Impact Analysis of Extreme Events on Flows in Spatial Networks

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***Abstract*— The objective of this study is to investigate the resilience of roads networks to extreme events using a GIS and network science approach. Using the specific case study of Chicago, three extreme event scenarios were simulated: (1) extreme flooding, (2) random zonal disturbance, and (3) central targeted disturbance. To measure their impacts and as a proxy for flows, we calculate and analyze how the betweenness centrality of each road segment is being redistributed in the network before and after each simulation. Moreover, by randomly selecting 100 nodes in the Chicago road system, we simulate 10,000 trips and examine how they are being affected by each extreme event scenario. Overall, we find that extreme events can have tremendous impacts. More importantly, different types of extreme events generate completely different impacts, and the notion of resilience therefore rapidly becomes sensitive to individual contexts, thus supporting the argument towards more scenario-based analyses.**

Keywords: Resilience, Urban Flows, Extreme Events, GIS analysis, Road Network

I. INTRODUCTION

In the past two decades, the increase in frequency and magnitude of extreme events such as flooding and hurricanes, caused by climate change, has become an important societal concern (1, 2). Creating robust strategies to mitigate the impacts of these phenomena has become an important goal of current scientific research. Resiliency can be referred as the ability of a system to spring back from a disruption or to the ability to withstand an excessive amount of stress before failing. Despite many positive and substantial initial efforts, much work remains to be done to develop cities and urban designs that are resilient to extreme events.

To achieve this goal, researchers have been trying to gain a deeper understanding of how cities and their infrastructure respond to different conditions. In order to do so, their attempts have increasingly moved from a static and top-down perspective to a perspective of cities as complex systems. In his book, *Cities and Complexity*, Michael Batty explains how our knowledge of cities is moving towards viewing urban processes as “a pattern that emerges from the myriad of decisions and processes required for a city to develop and expand physically” (3). Furthermore, he describes cities as complex systems that consist of “saturated flow systems that use capacity in what appear to be barely sustainable but paradoxically resilient network” (4).

By observing and analyzing past extreme events occurring in different cities around the world, one quickly comes to realize these large-scale events are also highly complex (5), and their potential impacts are often underestimated (e.g. 2011 Tōhoku tsunami in Japan (6)). Effort must there also be put into better preparing cities to face extreme events.

In parallel, the emerging discipline of network science provides a new approach for studying the complex nature of cities, where their topological structures highly affect the flows of human activities within them. Observing urban systems through the lens of networks (i.e., nodes and links) and their relationship with different flows of human commodities has shed light on different factors affecting urban processes (7). For instance, Bin Jiang studied how the flow of pedestrians, either on purpose or random, can be significantly dependent on the underlying networks’ characteristics (8).

Furthermore, the resilience of network infrastructure is also dependent on the location of its consisting elements; i.e., the location of its links and nodes, as well as the connectivity between these components (9). Similar to all other complex systems, a road transportation system can be modeled as a network of nodes/vertices and links/edges. Within network science’s realm, a series of studies have been conducted on road transportation network resiliency. Many of these studies have investigated road network vulnerability using different methods that are classified in different categories. Murray et al (10) categorizes these methods into four groups: scenario-based, strategy-based, simulation-based, and mathematical model-based. Specific to this topic, Jenelius et al. (11) focused on finding vulnerable sections of road networks. Taylor (12) examined the accessibility of a network in atypical situation. Several studies emphasize on the general integrity of a network using node-based and link-based disruption strategies (13, 14, 15, 16). Erath et al. (17) developed a statistical model to identify the main factors affecting vulnerability in Swiss road networks; they created the model through studying direct and indirect effects of road section failures. Huang et al (18) showed that the concept of robustness, or vulnerability to attack, relates to the decline of network performance due to the targeted removal of nodes or edges. Derrible and Kennedy (19)

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used a mathematical-based metric to study the robustness of worldwide metro networks.

