EQUITABLE RESILIENCE IN INFRASTRUCTURE SYSTEMS: EMPIRICAL ASSESSMENT OF DISPARITIES OF VULNERABLE POPULATIONS DURING SERVICE DISRUPTIONS

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Examining the Impact of Service Interruptions on Social Groups During Natural Disasters

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Natural disasters place tremendous pressure on critical infrastructure systems by testing their service reliability under extreme conditions. System failures are inevitable during harsh events, and prolonged disruptions could pose a serious risk to the mental, physical, and emotional well-being of community residents. However, research has shown that the infrastructure service disruptions will not be experienced the same way by the sub-populations in the community, and socially vulnerable groups tend to suffer more from such disruptions. The research paper suggests that different social factors including income, race/ ethnicity, education, age, medical conditions, house type, homeownership, and years of residence could magnify the disaster impact. The objective of this paper is to identify the social factors most influential to the differences in the disaster impact due to the service disruptions. The temporal and physical context of this study were the transportation, communication services, water, and power outages during and in the immediate aftermath of Hurricane Harvey in 2017. The research concluded that specific social groups were disproportionately affected. The findings demonstrate the need to integrate the social dimensions in disaster mitigation and planning practices in order to make improvements on the current condition of the infrastructure systems to address inequalities in risks experienced by the residents due to natural disasters.

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CHAPTER I

INTRODUCTION

Natural disasters place tremendous pressure on critical infrastructure systems by testing their service reliability under extreme conditions. Despite communities trying to implement the most ideal practices and engineering methods, system failures are not entirely preventable and are inevitable because of the magnitude, complexity, and interconnectedness of these critical lifelines (McDaniels et al. 2007). Flooded roads, broken water pipelines, or fallen cellular towers are all examples of system failures which threaten the well-being of the affected residents. Under normal conditions, minor disruptions from these and other services are expected, and they have little to no effect in the daily setting (Chang 2016). However, prolonged disruptions could pose serious threats to the physical, emotional, and mental well-being of residents in a community (Yoon 2012). This is because critical infrastructure such as the transportation, electric, water, communication, sanitation, and health systems (etc.) are "essential to the functioning of a society or community, both in routine circumstances and in the extreme circumstances of an emergency" (United Nations Office for Disaster Risk Reduction 2009). During and in the aftermath of a natural disaster, the demand for these services will remain continuous, and the need for certain services may even be elevated as affected residents are in a weakened state and attempt to return to a state of normalcy (Lindell and Prater 2003).

In the standard infrastructure resilience model, various measures and models primarily focus on the loss or destruction of physical systems due to disasters and extreme events. In the standard model, the goal is to eliminate the loss of service functions and improve the rapidity of function restoration in systems. However, due to various factors (such as resource constraints, as well as the ever-growing frequency and magnitude of natural hazards), complete elimination of infrastructure function losses would be practically impossible. Loss of function in infrastructure leads to impacts that risk the wellbeing of residents. In fact, an important shortcoming of the standard model is its lack of consideration for variation in the socio-demographic characteristics of subpopulations and the extent to which vulnerable populations (e.g., low-income families and older adults) are exposed to disproportionate risks due to service disruptions. This because the standard model of infrastructure resilience considers the public as a monolithic entity.

However, the public is not a monolithic entity; rather, subpopulations within a community use, access, and rely on the infrastructure and respond to service disruptions in varying ways. Recognizing this, recent reports by the National Academies (NAP 2012), the National Institute of Standards and Technology (NIST 2017), and the National Infrastructure Advisory Council (Berkeley and Wallace 2010) concluded that the current body of knowledge lacks fundamental information about societal impacts of infrastructure service disruptions in disasters. In fact, the existing literature has shown that specific segments of the community (such as low income, racial minority, and older populations) are disproportionately affected by disaster conditions (Flanagan et al. 2011); and therefore, would be potentially more vulnerable to disruptions in the infrastructure services. It also suggests that the pre-existing differences already found among residents, referred to in this research paper as "social factors", varies the disaster impact (Rufat et al. 2015).

However, after more than two decades of research on infrastructure resilience, little of the existing work explicitly or empirically considers the societal impacts of infrastructure service disruptions in disasters (NIST 2017; Paton et al. 2006). This knowledge gap has inhibited an equitable approach to infrastructure resilience that enables integration of humanistic considerations into the engineering design and prioritization of systems to achieve societal well-being. An equitable resilience approach is greatly needed to: (1) better prioritize infrastructure investments based on societal impacts and needs, and (2) identify effective interventions to modify expectations and norms, improve households' adjustment strategies and reduce well-being risks due to service disruptions. The social factors contribute to the resilience gap in the standard model (resilience curve shown in Fig. 1).

