Equitable Resilience in Infrastructure Systems: Empirical Assessment of Disparities in Hardship Experiences of Vulnerable Populations during Service Disruptions

Natalie Coleman[1]; Amir Esmalian[2]; and Ali Mostafavi, M.ASCE[3]

Abstract: The objective of this study was to examine social inequality in exposure and hardship experienced by various groups due to infrastructure service disruptions in disasters. After more than two decades, the existing literature related to infrastructure resilience mainly focuses on system performance and considers the impacts of service disruptions to be equal for the public. The public, however, is not a monolithic entity, and different subpopulations have distinct needs and expectations of infrastructure systems. Thus, the same duration of service loss will not be experienced equally by the affected residents. Social subpopulations in a community have preexisting differences, or sociodemographic characteristics, which account for differential variations in disaster experience, and often socially vulnerable groups are disproportionally affected. Unfortunately, there is limited empirical information regarding inequity in the societal impacts of infrastructure service disruptions during disasters. This study addresses this knowledge gap by developing an equitable infrastructure resilience approach that integrates both the physical characteristics of the infrastructure systems and the sociodemographic characteristics that contribute to risk disparity experienced by individual households. The risk disparity was assessed by considering both the duration of the service disruptions (exposure) and people's ability to withstand disruptions (zone of tolerance). The study investigated empirical data related to the transportation, power, communication, and water service disruptions caused by Hurricane Harvey in 2017 for Harris County residents. The results concluded that certain socially vulnerable groups reported significant disparity in the hardship people experienced due to infrastructure service disruptions caused by the disaster. The significant experienced hardship was rooted in the group's having a lower zone of tolerance for service disruptions, experiencing a significantly higher duration of service outages, or a coupling effect when there was both greater exposure and lower zone of tolerance. The findings further revealed the following: (1) households with low socioeconomic status reported a coupling effect for communication and water disruptions and reported a lower zone of tolerance for transportation and power disruptions; (2) racial minority groups reported a coupling effect for transportation, communication, and water disruptions and a lower zone of tolerance for power disruption; and (3) households with younger residents reported a coupling effect for communication disruption, greater exposure to transportation and water disruptions, and lower zone of tolerance for power disruption. The findings uncovered existing inequalities in exposure and hardship experienced due to infrastructure service disruptions for various vulnerable subpopulations. Hence, the study establishes the fundamental knowledge and empirical information needed for an equitable resilience approach in infrastructure systems in order to better prioritize investments and therefore effectively reduce the risk disparity of vulnerable populations during service disruptions. **DOI: 10.1061/(ASCE)NH.1527-6996.0000401.**

Introduction

Natural disasters place tremendous stress on critical infrastructure systems by testing their service reliability under extreme conditions (Mostafavi 2018). Communities often emphasize implementing the most ideal planning practices and engineering methods to maintain the functionality of critical infrastructure systems during disasters. However, 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 that threaten the well-being of affected residents. Under normal conditions, minor disruptions from these and other services are expected, with little to no effect in the typical daily setting. However, prolonged service disruptions can pose serious threats to the physical, emotional, and mental well-being of residents in a community (Chang 2016; Yoon 2012). In fact, critical infrastructure such as transportation, power, water, and communication systems are vital to maintaining the structure of a community. (UNISDR 2009; Mostafavi et al. 2018). 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 are often anxiously attempting to return to a state of normalcy (Clark et al. 2018; Lindell and Prater 2003). A resilience approach is needed to minimize the impact of infrastructure service disruptions and protect the well-being of residents, while remaining mindful of the relationship between critical infrastructure and the entire community (Berkeley and Wallace 2010; Trump et al. 2017).

[1]Undergraduate Research Assistant, Urban Resilience, Networks and Informatics Lab, Zachry Dept. of Civil and Environmental Engineering, Texas A&M Univ., College Station, TX 77843. ORCID: https://orcid.org/0000-0001-6779-5440. Email: cole_16499@tamu.edu

[2]Ph.D. Student, Urban Resilience, Networks and Informatics Lab, Zachry Dept. of Civil and Environmental Engineering, Texas A&M Univ., College Station, TX 77843 (corresponding author). Email: amiresmalian@tamu.edu

[3]Assistant Professor, Urban Resilience, Networks and Informatics Lab, Zachry Dept. of Civil and Environmental Engineering, Texas A&M Univ., College Station, TX 77843. Email: amostafavi@civil.tamu.edu

Note. This manuscript was submitted on June 16, 2019; approved on April 15, 2020; published online on June 18, 2020. Discussion period open until November 18, 2020; separate discussions must be submitted for individual papers. This paper is part of the ***Natural Hazards Review***, © ASCE, ISSN 1527-6988.