In this study and in line with the general push towards scenario-based analysis, our main objective is to the study the response of the city of Chicago road network to three different extreme events scenarios: (1) extreme flooding, (2) random zonal disturbance, and (3) central targeted disturbance. The responses are measured using the network science concept of edge betweenness centrality as a proxy for traffic flows. Moreover, we simulate 10,000 trips within the city of Chicago and measure how they are affected by the three scenarios.

In the next section, we first explain the methodology selected to carry out our analysis. We then review and discuss the results. In this work, the network properties are calculated through a combination of the software package ArcGIS and from various python scripts, notably by using ArcGIS model builder and the python library igraph (20).

II. METHODOLOGY

In order to study the effects of different extreme events on the resiliency of a road network, we have to overcome two main problems. The first problem is how to model different extreme event scenarios. The second problem is to define appropriate metrics to effectively measure the impacts of these extreme events. Here, we notably transform a road system into a topological network *G* composed of *N* nodes/vertices and *L* links/edges.

1. Extreme Flooding

In the first scenario, we assume that locations of Chicago's road network that overlay a certain flood zone are simply rendered inaccessible. To select this flood zone, we used the Federal Emergency Management Agency's (FEMA) 100-year floodplain dataset that assigns a yearly 1% chance of experiencing severe flooding in the Chicago region. To model this first scenario, the floodplains are superposed to the road network and the elements within the flooded area (i.e., the nodes and links) are removed.

2. Random Zonal Disturbance

In the second scenario, we assume that unknown causes, e.g., a hypothetical hurricane or ice storm that could strike different parts of a region, affect the road network and cut off multiple and distinct zones from the city. To model this event, we created 10 random points on the Chicago road network, and then removed a 1km buffer of the street network around each location, causing zonal disturbances.

3. Central Targeted Disturbance

In the third scenario, we assume that the Central Business District (CBD) of Chicago alone has become completely inaccessible, e.g., to simulate a terrorist attack. To create this model, we created 3 km buffer around a central location in the Chicago Loop, and removed the locations in the road network that fall into that area.

4. Edge Betweenness Centrality

To measure the impacts of these three scenarios, we first use the concept of edge betweenness centrality from network science (21). Betweenness centrality essentially measures how likely a node/edge is to be used to link any two pairs of nodes. Overall, betweenness centrality is a structural importance indicator based on the global information of the shortest paths connecting all pairs of nodes. A high betweenness of a node or edge shows that there are more shortest-paths passing through that node or edge (22). A node or edge with betweenness greater than the average could play an important role just like a bottleneck inside the network, and thus is a crucial part of a network in disturbance situation, if alternative routes are not provided in the network. It is also often used as one of the most representative indicators of network centrality (23).

Mathematically, node betweenness centrality is defined as (21):

$$C_{B_n}(i) = \sum_{s \neq i \neq t \in V} \left(\frac{\sigma_{st}(i)}{\sigma_{st}} \right) \quad (1)$$

Where σ_{st} is the total number of shortest paths from node *s* to node *t* and $\sigma_{st}(i)$ is the number of those paths that pass through node *i*. The definition of edge betweenness centrality is identical but applied to links as opposed to nodes.

Generally, node betweenness centrality is often used as a measure of the influence that a node has over the spread of information throughout the network. Here, it can be seen as a proxy to help us measure the volume of traffic passing through each intersection (24). Conceptually, it is close to the measure used in the GIS network analyst section except that distances are not considered. Moreover, betweenness centrality looks at all pairs of nodes as opposed to a random selection.

The resilience of a network is also a function of how the network properties respond to disturbances. To evaluate this aspect of resilience, we also measure how these network properties are being redistributed in a road network.

5. Modeling Trips

As a complementary metric to edge betweenness centrality and to account for distance, we can also simulate actual trips on the Chicago road system. Here, we first randomly choose 100 locations (i.e., intersections) in the road transport network. We then measure the shortest path between every pair of nodes in the normal conditions in that road network; this can either represent a typical home-work trip or an emergency trip for instance to reach a hostpital. Essentially, connecting these 100 nodes with one another is akin to simulating 10,000 trips.