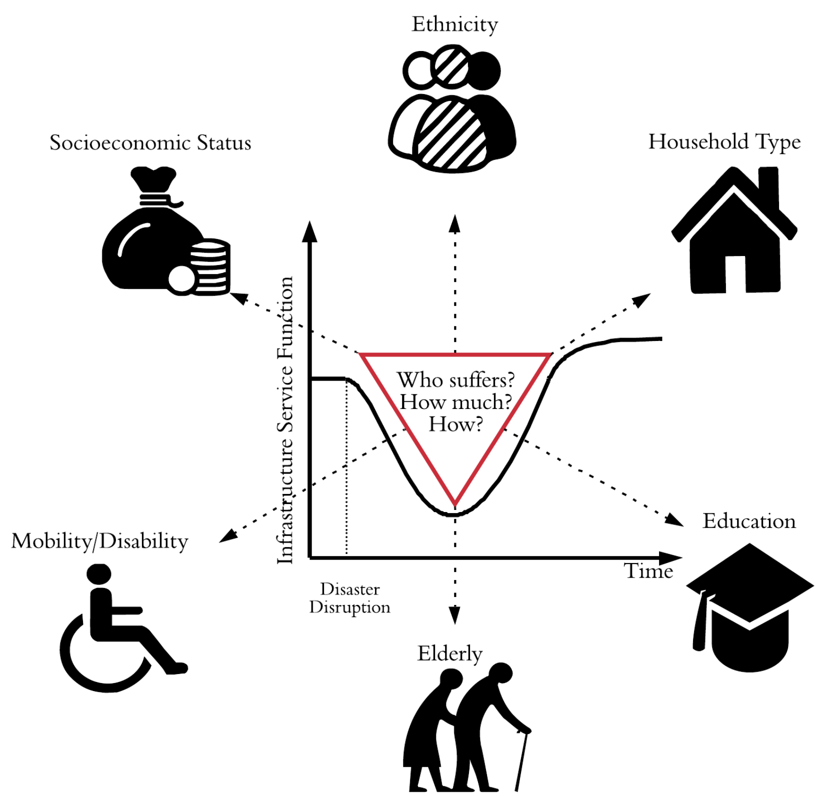

Fig.1 Equitable infrastructure resilience: integrating societal dimensions into standard infrastructure resilience framework

In the disaster literature, several studies have examined the relationship between social factors and the perception of risk (Lindell and Hwang 2008), preparedness (Baker 2011; Fothergill et al. 1999; Homey 2008), and initial impact with long-term recovery (Peacock et al. 2014) of households affected by disasters to fulfill the need for incorporating the social dimension into disaster mitigation and planning. However, little of the existing work has given any attention to evaluating the effects of infrastructure service disruptions on different sub-groups within the community. To address this gap, this study investigates the effect of social factors on experiences of the households resulting from the service disruptions and identifies the specific needs of different subpopulations to the infrastructure services. The objectives of the research are to (1) identify which social factors played a significant role in the disaster impact for each of the services, (2) better understand the needs that different sub-groups have on the infrastructure systems, and (3) determine different roles that the social factors play in the tolerability of the households to the service disruptions.

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CHAPTER II

CONCEPTUAL FRAMEWORK

Societal Impacts of Infrastructure Service Disruptions

Disaster risk is a combination of hazard and vulnerability factors (Flanagan et al. 2011). According to the United Nations International Strategy for Disaster Reduction (UNISDR), vulnerability is defined as the "characteristics and circumstances of a community, system, or asset that make it susceptible to the damaging effects of a hazard" (United Nations Office for Disaster Risk Reduction 2009). The ongoing research dialog has been attempting to define, measure, and evaluate both physical and social vulnerability for a community in dealing with disasters (Cutter 2012; Singh et al. 2014). This study examines the disproportionate experiences of households facing disruptions in critical lifelines by the integration of social and physical vulnerabilities (Fig. 2). Natural hazards cause damages to infrastructure systems and lead to subsequent service disruptions, but experiencing hardship arises when households are not able to cope with the service losses. In the proposed conceptual framework, the capacity of a household to withstand service disruptions is defined as the *zone of tolerance*. As tolerance to service disruptions increases, the household would have a higher ability to withstand the service losses, and consequently, their experienced hardship will be lower. This concept attempts to interpret situations where the hazard exposure cannot solely explain the disparity between the hardship levels. Tolerance of a household to service disruptions is influenced by the sociodemographic characteristics. The impacts of service disruptions on households is examined based on the experienced hardship. According to (Holand 2015), it is the combination of a household's duration of service disruption and household's relative dependence on the services of critical lifeline that intensifies the experienced distress and hardship. Using this conceptual framework, this study examines the relationship between households socio-demographic charactersitics, their zone of tolerance, and experienced hardship due to disruptions in various infrastructure services.

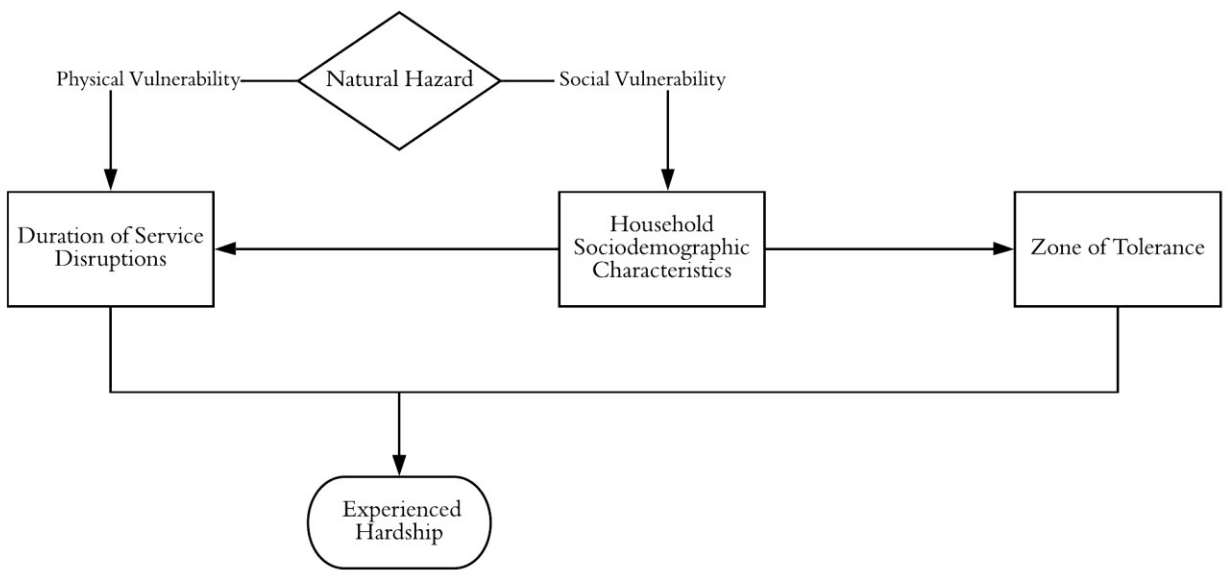

Fig. 2 Conceptual framework for assessing households' experience with infrastructure service disruptions

