Fire Station Accessibility, Assessment, and Improvement Considering Probabilistic Road Failure in Facing Flooding

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ABSTRACT

Sea-level rise exacerbates the risk of road disruption on accessibility to facilities such as fire stations, which impacts vulnerable neighborhoods disproportionately. To address this issue, we propose an integrated framework that considers the physical and social vulnerabilities of communities to better understand critical facility accessibility in the face of flooding. Using fire stations in Delaware as a case study, we estimated the travel time of different neighborhoods that represented nodes in the network under different flood disruption scenarios, including the closest fire station and the station assigned based on coverage area. The probabilistic flooding scenarios are generated based on FEMA flood risk maps, and a Monte Carlo approach is adopted to simulate and measure reachability and travel time. The proposed metric will inform the facility siting and service boundary design to improve accessibility to fire stations for equitable flood risk management.

INTRODUCTION

Transportation system play a crucial role in the movement of goods and people, and even more so for disaster relief and rescue efforts in the aftermath of a flood. However, with rising sea levels and urbanization in coastal areas, more communities are facing flooding risks and require reliable transportation access to critical services like fire stations for emergency response. Dong et al., (2019) developed a robust component-based method to measure the network robustness while integrating the community needs in the system functionality. Gangwal et al. (2023) extended this work by using a modified robust component method to identify communities without access to critical facilities such as hospitals, Emergency Medical Services, and Emergency Shelters, and estimated the travel time for access to these critical facilities. However, different from aforementioned facilities where people can choose to access, critical facilities such as fire stations have a designated operational zone. This unique operation mechanism motivates us to investigate the impact of flood on fire station accessibility.

The Fire and EMS Department (FEMS) in Washington, D.C. has established a standard response time of 5 minutes and 20 seconds for the first responding fire engine (Fire and EMS Department , 2023). Research has been conducted to minimize the response time by optimizing fire station location by minimizing the travel time and maximizing the coverage area (Yao et al., 2019; Bolouri et al., 2018; Indriasari et al., 2010). Gori et al. (2020) analyzed the access from fire stations in view of fluvial flooding during Hurricane Harvey. The flood-induced increase in travel time is estimated and vulnerabilities are mapped for different census tracts. However, we lack metrics to estimate the physical vulnerability of nodes when assessing the accessibility from fire stations (with and without zone constraints) during different disruption scenarios.

Moreover, although physical vulnerability helps assess the vulnerability of nodes, the impact varies based on the socio-demographic characteristics of the communities as different communities have different sensitivity levels to disruptions (Council, 2016). Rodríguez et al., (2007) showed that there are the disproportionate impacts on vulnerable communities due to disruptions, highlighting the importance of integrating physical and social vulnerabilities to effectively assess the damage caused by flood-induced disruptions.

Therefore, this research proposes a method to analyze the fire station access in response to the static flood scenarios, and simulated flood models (using Monte Carlo Simulations). Different scenarios with and without zone restrictions are used to quantify the physical vulnerability index. The physical vulnerability is then correlated with the social vulnerability to assess the disparities between communities. The proposed methodology is applied to the state of Delaware under the 100-year floods.

METHODOLOGY

Study Area and Data

The state of Delaware has the third highest proportion of land area that is at risk of coastal flooding in the continental US, and the area at risk is expected to rise by another 30% by 2050 Climate Central (2015). The study uses 100-year flood maps obtained from FEMA (see Fig. 1(a))., overlaid on Delaware's road network from OpenStreetMaps, consisting of 100,887 nodes (or intersections) and 117,491 edges (or roads). The accessibility of 62 fire stations is studied, with data collected from MyGeodata Cloud (MyGeodataCloud, 2023). Figure 1(b) shows the spatial distribution and corresponding zones obtained from the GIS database of state counties. We adopt the Social Vulnerability Index (SVI) created by the Centers for Disease Control and Prevention (CDC) which accounts for four main categories of community characteristics, including socioeconomic status, minority status, household composition disability, and housing type transportation.