This method has the benefit of being significantly less computer-intensive than calculating betweenness centrality, while accounting for practical transportation aspects. An alternative is to load real travel demand data in the same platform.

To perform this task, the ArcGIS network analyst tool, also called closest route, is used to find the optimal route to perform a trip from point A to point B. From a practical point of view, this can be seen as the number of successive flows that connect A and B, where there is a certain cost to pay when one uses each of them (e.g., travel time, fuel consumption, etc.). Using network analyst, we can develop "what if" scenarios, with which we can experiment alternative constraints in the network and evaluate the varying costs or times as results of those variations. With this method, we can analyze how the flow of individuals might be altered if these scenarios happen.

From running the tool, we can collect two metrics that can capture the impacts of the extreme events on the road network. The first metric is the percentage of the flows that cannot be completed after the extreme event, and the second one is the percentage of flows that are forced to travel longer distances in the road network due to the disruption.

III. Results and Discussion

Figure 1 shows the distribution of edge betweenness centralities in road network of Chicago in a) normal condition, b) extreme flooding, c) random zonal disturbances and d) central targeted disturbance. The main difference between the first scenario, i.e., extreme flood simulation, and the other two scenarios, i.e., random zonal and central targeted disturbances, consists in the way that the constraints are distributed in each scenario. Results in Table 1 indicate that road network of Chicago is more vulnerable to the extreme flooding event as the drop in maximum edge betweenness is much higher than the other two scenarios. Indeed, after the extreme flooding event, we see a drastic drop of 85.34% in the maximum edge betweenness centrality in the road network of Chicago (Fig. 1 b.). The main cause of this significant drop is the separation of Chicago road network into three isolated parts by the floodplain. After flooding, there is therefore a shift in the concentration of roads with higher edge betweenness centralities from the northern and the western parts of the city to the central and southern parts (Fig. 1 b.).

Similarly, there is a 30.48% reduction in maximum edge betweenness centrality in Chicago road network after the second scenario, the random zonal disturbances (Table 2). In the third scenario, despite the fact that the area of central targeted disturbance (i.e., 28.27 km^2) is close to the area of the random zonal disturbances (i.e., 31.4 km^2), we only have a 2% drop in the maximum edge betweenness centrality in Chicago road network, which may be interpreted as sign of resiliency in the road network against the third scenario in relation to the second scenario (Fig. 1 b. & c.). Also, after the central targeted disturbance in Chicago's road network, we can observe that there is a shift in roads with higher edge betweenness centralities to the western part of the network, generating a beltway around the central affected zone, and with high betweenness centralities (Fig. 1 c.).

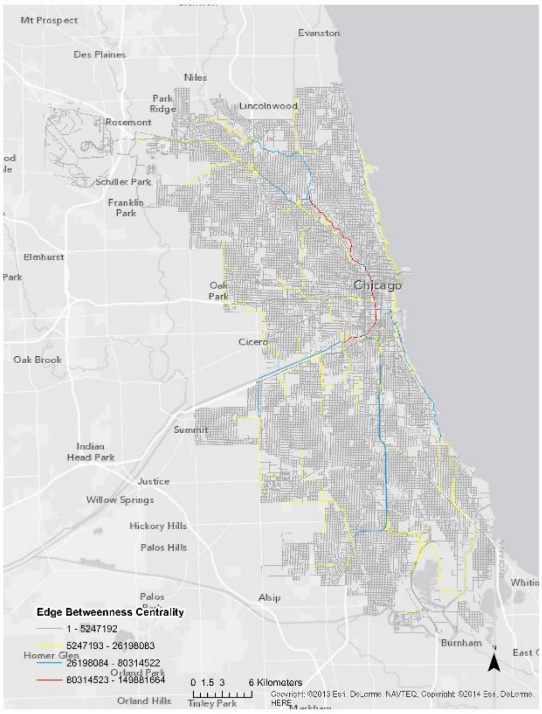
TABLE I. Topological Indicators changes in Chicago In Three extreme events Scenarios