Socio-demographic and Disaster Impact

In this study, various socio-demographic characteristics are considered in examining disparities due to infrastructure service disruptions. These social factors are obtained from the Center for Disease Control and Prevention's (CDC) social vulnerability index (SVI). The SVI subdivides the social factors into the following four categories: (1) socioeconomic status, (2) racial/ ethnic groups, (3) household composition, (4) housing style (Flanagan et al. 2011). Similarly, in this study, the social factors considered include: (1) the *socioeconomic status*, which is the income and education level of the household; (2) *racial/ethnic groups* to examine disparity among *minority groups*, which includes any race/ethnicity that is non-White; (3) *household* *composition*, which refers to the age distribution and medical conditions of the residents; and (4) *housing style*, which captures the residential type, ownership status, and tenancy (or years of residency).

Socioeconomic status

Generally, households with lower levels of income and education are perceived as more vulnerable to the effects of a natural disaster (Fothergill and Peek 2004). For example, Masozera et al. (2007) showed that lower-income households had difficulty responding to the incoming disaster, Hurricane Katrina, due to a lack of transportation to evacuate the impacted area. These households also struggled in the recovery process because they did not have flood insurance. Lower-income households are also typically correlated with a lower education status (Flanagan et al. 2011). Though education itself may influence the disaster impact, the direct connection is less apparent in disaster literature.

Racial/ Ethnic Groups

According to Fothergill et al. (1999), racial and ethnic minorities are linked to increased disaster risk. Minority groups are also typically corrected with other social groups including low-income, low-education, living in mobile/ apartments, and renting their residence. Although these groups are commonly correlated with lower-income households, there are specific issues connected with minorities that do not concern income. There is evidence of “cultural ignorance, ethnic insensitivity, racial isolation and racial bias in housing, information dissemination, and relief assistance” that could negatively affect the response and recovery process of minority groups to a future disaster situation (Fothergill et al. 1999). The issues of racial bias and isolation could also affect the capability of these populations in coping with infrastructure service disruptions.

Household composition

Among different age groups, children and the elderly are considered to have the highest vulnerability because of their general dependence and often fragile physical state (Rufat et al. 2015). According to Flanagan et al. (2011), elderly had disproportionately higher mortality rates during Hurricane Katrina. People with medical conditions were also more vulnerable to the impacts of the disaster. In another study of Hurricane Katrina, individuals with disabilities listed their personal barriers to disaster recovery through qualitative reports (Stough et al. 2015). One of the hardships frequently mentioned was their inability to access infrastructure, particularly in utilizing the transportation system.

Housing Style

Housing is considered another important factor influencing social vulnerability. For example, Peacock et al. (2014), in studies of Hurricane Andrew and Hurricane Ike, concluded that owner-occupied houses suffered less damage and recovered more quickly; meanwhile, renters were particularly more susceptible to the disaster impact. Households living in mobile homes were also less likely to have supply kit at home (Homey 2008), lowering their level of preparation for disasters. Additionally, mobile homes and apartments are less structurally sound to withstand the physical consequences of natural disasters (Fothergill and Peek 2004).

The above discussion shows that specific socio-demographic characteristics of households influence their vulnerability to disasters. However, the existing literature does not examine the influence of these socio-demographic characteristics on the ability of households to cope with different infrastructure service disruptions. To this end, this study employed empirical data from a household survey in the aftermath of Hurricane Harvey to uncover the relationship among socio-demographic characteristics, zone of tolerance, and hardship of households facing various infrastructure service disruptions.

CHAPTER III

METHODOLOGY

Study Context

This study employed a household a survey in the aftermath of Hurricane Harvey to gather empirical data regarding service disruptions and impacts on households in Harris County. In particular, this study evaluated the effect of the service disruptions due to transportation, power, communication service, and water outages. Residents who remained shelter-in-place throughout Hurricane Harvey faced different service disruptions, especially during the peak intensity of the storm. Major roads in the Houston metro area such as I-10, I-45, and US-59 were inundated (Blake and Zelinsky 2017), where the flooded roads and subsequent road reparations caused traffic congestion. Harris County residents also received a total of 76 boil water notices, with only three wastewater treatment plants being destroyed (Davis 2018). According to the Federal Communications Commission reports, 160 cellular sites were down, about 5.1% of the total cellular coverage in the county (Federal Communications Commission 2017). Finally, approximately 336,000 electrical outages impacted Texas customers (CBS/ AP 2017). The length and intensity of each of these service disruptions varied depending on the location of households.

Survey Development

A web-based survey was designed for the assessment of households' experience with infrastructure systems disruptions. The survey was distributed using the Qualtrics system, an online survey panel service and a private company in the U.S. Qualtrics specializes in online/ data collection and has been used by several academic institutions across the nation, with several studies reporting results based on the data collected by Qualtrics. For this study, Qualtrics used stratified sampling strategy from a census representative panel for survey development. The target subjects were the residents of Harris County who were above 18 years old. A soft-launch of the survey was released in May 2018 and collected 47 initial responses, which were used to check the quality of the questions and determine if the survey was ready for complete data collection. In total 1,742 responses were collected. The response with incomplete information and those related to households who had evacuated their house before Hurricane Harvey were eliminated from the analysis. The rationale for this selection was that, for the people who evacuated and had to move to shelters or other places, the relevance of infrastructure service disruptions becomes of secondary importance since they have already lost their shelter (the primary place in which infrastructure services are utilized). After data filtering, 1,052 responses were used in the statistical analysis, which is sufficient for household survey analysis as suggested by Lindell and Hwang (2008), which recommends using a sample frame larger than 400 drawn from diverse locations. Fig. 3 shows the study area of the collected responses from each ZIP code inside the area of interest.

