated restored network from upper-level problem

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

Subject to:

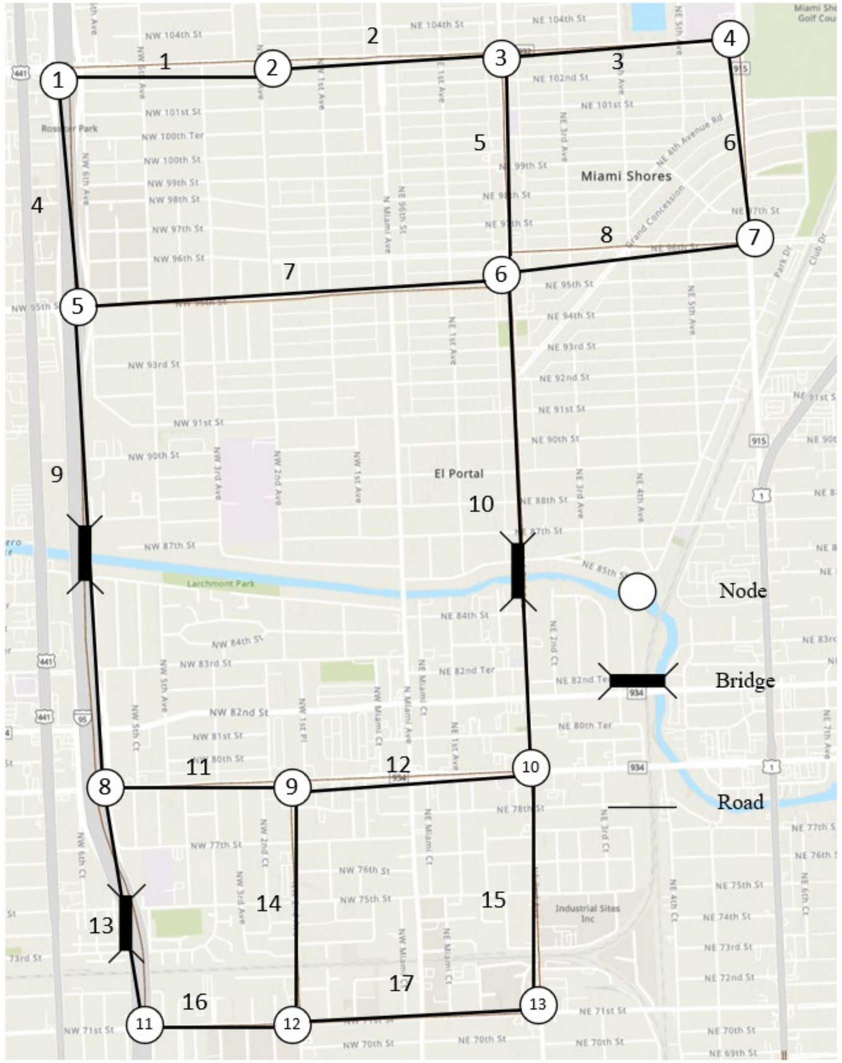
$$t_a(w, c_a^0 + c_a^1) = t_0\left(1 + \alpha\left(\frac{w}{c_a^0 + c_a^1}\right)^{\beta}\right), \quad (25)$$

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

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

Equitable Restoration Optimization Problem (EROP)