Scenarios	Max Edge Betweenness		
Extreme Flooding	Before	After	% Change
	149881664	21970940	-85.34
Random Zonal Disturbance	Before	After	% Change
	149881664	104228963	-30.48
Central Targeted Disturbance	Before	After	% Change
	149881664	146839736	-2.02

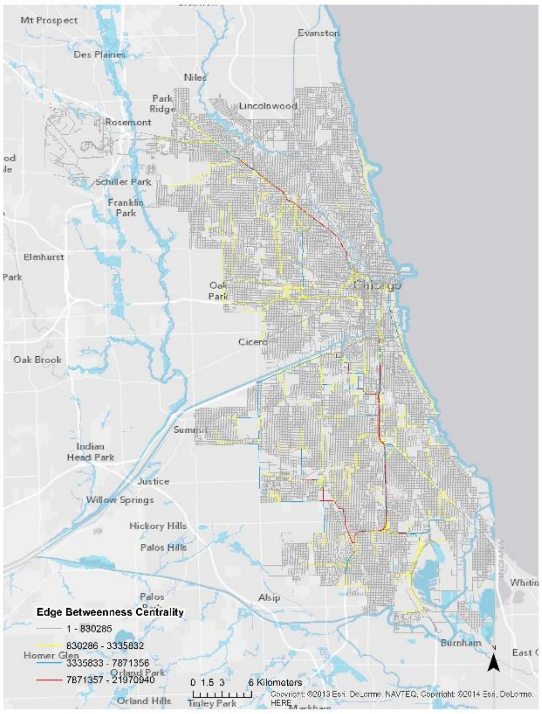
By running the network analyst tool in ArcGIS on 100 randomly selected nodes, we find comparable results (Table 2). Indeed, in the first scenario, the assumed 10,000 flows are impacted significantly by the extreme flooding event, which is again due to the partition of Chicago in three zones (Fig. 2 b.). As a consequence, 60.27% of the trips could not be completed after the removal of the floodplains and of the remaining, 13.68% were forced to travel longer distances. In the second scenario, random zonal disturbances, overall, 4% of the trips in the normal condition could not be completed after random zonal disturbances and of the remaining, 52.75% were forced to travel longer distances (Fig. 2 c.). In the third scenario, central zone disturbance, 3% of the trips could not be completed and of the remaining, 29.22% were forced to travel longer distances (Fig. 2 d.). These results suggest that there are different levels of resiliency between the first scenario and the other two scenarios. Based purely on these results, we can infer that although the road network in random zonal disturbances and central targeted disturbance scenario both have similar uncompleted flows, 4% and 3% respectively, the road network is relatively resilient since it can provide alternative routes to complete a trip. This is partially thanks to the grid structure of the Chicago road network, which remains fully connected in these scenarios unlike in the flooding scenario.

TABLE II. GIS Network analysis results for three extreme events scenarios

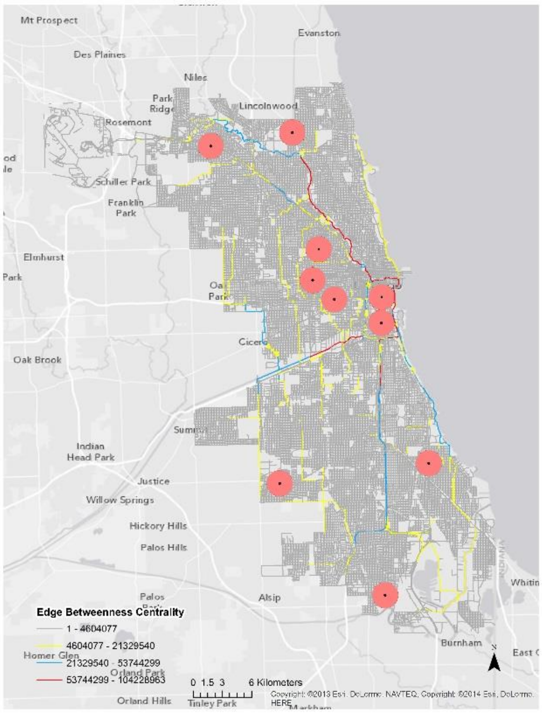
Scenarios	Not Completed Trips (%)	Longer Traveled Trips (%)
Extreme Flooding	60.27	13.68
Random Zonal Disturbance	4	52.75
Central Targeted Disturbance	3	29.22