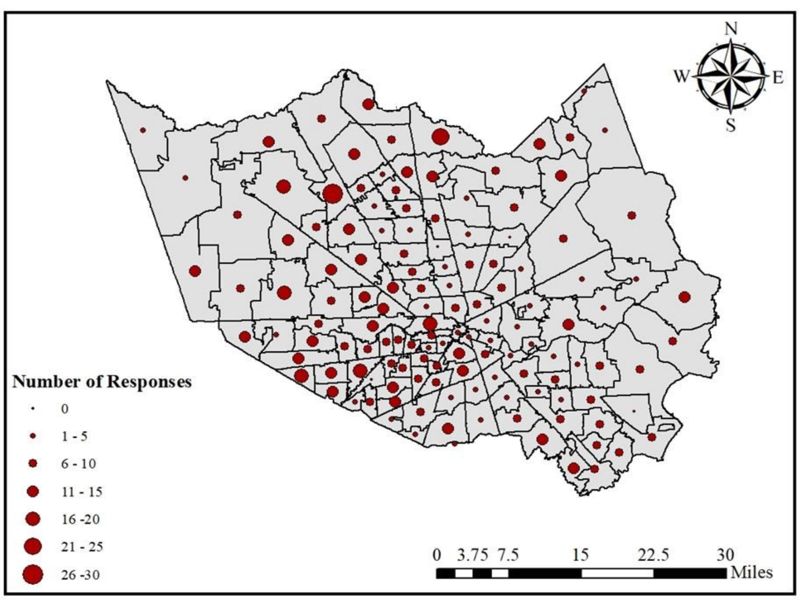

Fig. 3 Map of Harris County and the distribution of collected data from each ZIP code

Measures

The following tables show how the factors were coded for the statistical analysis. Social factors were considered to be independent because the research study hypothesizes that they will influence the dependent factors of the disaster impact (e.g. experienced hardship, exposure of service disruption, and zone of tolerance). First, the survey collected the social characteristics of the individual households (Table 1).

Table 1- Independent Factors Tested in the Survey

Independent Factors	Input
Income	Less than $25,000 (=1), $25,000-$49,999 (=2), $50,000-$74,999 (=3), $75,000- $99,999 (=4), $100,000 -$124,999 (=5), $125,000-$149,999 (=6), and More than $150,000 (=7)
Education	Less than High School (=1), High school graduate or GED (=2), Trade/ technical/ vocational training (=3), Some college (=4), 2-year degree (=5), and 4-year degree (=6), and Post Graduate Level (=7)
Race/ Ethnicity	White (=1), Non-White (=2)
Less than 10 years old	Yes (=1), No (=2)
Older than 65 years old	Yes (=1), No (=2)
Mobility Issues	Yes (=1), No (=2)
Chronic Medical Condition	Yes (=1), No (=2)
Home ownership	Full payment/ mortgage loan (=1), Rented the residence (=2)
Residence type	Single-family home (=1), Apartment/ Mobile home (=2)
Years of Residence	Time living in the residence (# of years)

Then the survey collected data relating to the disaster impact (Table 2). The dependent factors of hardship, exposure, and zone of tolerance were measured to determine the impact of the transportation, power, communication and water service disruptions.

Table 2- Dependent Factors Tested in the Survey

Dependent Factors	Input
Hardship:	
What was the extent of overall hardship that your household experienced due to [service disruption] posed by Hurricane Harvey?	None at all (=1), A little (=2), A moderate amount (=3), A lot (=4), and A great deal (=5) for transportation, communication, water, and power services
Exposure of Service Disruption:	
How many days was the total duration of your household's [service disruption]?	Reported in the number of days for road closures (D), power outages, cellular outages (D-1), wireless service outages (D-2), water disruption (D-1), and water boil-notices (D-2)
Zone of Tolerance:	
Overall, my household is capable of tolerating the [service disruption] for [response].	Reported in the number of days for transportation, communication, water, and power disruptions.

Analysis

The collected data was analyzed by considering the inherent ordering present in the variables of the test. This type of analysis provides more statistical power for detecting the dependency among the variables (Agresti 2007). The analysis was conducted using bivariate correlations through the Spearman statistical method. The non-parametric test is more representative of the dataset because the majority of the outcomes were either ordinal, ranked, and subject to outliers (Longnecker and Ott 2010). The values were determined to be statistically significant when the p-value was less than or equal to 0.05 and 0.01. The objective of the analysis was to understand the relationship among the socio-demographic factors, hardship experienced, exposure to service disruptions, and zone of tolerance by the households.

CHAPTER IV

RESULTS

Demographic Information

The household survey collected a sample from residents in 140 out of 145 zip codes in Harris County in the aftermath of Hurricane Harvey. Table 3 summarizes the demographic information of the respondents. Comparing the sample with the U. S. Census data, the dataset collected is representative of the population in the county. It represents diversity of the demographic information for conducting tests related to the relationships between the socio-demographic factors and infrastructure service disruption zone of tolerance and hardship.