Modeling Road Failure

To identify flooded roads, the flood map is overlaid with Delaware's road network (shown in Fig. 1(a)). In this study, we model road disruption using two methods. The first method involves removing edges in the Special Flood Hazard Area (SFHA) on the flood map. The second method assigns each road in the flood zone a probability of failure based on the flood zone's 1% chance of flooding during a 100-year flood. The flooded edges were then removed from the network and the travel time to each node from its fire station were calculated. The study checks for flooded or isolated nodes and their reachability within 5 minutes. We employed a Monte Carlo simulation with 1000 edge disruption scenarios to obtain the network's overall performance.

Estimating Overall Accessibility

The first step in this study is the construction of a road network model for the study area. The links represent individual sections of roads, the intersections of the roads are represented as nodes, and the location of each fire station is approximated to that of its closest road intersection. For network modeling purposes, fire stations were treated as nodes, but their unique identification numbers were stored. Each link is assigned a weight based on the travel distance. The total travel time (in minutes) from a fire station to a node is estimated using the RAND Institute Travel Time Equation (Municipal Technical Advisory Service, 2022):

$$T = 0.65 + KD \quad (1)$$

where $K = 1.7$ and D is the travel distance in miles. We assume the average travel speed of the fire engine to be 35 mph.

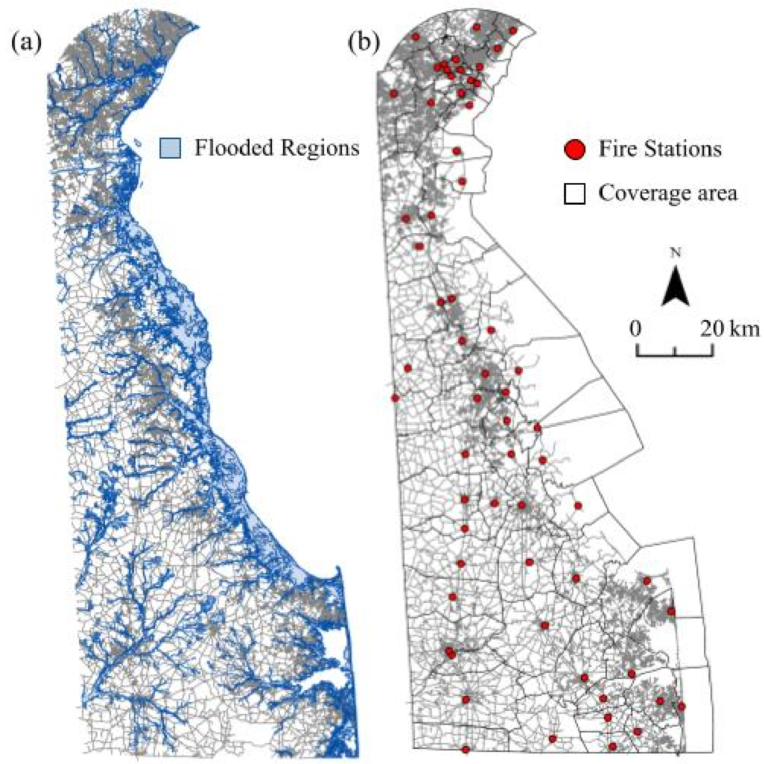

Figure 1: Study Site, Delaware. (a) 100-year flood map overlaid with the road network of Delaware. (b) The spatial distribution of fire stations and corresponding zones of service.

Eq. 1 is used to estimate travel time for different road failure scenarios. Firstly, the travel time is estimated for four standard scenarios: (i) fully functional network with access to the closest fire station; (ii) fully functional network with zone constraints; (iii) disrupted network with access to the closest fire station; and (iv) disrupted network with zone constraints.

Next, accessibility is assessed for probabilistic failure using Monte Carlo as discussed under modeling road failure. During each run of the Monte Carlo simulation, a set of disrupted edges are generated based on the assigned disruption probabilities and are removed from the network. We then identify the accessible nodes, isolated nodes, and estimate the travel time using Eq. 1 for the fire station based on zone constraints and the two closest fire stations (see Fig. 2). The accessibility parameters such as flooding, travel time, and accessibility within a defined travel time threshold are estimated for each run. The estimated parameters are further used to calculate the overall physical vulnerability.