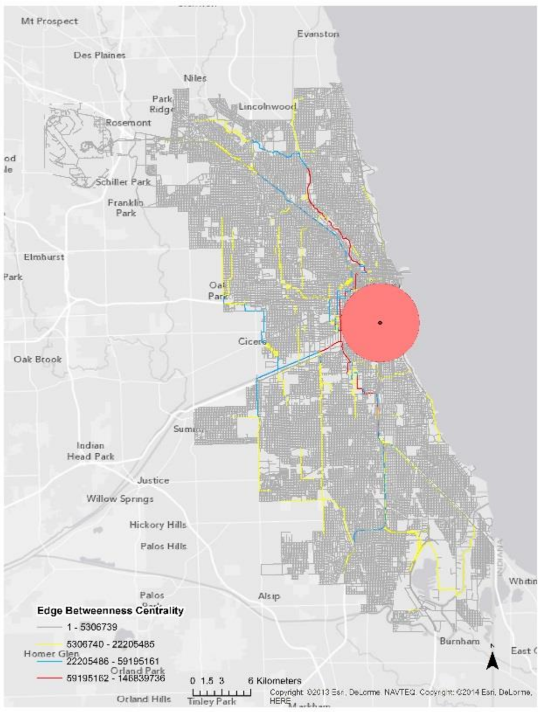
a) Normal Condition



b) Extreme Flooding

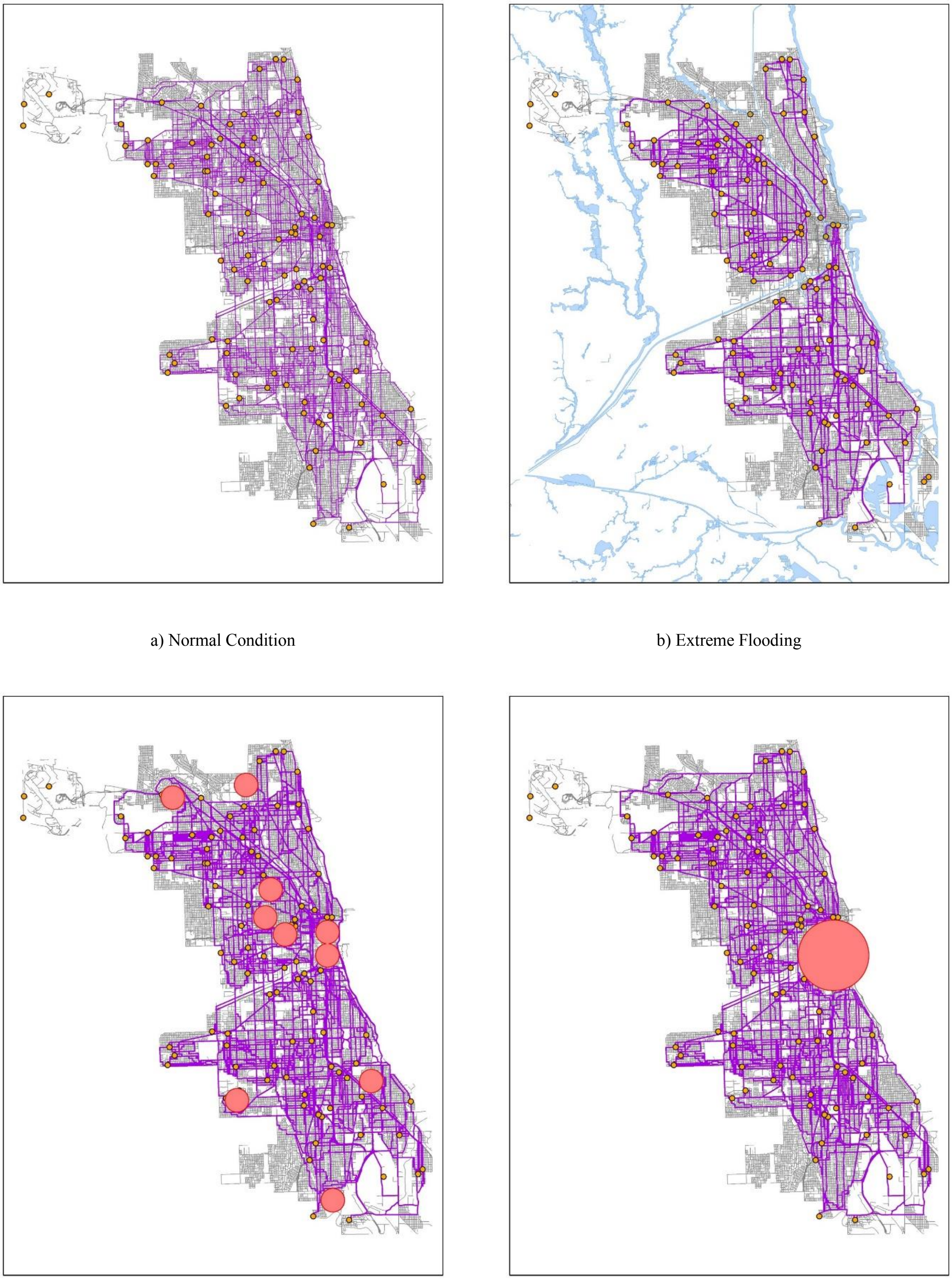


c) Random Zonal Disturbance



d) Central Targeted Disturbance

Fig. 1. Edge betweenness centrality in Chicago road network



a) Normal Condition

b) Extreme Flooding

c) Random Zonal Disturbance

d) Central Targeted Disturbance

Fig. 2. Flows of connection for connection of 100 random locations to each other in Chicago road network

IV. CONCLUSION

The main objective of this work was to measure the impact of different extreme event scenarios on road systems, where we considered three specific scenarios: (1) extreme flooding, (2) random zonal disturbance, and (3) central targeted disturbance. To estimate the impacts of these three scenarios, we measured the differences in edge betweenness centrality of the road system before and after each event. Moreover, we analyzed how 10,000 trips were affected by each scenario.

The main finding of this study is that resilience to extreme events is a relative notion and that a system can be resilient to one type of event but not to another.

Indeed, due to the way that the 100-year floodplain is distributed over the Chicago's road network, the city is split in three sections, thus significantly impacting the connectivity of the roads. Numerous trips therefore cannot be completed and drastic changes can occur in the flow of activities in the city. This analysis can guide policy makers towards applying preventive strategies towards this kind of event by building elevated bridges that would not be affected by a major flood.

Modeling random zonal disturbances in Chicago shows that the shape and structure of the city's road network can be relatively resilient to this type of disruption. In fact, the grid-shaped road network of Chicago can prove to be resilient to various zonal events. Comparing the random zonal disturbances to a central targeted disturbance shows that in terms of topology, Chicago's road network is not heavily dependent on the central business district. This can guide policy makers in Chicago to build on the city's strength and improve its internal connectivity.

Measuring a road network's resiliency through different metrics can help us understand our city's strengths and weaknesses. These tools can be used by policy makers and planners to prepare Chicago, and other cities around the world be prepared for any possible extreme events in the future. There are other political and structural complexities that affect a city's resiliency. These methods should be improved and compared with other methods of analysis, in order to help our city's become resilient to any possible disaster in the future.

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