Table 3- Demographic Information of Survey Respondents

Variables	Categories	Frequency	Percent
Age*	Less than 2 years	69	4.13%
	2-10 years	200	11.97%
	11-17 years	211	12.63%
	18-64 years	842	50.39%
	65 years or older	349	20.88%
Education	Less than high school	23	2.13%
	High school graduate or GED	144	13.36%
	Trade/ technical vocational training	51	4.73%
	Some college	191	17.72%
	2-year degree	96	8.91%
	4-year degree	332	30.80%
	Post Graduate level	235	21.80%
	Other	6	0.56%
Income	Less than $25,000	160	14.84%
	$25,000-$49,999	232	21.52%
	$50,000-$74,999	241	22.36%
	$75,000-$99,999	145	13.45%
	$100,000-$124,999	94	8.72%
	$125,000-$149,999	78	7.24%
	More than $150,000	128	11.87%

Table 3 Continued- Demographic Information of Survey Respondents

Ethnic Identity	White	641	59.46%
	Hispanic or Latino	128	11.87%
	Black or African American	208	19.29%
	American Indian or Alaska Native	8	0.74%
	Asian	40	3.71%
	Native Hawaiian or Pacific Islander	3	0.28%
	Other	50	4.64%
Home Ownership	Owner	742	68.84%
	Rented	314	29.13%
	Other	22	2.04%
Residence Type	Single family home	796	73.84%
	Apartments/ Mobile Units	257	23.84%
	Other	25	2.32%
Difficulty in Mobility	Yes	135	12.52%
	No	943	87.48%
Chronic Medical Condition	Yes	330	30.61%
	No	748	69.39%

* Number of households with at least one resident in the category

Societal Impact of Infrastructure System Disruption

The household's experiences with the disruptions in transportation, power, communication, and water services was measured through three components: hardship, zone of tolerance, and exposure of the disruption. The social factors were hypothesized to be statistically correlated to the zone of tolerance and hazard exposure, which will in turn influence the hardship experienced. Being socially vulnerable is related to higher hardship, lower zone of tolerance, and higher exposure to disruptions. Consistent with the hypotheses, the data shows that most of the socially vulnerable groups have reported greater hardship from the infrastructure service losses. These groups have also reported holding lower zone of tolerance to the disruptions in services which affected their experienced hardship. Lastly, some socially vulnerable groups reported experiencing significantly higher duration of service outages compared to others causing them experiencing higher hardship. Table 4 summarizes the results for the experience of each group when facing service losses. In the remainder of this section, the results related to the variations in zone of tolerance and hardship among different sub-populations are explained.

Table 4- Correlations between Social Factors and Infrastructure Services

Social Factors	Transportation			Power			Communication				Water			
	H	D	T	H	D	T	H	D-1	D-2	T	H	D-1	D-2	T
Income	-0.050	-0.061	.159**	-.179**	-0.043	.149**	-.137**	-.095**	-0.062	.135**	-.148**	-.070*	-.072*	.126**
Education	-.127**	-0.046	.111**	-.162**	-0.056	.081**	-.144**	-.102**	-.083*	.087**	-.127**	-.095**	-.081*	.091**
Minority	.146**	.126**	-.072*	.142**	0.051	-.124**	.157**	.094**	.071*	-.099**	.154**	0.057	.113**	-.140**
Less than 10 years	.174**	.107**	-0.002	0.064+	0.029	-.077*	.079*	.132**	0.050	-.088**	.099**	0.050	.098**	-0.057
Older than 65 years	-.187**	-.146**	0.008	-0.055	-0.034	0.054	-.079*	-.108**	-0.057	.073*	-.105**	-0.037	-0.052	.073*
Mobility Issues	-.136**	-.103**	0.041	-.101**	-0.067+	0.014	-0.016	-.167**	-.080*	-0.043	-0.048	-0.066+	-0.037	-0.004
Chronic Medical	-0.061+	-0.063	-0.035	-0.001	-0.058	0.040	0.050	-0.056	-0.026	-0.004	0.031	-0.044	0.016	0.013
Residence Type	-0.010	-0.031	-.131**	.084*	0.006	-.146**	0.041	0.035	-0.016	-.094**	.101**	.079*	0.014	-.126**
Homeownership	0.046	0.009	-.122**	0.055	-0.014	-.163**	0.037	0.043	-0.052	-.129**	.113**	.073*	0.059	-.144**
Years of Residence	-.086**	-.071*	0.037	-0.044	-0.036	.123**	-0.020	-0.021	0.037	.093**	-0.059	-0.019	-.073*	.100**

*, ** significant at 5% and 1%%, respectively.

In this table, T stands for tolerance, H is the hardship, and D is the duration of service disruptions.

Socioeconomic Status

Income

Lower income households reported statistically significant higher hardship in regards to disruptions from the power, communication, and water services. The social group experienced significantly greater exposure to the disruptions from the cellular service, water availability, and water quality along with significantly lower zones of tolerance for these systems. Therefore, in regards to the communication and water services, both the level of exposure and zone of tolerance contributed to the higher hardship. These households did not experience a significant difference in the level of exposure to the power disruption; however, they were still disproportionately impacted due to a significantly lower zone of tolerance. Despite having similar levels of exposure, their inability to tolerate the power disruption in comparison to higher income households accounted for the higher hardship.

Education

Lower education levels are typically correlated with lower income households, but the two social categories had slightly different results. Along with repeating the statistical significance pattern of the income social group, households with lower education levels reported significantly higher hardship from the transportation disruption due to significantly greater exposure to flooded roads.

The table of correlations (Table 4) compares the income and education social groups on an increasing scale from low to high levels while the bar graph (Fig. 4) divides the social groups into two categories. Fig. 4 shows that households with an income lower than $50,000 and with an education below a completed college degree, respectively, reported higher hardship from the four service disruptions. Households with a lower socioeconomic status were disproportionately impacted because of greater exposure to disruptions and/ or a lower ability to tolerate disruptions.