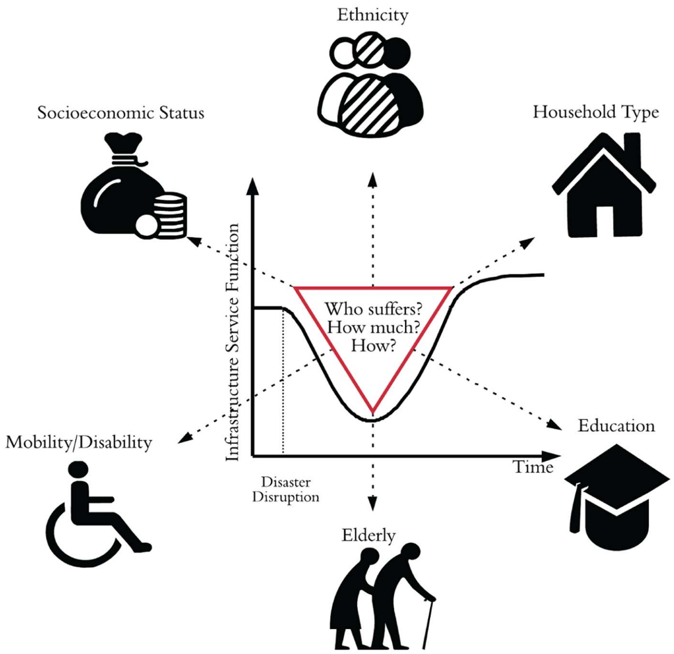

Fig. 1. Equitable infrastructure resilience: integrating societal dimensions into standard infrastructure resilience framework.

In the standard infrastructure resilience model, as shown in the resilience curve in Fig. 1, various measures primarily focus on the destruction of infrastructure systems due to 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. Unfortunately, due to various factors such as resource constraints, as well as the ever-growing frequency and magnitude of natural hazards (Rasoulkhani and Mostafavi 2018), complete elimination of infrastructure function losses is practically impossible. An important shortcoming of the standard model is its lack of consideration for the variation in the sociodemographic characteristics of subpopulations and the extent to which vulnerable populations (e.g., low-income families and racial minorities) are disproportionately exposed to risks due to service disruptions. This disparity is because the standard model of infrastructure resilience considers the public as a monolithic entity.

Yet the public is not a monolithic entity; rather, various subpopulations within a community use, access, and rely on the infrastructure and respond to service disruptions in different ways. In recognition of this incongruity, recent reports by the National Academies (National Research Council 2012), the National Institute of Standards and Technology (ATC 2016), and the National Infrastructure Advisory Council (Berkeley and Wallace 2010) have concluded that the current body of knowledge lacks fundamental information about the various societal impacts of infrastructure service disruptions caused by disasters. In fact, the existing literature has shown that specific segments of the community (such as low income, racial minority, and young children) are disproportionately affected by disasters (Flanagan et al. 2011), and therefore are potentially more vulnerable to service disruptions. These reports also suggest that the preexisting differences already found among residents, referred to in this research paper as sociodemographic characteristics, may magnify the impact of a natural disaster (Rufat et al. 2015).

Undeniably, even after more than two decades of research on infrastructure resilience, little of the existing work explicitly or empirically considers the sociodemographic impact of infrastructure service disruptions in disaster settings (Paton et al. 2006; ATC 2016). This knowledge gap has prevented an equitable approach to infrastructure resilience, one that enables the integration of humanistic considerations into the engineering design and prioritization of systems in order to achieve reasonable and fair societal well-being (Doorn et al. 2018; Murphy and Gardoni 2006). An equitable infrastructure resilience approach is desperately needed so as 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 caused by service disruptions.