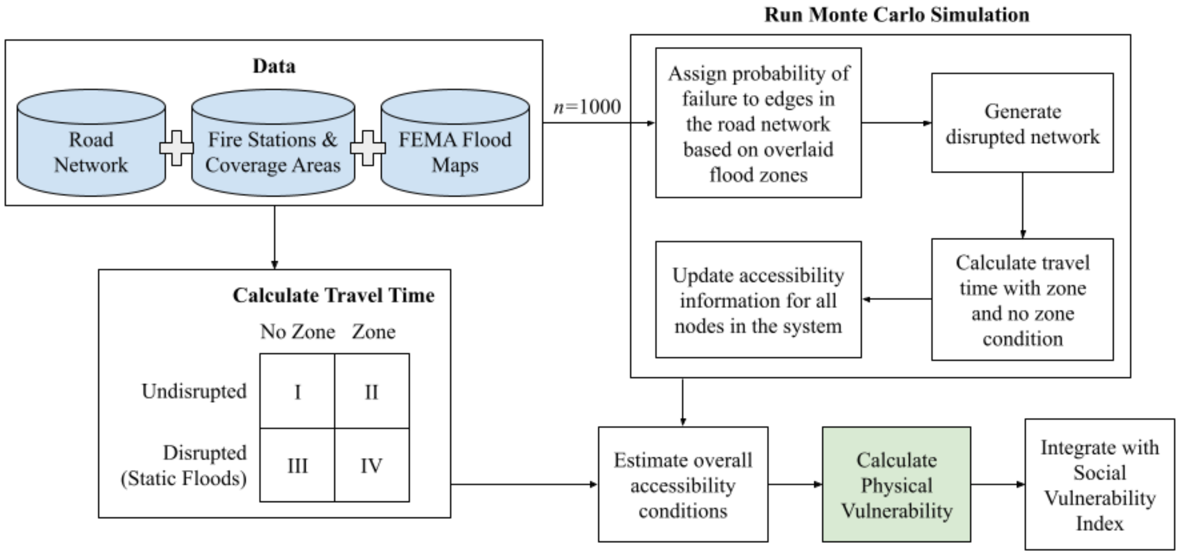

Figure 2: Flow chart depicting the methodology.

Overall Physical Vulnerability Assessment

Five different travel time estimates from different scenarios are combined to calculate the overall physical vulnerability index. These include travel time for the undisrupted network with & without zone constraints, travel time for the disrupted network with & without zone constraints, and travel time for the Monte Carlo Simulations. The score for each scenario is estimated using a Sigmoid function as it is always positive and elevates the values beyond the threshold value while having an upper bound. The following modified Sigmoid function is used to estimate the score (S_i) for a given travel time value (t):

$$S_i(t) = \frac{100}{1 + e^{-(0.4t - t_0)}} \tag{2}$$

The maximum value in Eq. 2 is set to a higher number for ease of differentiation between the scores. The value of t_0 equals 5. Therefore, the output for travel time greater than 5 minutes increases significantly. The individual scores obtained from Eq. 2 are added together with equal weights to get the overall physical vulnerability index (P_v).

$$P_v = \sum_{i=1}^{5} S_i$$

RESULTS

Accessibility from fire stations to the nodes for the undisrupted network with and without zone constraints is shown in Figure 3. While estimating the travel time without zone constraints, we account for the closest fire station. The results indicate the presence of spatial clusters of negatively affected nodes near the borders of different zones. Even when the zones are not in place, many nodes in the outer rings of zones experience significantly longer travel times as compared to the ideal travel time of a fire station. Especially, the regions around Glasgow and Long Neck experience significantly high travel time.