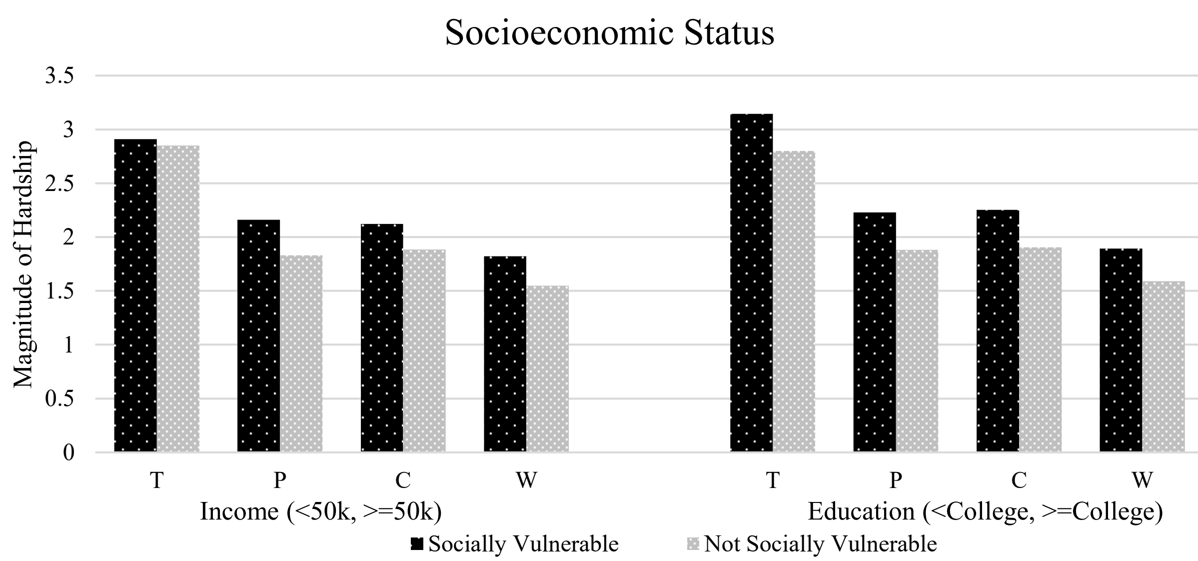

Fig. 4 Levels of self-reported hardship by income and education social groups

Racial/ Ethnic Groups

Minority households reported significantly higher hardship from all the infrastructure service disruptions (Fig. 5). They experienced significantly greater exposure to disruption in the transportation, cellular, wireless and water quality services along with significantly lower zones of tolerance for the respective services. This coupling effect, which is created when households have significantly greater exposure and a significantly lower zone of tolerance, magnifies the impact of the service disruption. In regards to the power service, where there was no significant difference in the level of exposure, minority households were still disproportionately impacted because they had a lower ability to withstand the disruption. The results indicate that minority groups were socially vulnerable because of their greater exposure and lower ability to withstand the service disruptions.

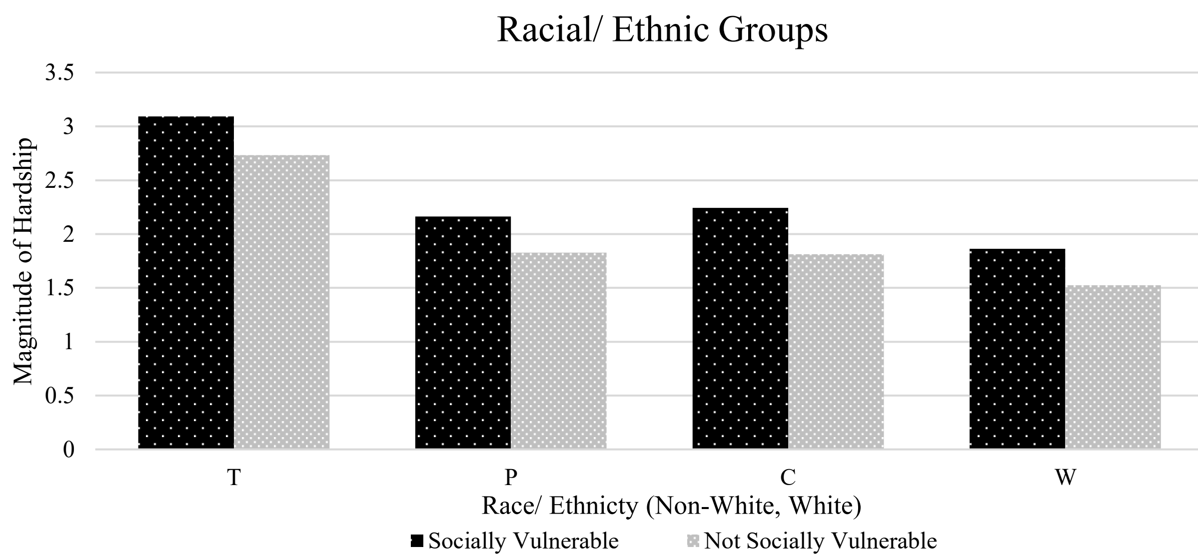

Fig. 5 Levels of self-reported hardship by race/ ethnic social groups

Household Composition

Age Groups

Households with children younger than 10 years old reported significantly higher hardship from all the infrastructure service disruptions (Fig. 6). For the transportation and water quality services, this social group experienced significantly greater exposure to the disruptions but had no difference for the zones of tolerance. These households were residing in areas that were disproportionately affected by disruptions in the transportation and water quality services. In regards to the power service, they did not experience a significant difference in exposure but did report a significantly lower zone of tolerance, which resulted in the social group experiencing higher hardship. For the communication service, these households experienced significantly greater exposure to the disruption in the cellular service along with a significantly lower zone of tolerance. This coupling effect accounted for the higher hardship for households with young children.

Although the elderly is considered a socially vulnerable group, households with residents above 65 years old reported significantly lower hardship from disruptions in the transportation, communication, and water services (Fig. 6). This can be explained by the households experiencing significantly less exposure to transportation, water quality, and cellular disruptions, which suggests that households with elderly residents were in less impacted areas. In addition, these households reported a significantly higher zone of tolerance for the communication service, which could have further influenced the lower reported hardship.

Difficulty with Mobility

Households with residents having mobility issues experienced statistically significant greater exposure to all four infrastructure disruptions (Fig. 6). These households were in areas that were more exposed to the service disruption, which translated to significantly higher hardship for the transportation and power services but not for the communication and water services. In this case, these households were particularly sensitive to the disruption of the transportation and power services.