In the disaster literature, several studies have examined the relationship between sociodemographic characteristics and the perception of risk (Lindell and Hwang 2008; Paton et al. 2006), level of preparedness (Baker 2011; Fothergill et al. 1999; Horney 2008), and the initial impact and long-term recovery process of individual households affected by a natural disaster (Peacock et al. 2014). Previous studies have also shown that sociodemographic characteristics can be significant indicators of the disaster impact such as the percentage of damaged structures (Burton 2010) and the projected economic loss (Sutley et al. 2017). These research studies illustrate the need for incorporating social dimensions 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 subpopulations. Therefore, our research study holistically views the disaster impact on individual households through three dimensions: the experienced hardship, the extent of exposure, and the zone of tolerance. The experienced hardship will be used as an indicator to measure the negative impacts that individual households faced during disaster-induced service disruptions. The study theorizes that the experienced hardship is a factor of both the duration of the service disruption (extent of exposure) and the ability of the household to withstand the service disruption (zone of tolerance). Households would report higher hardship if they experience a long period of the service outage. Affected households would also report higher hardship if they do not have the resources to withstand such outages (Esmalian et al., forthcoming).

Therefore, the objectives of the research are to answer the following questions:

1. To what extent are different social subpopulations impacted by different service disruptions?
2. Are the impacts disproportionally affecting socially vulnerable subpopulations?
3. Which subpopulations experience the greatest social impact?
4. Which infrastructure service disruptions cause greater hardship to which subpopulations?
5. To what extent is the experienced hardship due to the extent of exposure compared to the zone of tolerance of subpopulations?
6. Are there disparities among socially vulnerable subpopulations in terms of exposure to extended service disruptions as well as the zone of tolerance?

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, vulnerability is defined as the "characteristics and circumstances of a community, system, or asset that make it susceptible to the damaging effects

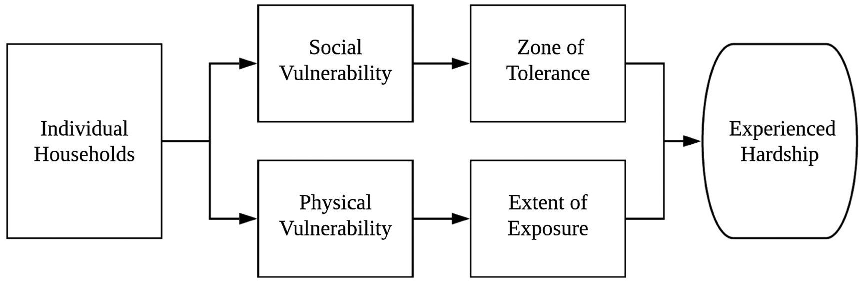

Fig. 2. Conceptual framework for assessing households' experience with infrastructure service disruptions.

of a hazard" (UNISDR 2009). The ongoing research dialog in the disaster research community has been attempting to define, measure, and evaluate both the physical and social vulnerability of communities when dealing with disasters (National Research Council 2012). The purpose of the research study is to integrate both physical and social vulnerabilities, and thus, the study proposes the following conceptual framework (Fig. 2) to examine the disproportionate experiences of diverse households in a disaster situation. Our work further aims to develop the empirical data needed for an equitable infrastructure resilience approach, one designed to fill the knowledge gap of the societal impacts of infrastructure service disruptions (Berkeley and Wallace 2010), and holistically understand disaster impact (National Research Council 2012).

In the conceptual framework, the experience of individual households during service disruptions is measured through (1) the experienced hardship, (2) the extent of exposure, and (3) the zone of tolerance (Fig. 2). For the purposes of this study, the self-reported experienced hardship is the main indicator for measuring the negative consequences or impact resulting from an infrastructure service disruption. By examining the relationship between the extent of exposure and the zone of tolerance to the experienced hardship, the research study focuses on understanding the disparity in societal risks. The *extent of exposure* measures the number of days of service disruptions. This is affected by physical vulnerabilities in the individual household and community such as a weakened infrastructure system prone to damage. As the extent of exposure increases, the experienced hardship would also increase. However, the duration of the service disruption cannot solely explain the disparity in hardship. Households also have varying levels of ability to withstand the disruptions. This is measured by using the *zone of tolerance*. The zone of tolerance refers to the ability of households to withstand service disruptions. For instance, the number of days a household is able to withstand a prolonged power outage caused by a disaster. As the zone of tolerance to service disruptions increases, the experienced hardship would decrease because the household has a higher ability to withstand the service losses. This factor is influenced by the social vulnerabilities in a household, which will be further discussed in the following section. As such, the framework implements the combination of a household's duration of service disruptions and the household's relative dependence on critical lifeline services to capture the underlying mechanism behind the disproportionately experienced hardship of the socially vulnerable populations.