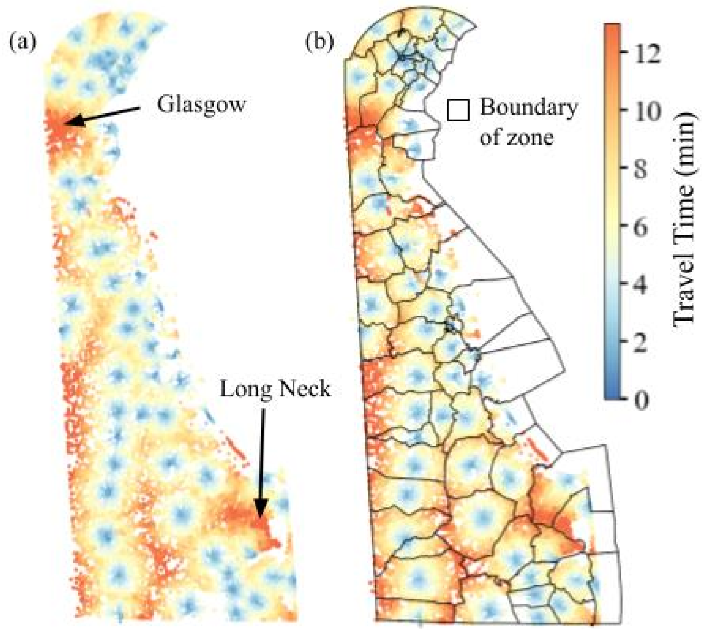

Figure 3: Fire station accessibility is assessed for two different scenarios. (a) Travel time (in minutes) to nodes is estimated from the (a) closest fire stations when the zone constraints are not in place and (b) specific fire stations based on the zone constraints.

Figure 4 shows the travel time from fire stations to the nodes after a 100-year flood. Red colored nodes represent the isolated nodes and the navy-blue nodes represent the inundated nodes. The results show that flooding not only impacts communities through inundation but also through isolation, as some nodes are not inundated by flood directly but are not accessible due to road disruptions. The effect of isolation is further exacerbated when the fire station coverage areas are followed. The study area has a high level of vulnerability to flooding, as the majority of the nodes are not accessible within the ideal travel time of 5 minutes. After floods, around 74% (74,935) of the nodes are accessible without zone constraints (see Figure 4(a)) out of which around 35% (36,023) nodes are not accessible within the defined threshold. Similarly, 60% (61,214) of the nodes are accessible when the assigned zones are followed (see Figure 4(b)). The decrease in the nodes with accessibility is a result of the increased percentage of isolated nodes (an increase of almost14%). These isolated nodes are concentrated mainly near Bethany Beach, Long Neck, and Laurel. We also observe nodes with significantly high travel times near Smyrna.

Flooding is a persistent threat to accessibility, particularly in coastal regions, where rising sea levels have exacerbated the danger in recent years. Therefore, it is essential to prepare for such events and to take them into consideration when assessing risk. We model complete disruption and probabilistic disruptions to account for different scenarios and also exhibit high levels of physical vulnerability.

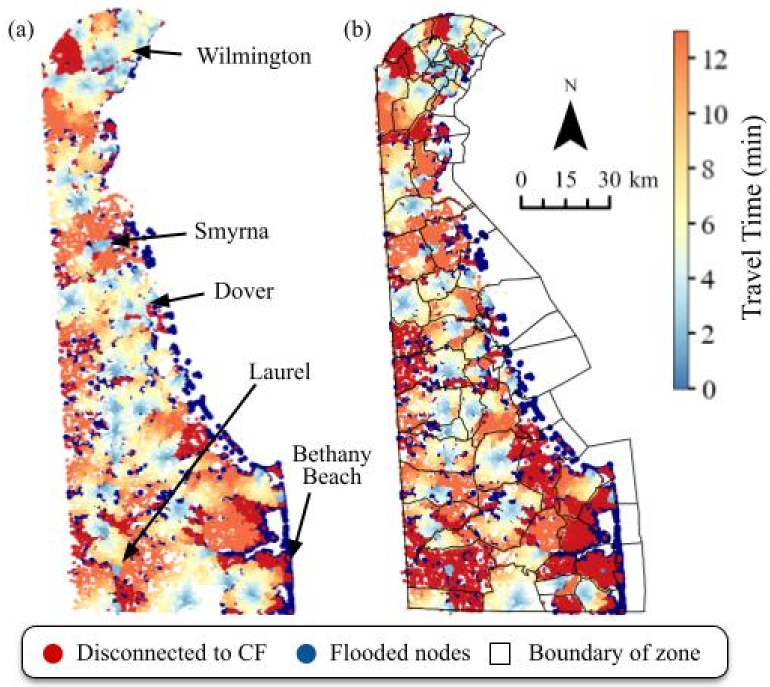

Figure 4: Fire station accessibility after a 100-year flood is depicted (a) without zone constraints and (b) with zone constraints. The flooded and disconnected nodes are represented in navy blue and red colors respectively.