Medical Condition

Households with residents having chronic health conditions had mixed results for the hardship across the services (Fig. 6). They did report significantly higher hardship from the transportation disruption, but there was no difference in either the level of exposure or zone of tolerance.

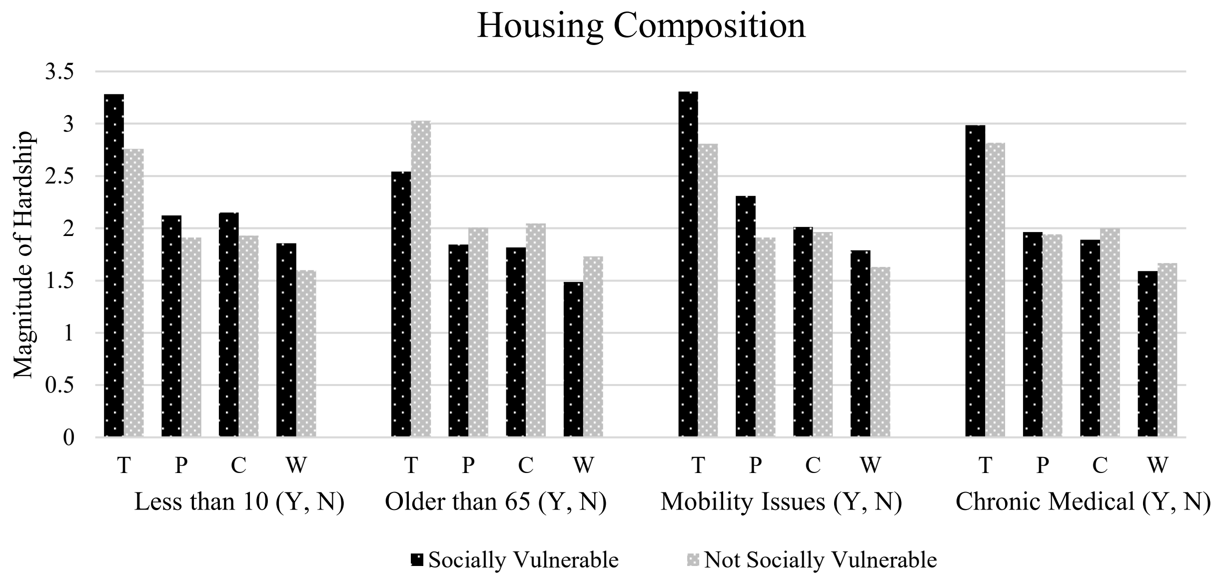

Fig. 6 Levels of self-reported hardship by age and medical social groups

Housing Style

Residence type

According to the statistical analysis, residents living in mobile homes/ apartments reported significantly higher hardship from the power and water disruptions in comparison to residents living in standard homes (Fig. 7). To explain this disparity, these households experienced significantly greater exposure to a disruption in the water availability along with lower zones of tolerance for both the power and water services. They also reported significantly lower zones of tolerance for the transportation and communication services but these did not correlate to significant differences in hardship. It shows that the residence type is more sensitive to power and water disruptions.

Home Ownership

Renters reported significantly higher hardship from the water disruption (Fig. 7). They also experienced significantly greater exposure to the disruption in water availability along with a lower zone of tolerance. Similarly, to the residence type social group, they also reported significantly lower zones of tolerance for the remaining services but these did not correlate to significant differences in hardship. It suggests that renters were more sensitive to the water disruptions and had lower ability to withstand all service disruptions.

Years of Residency

Households with new residents reported significantly greater hardship to the transportation service due to greater exposure to flooded roads.

A common pattern is that socially vulnerable groups in the housing style section (e.g., mobile homes/ apartments, renters, and newer residents) often reported statistically significant lower zones of tolerance which would typically correlate with higher hardship from the respective service disruption.

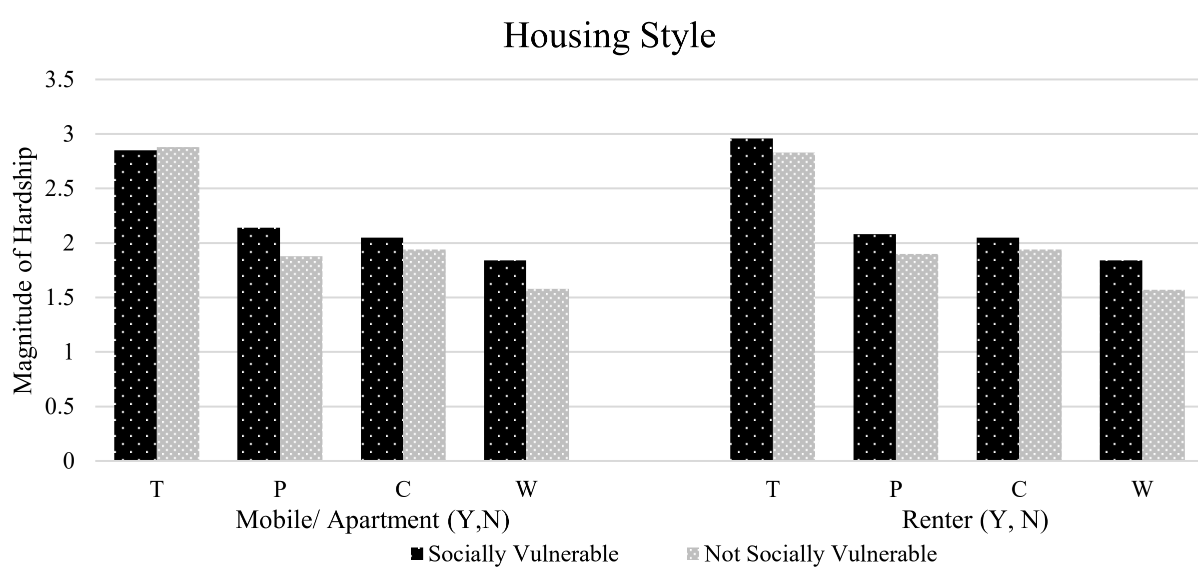

Fig. 7 Levels of self-reported hardship by residence type and home ownership status