Sociodemographic Characteristics and Disaster Impact

For the research study, various sociodemographic characteristics were considered in order to examine the variation in disaster risk disparity resulting from infrastructure service disruptions. These characteristics were obtained from the Centers for Disease Control and Prevention's (CDC) social vulnerability index (SVI). The SVI subdivides the sociodemographic characteristics into the following four categories: socioeconomic status, racial/ethnic groups, household composition, and housing style (Flanagan et al. 2011). Similarly, in this study, the sociodemographic characteristics considered specifically include: *socioeconomic status*, which refers to the income and education level of the household; *racial/ethnic groups* to examine disparity among *racial minority groups*, which includes any race/ethnicity that is non-White; *household composition*, which refers to the age distribution and medical conditions of the residents; and *housing style*, which includes the residential type, home-ownership status, and tenancy (or years of residency).

Socioeconomic status: According to Fothergill and Peek (2004), households with lower income are more vulnerable to disaster impact as they are more likely to face significant physical damage and less likely to prepare for incoming disasters, among other reasons. Additionally, Masozera et al. (2007) showed that lower-income household members had difficulty responding to the incoming Hurricane Katrina due to a lack of transportation to evacuate the impacted area. These households also struggled in the recovery process because they could not afford to 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, its direct connection is less apparent in disaster literature and needs further research.

Racial/ethnic groups: Racial and ethnic minorities are linked to increased levels of disaster impact. There is evidence of racial and ethnic bias that could negatively affect the response and recovery process of minority groups (Fothergill et al. 1999). Marsh et al. (2010) discussed how institutionalized racial inequality is created through strategic municipal planning, meaning that minority communities could be excluded from receiving the necessary infrastructure and services. In particular, Chakraborty et al. (2014) concluded that Black and Hispanic residents were more likely to reside in high risk (100-year) flood zones. The issues of racial bias and isolation can also affect the capability of these populations in coping with infrastructure service disruptions.

Household composition: Among the age groups, the elderly and children are considered to have the highest vulnerability because of their often fragile physical/mental state and general dependency (Rufat et al. 2015). Also, during Hurricane Katrina, elderly residents accounted for the majority of fatalities and had disproportionately higher mortality rates (Flanagan et al. 2011). Children have great difficulty recovering from a disaster (Aptekar and Boore 1990) because they are too young to emotionally process events and therefore require greater support from family members. According to Westbrook Lauten and Lietz (2008), in the immediate aftermath of Hurricane Katrina, children reported increased family

Nat. Hazards Rev., 2020, 21(4): 04020034

separation, fewer friends, and less participation in after-school activities. People with medical conditions are also more vulnerable to disaster impact. 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 transportation systems.

Housing style: Housing is considered another important factor of social vulnerability. Mobile homes and apartments are less structurally sound in withstanding the physical consequences of natural disasters (Fothergill and Peek 2004). Households living in mobile homes are also less likely to contain vital survival kits (Horney 2008), lowering their level of preparation for disasters. In studies of Hurricane Andrew and Hurricane Ike, Peacock et al. (2014) concluded that owner-occupied houses suffered less damage and recovered more quickly; additionally, renters were particularly more susceptible to the disaster impact.

There is a need to optimize and prioritize the performance of infrastructure systems during a disaster setting to maintain the well-being of *ALL* community residents (Chang and Nojima 2001; Gomez and Baker 2019). However, the existing literature does not examine the influence of sociodemographic characteristics on the ability of households to cope with different infrastructure service disruptions. Although the standard infrastructure resilience model fails to consider the specific needs of socially vulnerable populations, the preceding discussion shows that particular sociodemographic characteristics of households do influence disaster impact. To this end, our study employs empirical data from a household survey in the aftermath of Hurricane Harvey in order to uncover the relationship among sociodemographic characteristics, the zone of tolerance, and hardship of households facing various infrastructure service disruptions.