Data sources and restoration plan



Bridge and roadway network for Miami Shores

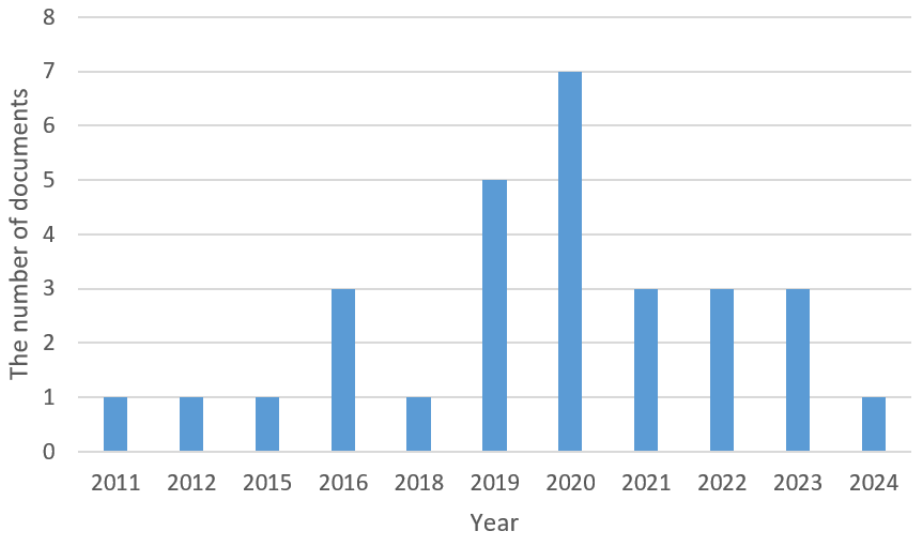
Road	Link	Maximum recovery capacity	$\mu = 0.2$	$\mu = 0.5$	$\mu = 0.8$
1	1 → 2	7.38	7.38	6.26	4.67
	2 → 1	7.38	0.18	4.80	4.73
3	3 → 4	42.17	13.85	16.17	15.65
	4 → 3	42.17	3.96	0	15.38
5	3 → 6	22.31	6.00	10.40	0.42
	6 → 3	22.31	0.42	0.21	0
7	5 → 6	12.56	5.58	3.52	2.02
	6 → 5	12.56	0.69	0.29	0
8	6 → 7	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

Equitable restoration plan

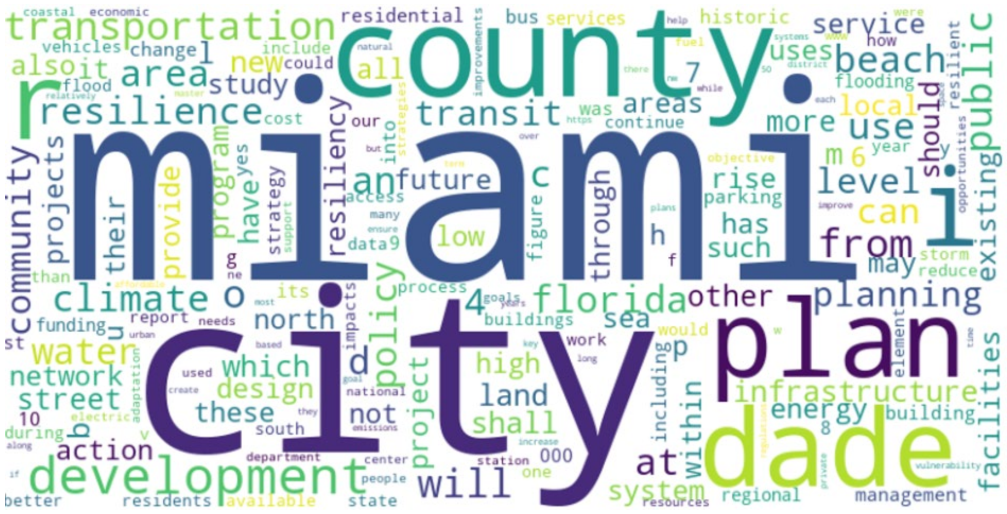
Multisector stakeholder collaboration and engagement for transportation resilience

Data collection

- The document topics needed to pertain to “transportation” and at least one of “emergency,” “resilience,” or “disaster,” ensuring the relevance of the selected documents.
- A total of 29 documents in our analysis