CHAPTER V

DISCUSSION

Households' experiences with prolonged service disruptions is related to the duration of the exposure and their ability to tolerate negative impacts. Social groups in the community do not experience hardship caused by disruptions equally because they do not have the same exposure to the service outages and tolerability to withstand those outages. Greater exposure indicates that the areas in which these people are residing are more prone to the service losses and/ or the restoration time of services is longer by comparison. These households are in areas that are less maintained and structurally vulnerable to the exposure. Additionally, these groups are less capable of protecting their households from the risks of service losses because of their lowered ability to prepare for and adjust to the natural disasters (Lindell and Hwang 2008; Russell et al. 1995). Each household has specific needs and expectations of the services which must be considered in the aftermath of natural disasters (Clark et al. 2018). The following discussion will highlight significant findings and discuss particular social groups in terms of the four infrastructure services: transportation, power, communication, and water.

Greater Exposure to the Transportation Disruption

Survey respondents from the Harris County area were more exposed to the transportation disruption compared to the power, communication, and water disruptions. In particular, households with residents of minority groups, less than 10 years old, mobility issues, and fewer years of residence faced risk disparity because of greater exposure, which in this case referred to the number of days roads were flooded. Specifically, results concerning households with mobility issues align with the findings of Stough et. al. (2015). In the qualitative study, people with physical disabilities mentioned their inability to access the transportation system as a personal hardship. For Hurricane Harvey, households with mobility issues reported significantly higher hardship and were more exposed to the transportation disruption.

Lower Zone of Tolerance for the Power Disruption

Residents of lower income levels, lower education levels, minority groups, less than 10 years, and mobile/ apartments reported significantly greater hardship due to a significantly lower zone of tolerance. This means that exposure alone cannot explain the difference in hardship, and that the ability to tolerate the disruption must also be considered. Similarly, Baker (2011) concluded that households from low-income, non-college graduates, minority, and mobile/multi-unit social groups had lower preparedness scores for recent hurricanes. For example, households with power generators could have allowed them to have sense of stability throughout the duration of the power disruption, since their needs and expectations were being met to a certain degree.

Coupling Effect for Communication and Water Disruptions

Households with lower income levels, lower education levels, and minority groups were disproportionately impacted because of significantly greater exposure and a lower zone of tolerance for the communication and water disruptions. In addition, households with young children experienced a coupling effect for the communication disruption while renters and mobile/ apartment dwellers had a coupling effect for the water disruptions. It has already been discussed that the physical location of these households is an important indicator for the intensity of the exposure. When Faber (2015) investigated the impact of Superstorm Sandy, he found that households living below the poverty line were in more flooded tracts than dry tracts at statistically significant levels. Additionally, Peacock et al. (2014) consistently found that low-income, multi-unit, and renting households lost more of their initial values, with the recovery rate varying from significant to no difference in the following years. However, the significantly lower zone of tolerance demonstrates that these social groups were also able to withstand a service disruption. Families, especially, may have a greater need to protect the overall well-being of their children, particularly the ability to call for help.

In contrast, households with older residents had significantly lower hardship for communication and water services, which is contradictory to the general social vulnerability indexes (Flanagan et al. 2011). However, the older generation is generally viewed as being independent and unaccustomed to current technology standards (i.e., laptops, computers, mobile devices, etc.), which could explain why households with elderly residents have more tolerance to the communication disruptions. Age may also be related to years of preparedness, giving households with older residents a greater advantage to withstand the disaster impact (Rufat et al. 2015). In the case of Hurricane Harvey, this greater sense of awareness and preparation of the household could have outweighed the supposed fragility and vulnerability associated with elderly residents.

CHAPTER VI

CONCLUSION AND FUTURE RESEARCH

Evidence suggests that there is an increasing trend in the number of infrastructure disruptions (Chang 2016). These losses may include an inability to travel, exchange information, access water, and utilize electrical services. Regardless of the severity of the disaster-stricken areas, the demand for these critical lifeline services will not stop, and this produces a need to develop resilient disaster mitigation and planning techniques that will maintain the sustainability of the infrastructure services in the face of extreme weather conditions. Current strategies primarily focus on the physical vulnerabilities brought on by a natural disaster while failing to understand the social vulnerabilities. However, it essential to cross-analyze physical and social vulnerability because these concepts have a correspondent relationship (Lee 2014). Despite the complexities in creating a disaster-resilient community, community organizations are tasked to provide insight and solutions to these issues pertaining to infrastructure systems (McDaniels et al. 2015). Funds and resources are limited; therefore, it is essential to prioritize areas that would greatly benefit from the restoration of the services. One such way is to consider the social characteristics of households, which the research paper has demonstrated has a statistical influence in the ability of the households to withstand service disruptions. In this explanatory analysis, we examined the societal impacts of prolonged infrastructure service disruptions. Experiences of different social subgroups in the community were studied during the road closures, power outages, water disruptions, and disruptions in communication services to understand their specific needs during such severe conditions. The results also highlighted the varying impacts of prolonged disruptions on households based on their social attributes. Households which are considered to be socially vulnerable have shown to experience more hardship from the service losses. This higher hardship is either related to their higher exposure to higher probability and duration of the disruptions or lower tolerability to withstand the risks.

Although the research examines the individuality of the households with relation to their exposure, tolerance, and hardship of the infrastructure services, the findings also have the potential to influence the larger scope of the community area. Homes designed and constructed to withstand extreme environmental conditions will not necessarily be protected against the disruption of critical linkages to other parts of the community (Lindell and Prater 2003). Therefore, it is essential to improve the experience of each specific area to increase not only the resilience of a household but also the entire affected community.

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