Methodology

Study Context

Our study employed a household survey taken in the aftermath of Hurricane Harvey to gather empirical data regarding service disruptions and their impact on households in Harris County. In particular, the study evaluated the effect of service disruptions due to transportation, power, communication service, and water outages. Residents who remained sheltered-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 2018), and the flooded roads and subsequent road repairs caused traffic congestion. Utility companies reported a total of approximately 336,000 electrical outages, which impacted Texas customers (CBS/AP 2017). According to the Federal Communications Commission reports, 160 cellular sites were not operational. Finally, Harris County residents also received a total of 76 boil-water notices, and three wastewater treatment plants were destroyed (Davis 2018). The specific 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 various households' experience with infrastructure systems disruptions. The survey was distributed using the Qualtrics system, which is an online survey panel service and a private company in the United States. 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 a stratified sampling strategy from a census-representative panel especially designed for survey development. The target subjects were the residents of Harris County who were above 18 years old. A *soft-launch*, or pilot launch, of the survey, was released in May 2018 and resulted in 47 initial responses. This was to ensure the quality of the questions and determine if the survey was ready for complete data collection. The official survey launch was released in June 2018, and a total of 1,742 responses were collected. Responses with incomplete information and those related to households whose residents 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 was of secondary importance since people 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. The collected responses from each ZIP Code inside the target survey area are shown in Fig. 3.

Measures

The survey collected the sociodemographic characteristics of the individual households (Table 1), along with factors describing the disaster impact (Table 2). Tables 1 and 2 show how the variables were coded for the statistical analysis.

Survey responders were asked to evaluate their experiences on the transportation, power, communication, and water service disruptions by answering questions relating to the (1) experienced hardship, (2) exposure of service disruptions, and (3) the zone of tolerance. The left column of Table 2 provides the sample format of the survey questions.

Analysis

The analysis was conducted using bivariate correlations through the Spearman statistical method. This nonparametric test is more representative of the data set because the majority of the outcomes were either ordinal or ranked (Ott and Longnecker 2010). 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 association of sociodemographic characteristics with the hardship experienced, exposure to service disruptions, and the zone of tolerance.

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 United States Census Bureau data, the data set collected is representative of the population in the county. Moreover, the sample represents the diversity of the demographic information for conducting tests related to the relationships between sociodemographic characteristics and disaster impacts.