The number of documents in different years

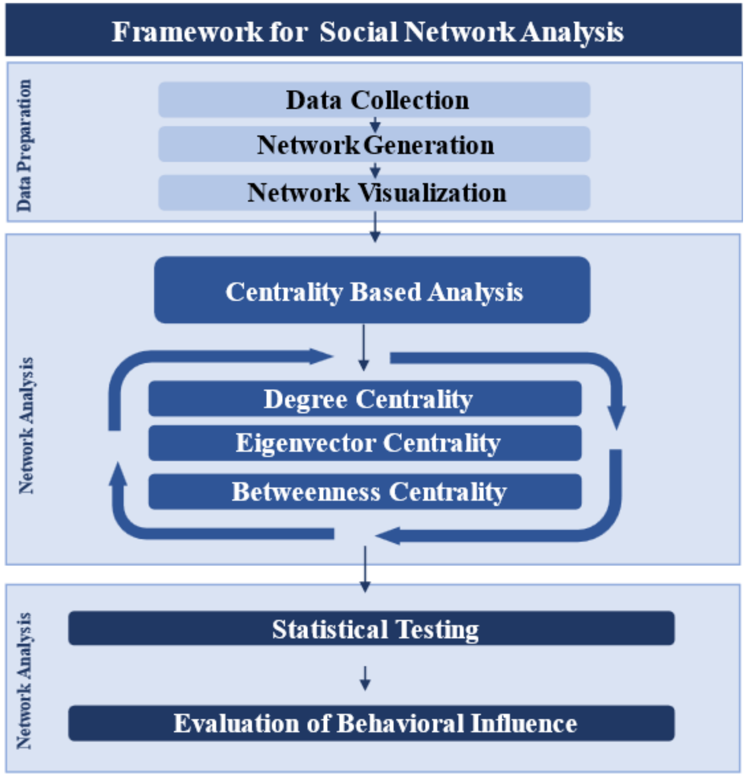


Word cloud of the documents

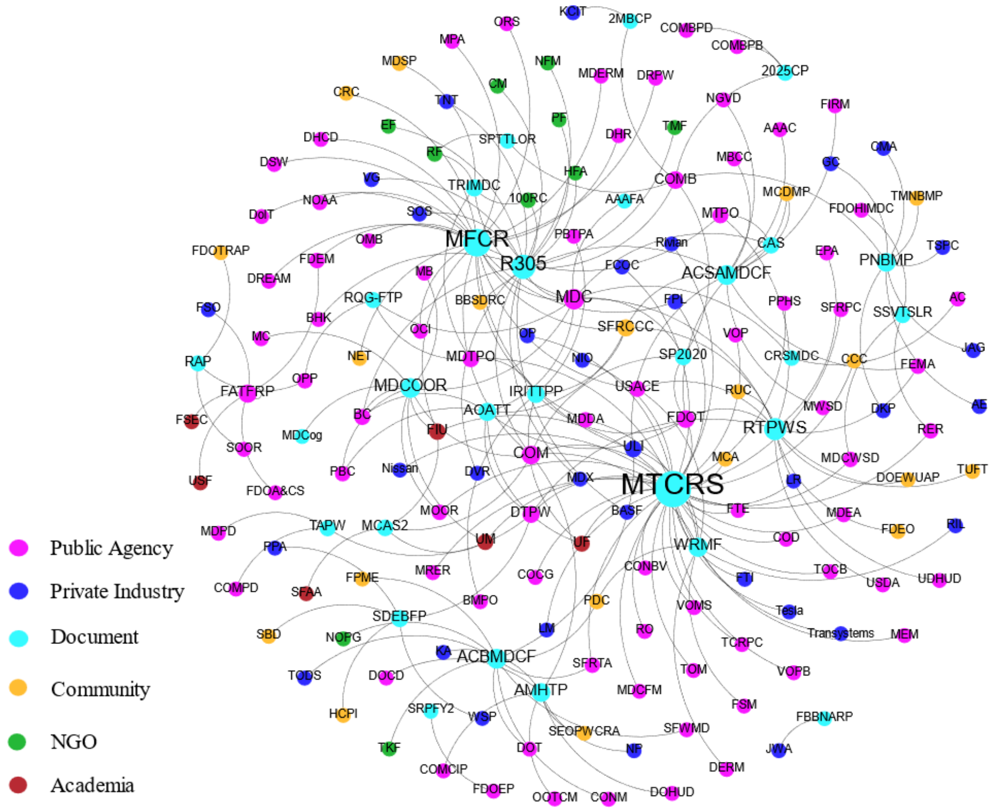
Multisector stakeholder collaboration and engagement for transportation resilience

Bipartite Social Network Analysis

- The network comprises 176 nodes and 216 connections, with 147 nodes representing stakeholders and 29 nodes representing transportation resilience planning documents.