It is worth noting that physical vulnerability is not the sole determinant of a community's vulnerability to disasters, as socio-demographic factors play a critical role in determining how well a community can cope with disaster disruptions. We examine the overall Social Vulnerability Index (SVI) to provide a more holistic assessment when combined with physical vulnerability. The percentage of nodes with physical vulnerability greater than 0.7 is overlaid on the SVI map, producing a three-dimensional graph, as shown in Figure 5(b). Census tracts are color-coded according to their overall SVI value, and the height of the bar is divided into four categories based on the percentage of nodes with high physical vulnerability. We can observe regions near Long Neck and Glasgow have more than 75% nodes whose physical vulnerability is greater than 0.7. While the majority of the high-vulnerability nodes are concentrated in less vulnerable communities, we have some nodes with high physical vulnerability which are located in highly vulnerable regions near Laurel.

DISCUSSION AND CONCLUSION

This study contributes to existing knowledge about equitable access to critical facilities such as fire stations and provides valuable insights into the complex nature of community vulnerability to flooding and underscores the need for a holistic and multi-faceted approach to assessing vulnerability. In this study, additional to static flood scenarios, multiple flood disruption scenarios are generated and a Monte Carlo simulation is conducted to capture the network's overall performance. The fire station access to all the nodes in the network is studied for different flood scenarios. The implications of having fixed zone boundaries for accessibility are also assessed. The results highlight the importance of incorporating both physical and social vulnerability factors to better understand disparities in accessibility to critical facilities during disruptions. The spatial representation of the network reveals a high degree of clustering of nodes with higher vulnerability in certain regions. This study provides valuable insights into the complexities of equitable access to critical facilities during disasters and highlights the need for policymakers to prioritize support for vulnerable communities. The results can be useful for decision-makers to develop plans for disaster rescue and relief and enact policies on critical facility relocation. Furthermore, the physical vulnerability index can be used for targeted infrastructure protection.

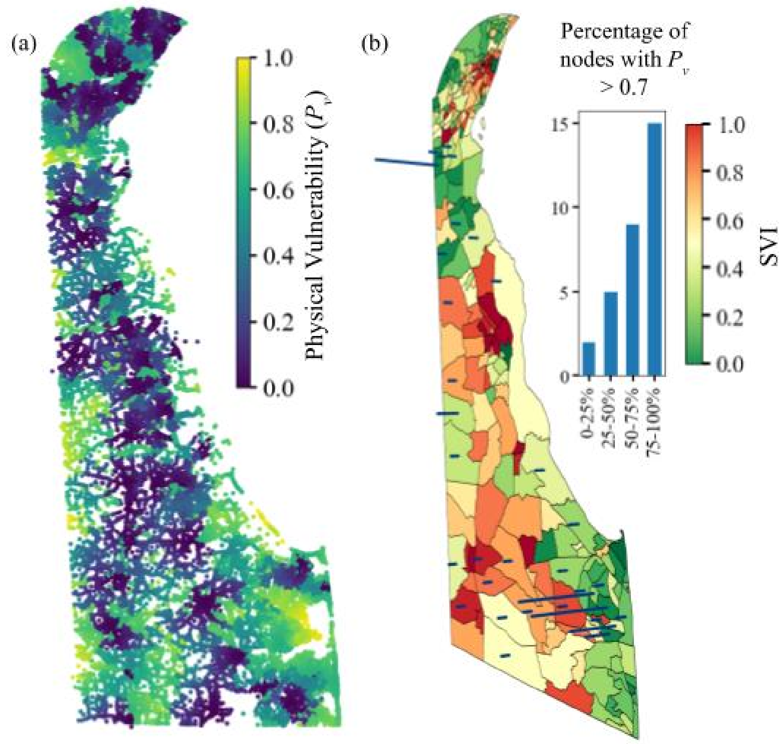

Figure 5: Physical and social vulnerability for fire station accessibility. (a) Spatial distribution with the physical vulnerability of the nodes is depicted for fire station access to nodes in the event of floods. (b) Integrated 3D plot of the nodes with high physical vulnerability overlaid on top of social vulnerability index is presented.

The current study focuses on physical vulnerability at the node level and the impact of floods on communities is assessed on a census tract level. Future work can benefit from the fine-grained socio-demographic characteristics at the property level. The current study uses static and probabilistic disruption scenarios derived from FEMA's 100-year flood map. For increased accuracy of access disparities and to improve the vulnerability index, dynamic flood disruption sequence can be modeled using hydrological and hydraulic models.

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