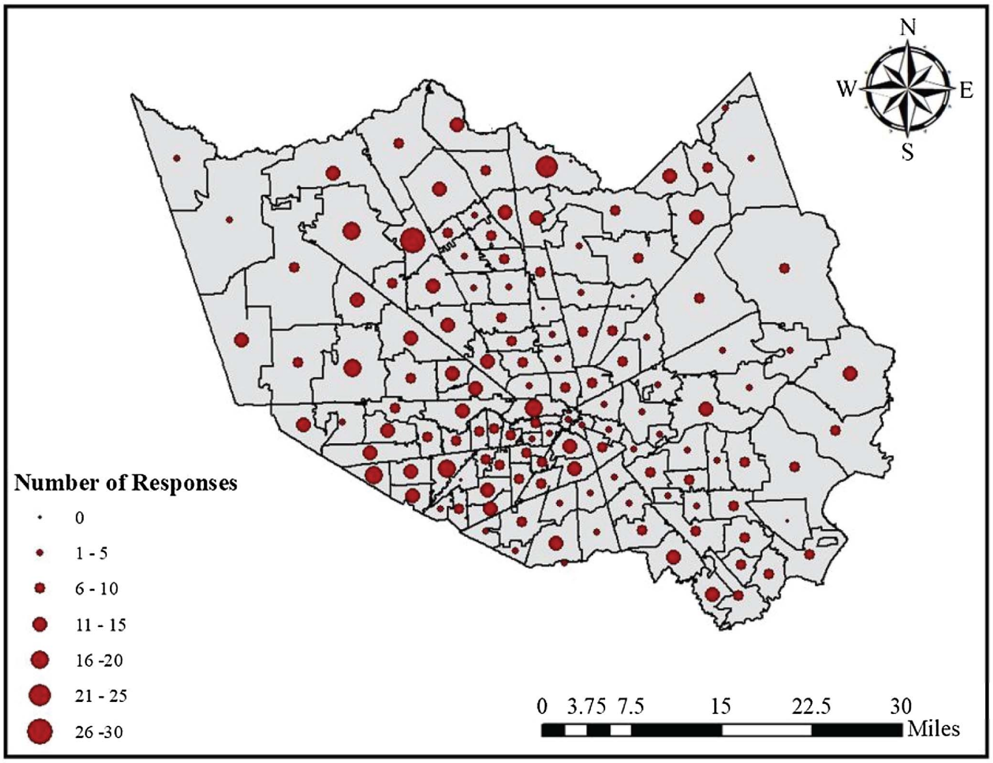

Fig. 3. Map of Harris County and distribution of collected data from each ZIP Code.

Table 1. Description of the sociodemographic characteristics

Characteristics	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), 4-year degree (=6), and postgraduate level (=7)
Racial/ethnic minority	Non-White (=1), White (=0)
Children (younger than 10 years)	Yes (=1), No (=0)
Elderly (65 years or older)	Yes (=1), No (=0)
Mobility issues	Yes (=1), No (=2)
Chronic medical condition	Yes (=1), No (=2)
Homeownership	Rented the residence (=1), Full payment/ mortgage loan (=0)
Residence type	Apartment/mobile home (=1), single-family home (=0)
Years of residence	Time living in the residence (# of years)

Table 2. Description of disaster impact factors

Factors/questions	Response input
(1) Experienced 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
(2) 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)
(3) Zone of tolerance: Considering an upcoming severe hurricane (like Harvey), how would you complete the following statement? Overall, my household is capable of tolerating the [service disruption] for [response] days.	Reported in the number of days for transportation, communication, water, and power disruptions

Table 3. Demographic information of survey respondents

Variables	Categories	Frequency	Percent
Age[a]	Younger than 2 years	67	6.22
	2–10 years	197	18.27
	11–17 years	209	19.39
	18–64 years	838	77.74
	65 years or older	347	32.19
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
	Postgraduate 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
Racial/ethnic minority	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

[a]Number of households that reported having at least one resident in the category.

Societal Impacts of Infrastructure Service Disruptions

Each responding household's experiences with disruptions in transportation, power, communication, and water services was measured through three dimensions: experienced hardship, exposure to service disruptions, and zone of tolerance. The sociodemographic characteristics were hypothesized to be statistically correlated to the exposure and zone of tolerance, which would, in turn, influence the experienced hardship. Being socially vulnerable is related to higher hardship, greater exposure to disruptions, and lower zone of tolerance. Consistent with the hypotheses, the data showed that most of the socially vulnerable subpopulations reported significantly greater hardship from the infrastructure service losses. Some of these socially vulnerable subpopulations reported experiencing a significantly greater exposure to service outages compared to others, causing them to experience higher hardship. Certain groups also reported a significantly lower zone of tolerance to service disruptions, which affected their experienced 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 hardship among different subpopulations are explained.

Socioeconomic Status

Income: Based on the table of correlations (Table 4), lower income households reported statistically significant higher hardship in regard to disruptions from power, communication, and water services. Additionally, the correlation results showed that lower income households experienced significantly greater exposure to disruptions from cellular service, water availability, and water quality, along with significantly lower zones of tolerance for these services. Therefore, in regard to communication and water services, both the level of exposure and zone of tolerance contributed to higher hardship. These households did not experience a significant correlation difference in the level of exposure to power disruption; however, they were still disproportionately impacted due to a significantly lower zone of tolerance. Despite having similar levels of exposure, lower income households were unable to tolerate power disruptions when compared to higher income households, which accounted for lower income households reporting higher hardship.

Education: Lower education levels often correlated with lower income households, but the two social categories had slightly different results in terms of the impacts of service disruptions. Along with repeating the statistical significance pattern of lower income households, households with lower education levels reported significantly higher hardship from transportation disruption due to the significantly lower zone of tolerance (Table 4).