Framework of social network analysis

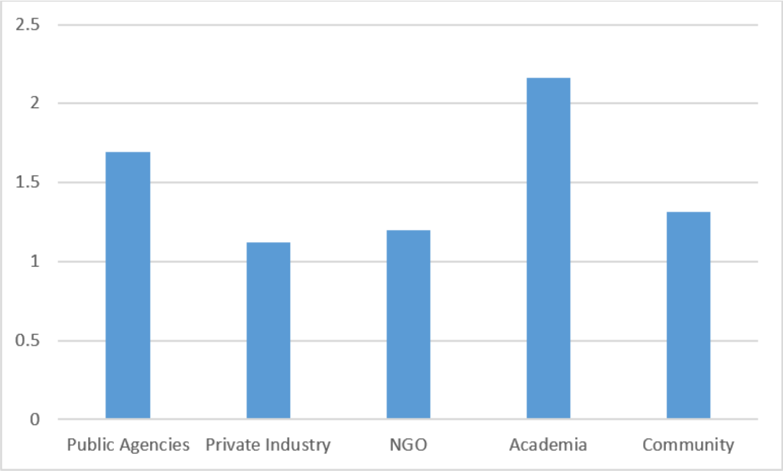


Bipartite network visualization

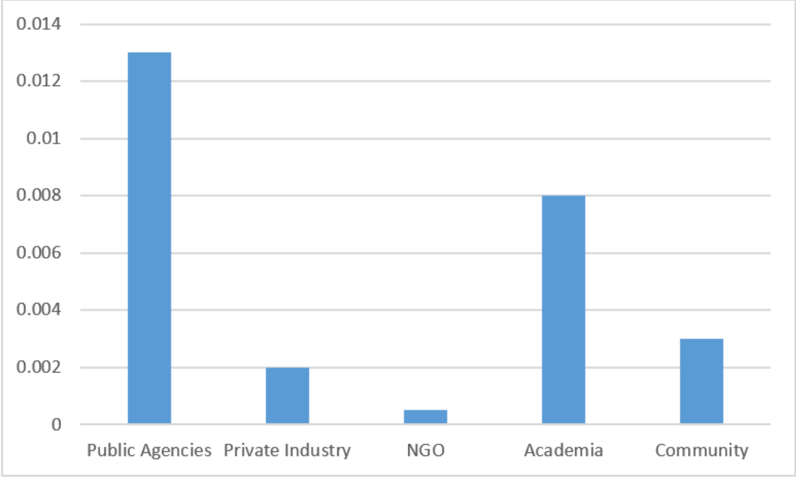
Multisector stakeholder collaboration and engagement for transportation resilience

Network centrality Analysis

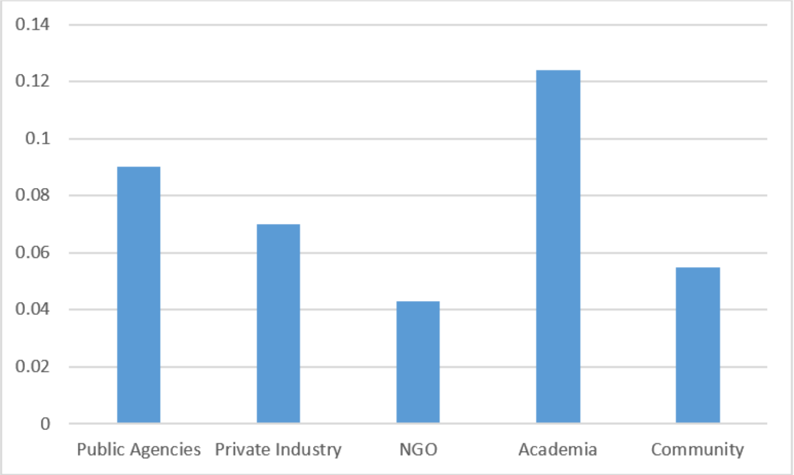
- Public agencies and academic stakeholders play a crucial role in transportation resilience efforts by providing evidence-based recommendations, cutting-edge knowledge, and innovative solutions.
- Three centrality measures are to identify and quantify the relative importance of different stakeholder sector within our network.



Average degree centralities by stakeholder sector



Average eigenvector centralities by stakeholder sector



Average betweenness centralities by stakeholder sector

Conclusion

- Enhancing community resilience post-hurricanes in coastal areas through bridge and roadway network restoration.
- Creation of flooding maps, development of an optimization model integrating equity considerations, and establishment of collaborative networks across sectors.
- Utilizing FEMA data and GIS technology to identify vulnerable road segments and categorize flood risks.
- Correlation between accessibility and essential service facilities, emphasizing the need for prompt network restoration to prevent underserved communities during emergencies.
- Integration of equity considerations into restoration planning, with pilot studies demonstrating parameter influences on outcomes.
- Bipartite Social Network Analysis reveals limited engagement from private industries and community residents.

Future Study

- Develop high-resolution 3D flooding inundation framework for accurate prediction of flooding levels.
- Create dynamic accessibility models accounting for elastic demand and evolving road conditions.
- Refine optimization models to better incorporate equity considerations.
- Explore policy interventions prioritizing equity, sustainability, and resilience.
- Engage stakeholders in research and policy formulation.
- Foster collaboration between policymakers, planners, and practitioners.

Thank you!