The correlation table compares the income and education social groups on an ordinal scale from lower to higher levels of socioeconomic status. Meanwhile, the bar graph (Fig. 4) and mean values table (Table 5) divide the income and education social groups into two categories. To begin, Fig. 4 shows that households with an income lower than $50,000 and with education below a completed college degree, respectively, reported higher hardship from the four service disruptions. In general, households with a lower socioeconomic status were disproportionately impacted because of greater exposure to disruptions and/or a lower ability to tolerate disruptions. Table 5 presents the statistics for the duration of the disruptions of services and households' zone of tolerance to service outages. The results from the table indicate that lower income households (annual income less than $50,000) and households with a low education level (less than or equal to having a college degree) experienced greater exposure of service disruptions, as well as a lower zone of tolerance.

Racial/Ethnic Minority

According to the correlation table, racial minority households reported significantly higher hardship from all the infrastructure service disruptions. Racial minority households also experienced significantly greater exposure to disruption in 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 service disruption. In regard to power service, in which 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 from the correlation table indicate that minority groups were socially vulnerable because of their greater exposure and lower ability to withstand service disruptions. For example, Fig. 5 shows that minority subpopulations reported higher hardship from all service disruptions, and Table 5 reports how racial minority groups experienced a higher duration of infrastructure service disruptions and held a lower zone of tolerance to the services.

Table 4. Correlations between sociodemographic characteristics and infrastructure services

Var.	Income	Education	Racial minority	Children	Elderly	Mobility issues	Chronic medical	Residence type	Home owner-ship	Years residence
Transportation										
H	−0.050	−0.127[a]	0.146[a]	0.174[a]	−0.187[a]	−0.136[a]	−0.061[b]	−0.010	0.046	−0.086[a]
D	−0.061	−0.046	0.126[a]	0.107[a]	−0.146[a]	−0.103[a]	−0.063	−0.031	0.009	−0.071[b]
T	0.159[a]	0.111[a]	−0.072[b]	−0.002	0.008	0.041	−0.035	−0.131[a]	−0.122[a]	0.037
Power										
H	−0.179[a]	−0.162[a]	0.142[a]	0.064[b]	−0.055	−0.101[a]	−0.001	0.084[b]	0.055	−0.044
D	−0.043	−0.056	0.051	0.029	−0.034	−0.067[b]	−0.058	0.006	−0.014	−0.036
T	0.149[a]	0.081[a]	−0.124[a]	−0.077[b]	0.054	0.014	0.040	−0.146[a]	−0.163[a]	0.123[a]
Communication										
H	−0.137[a]	−0.144[a]	0.157[a]	0.079[b]	−0.079[b]	−0.016	0.050	0.041	0.037	−0.020
D1	−0.095[a]	−0.102[a]	0.094[a]	0.132[a]	−0.108[a]	−0.167[a]	−0.056	0.035	0.043	−0.021
D2	−0.062	−0.083[b]	0.071[b]	0.050	−0.057	−0.080[b]	−0.026	−0.016	−0.052	0.037
T	0.135[a]	0.087[a]	−0.099[a]	−0.088[a]	0.073[b]	−0.043	−0.004	−0.094[a]	−0.129[a]	0.093[a]
Water										
H	−0.148[a]	−0.127[a]	0.154[a]	0.099[a]	−0.105[a]	−0.048	0.031	0.101[a]	0.113[a]	−0.059
D1	−0.070[b]	−0.095[a]	0.057	0.050	−0.037	−0.066[b]	−0.044	0.079[b]	0.073[b]	−0.019
D2	−0.072[b]	−0.081[b]	0.113[a]	0.098[a]	−0.052	−0.037	0.016	0.014	0.059	−0.073[b]
T	0.126[a]	0.091[a]	−0.140[a]	−0.057	0.073[b]	−0.004	0.013	−0.126[a]	−0.144[a]	0.100[a]

Note: H = hardship; T = tolerance; and D = duration of service disruptions. D1 and D2 in Communication refer to cellular outages and wireless service outages, respectively. D1 and D2 in water refer to water availability and water boil-notices, respectively.
[a]Significant at 1%.
[b]Significant at 5%.

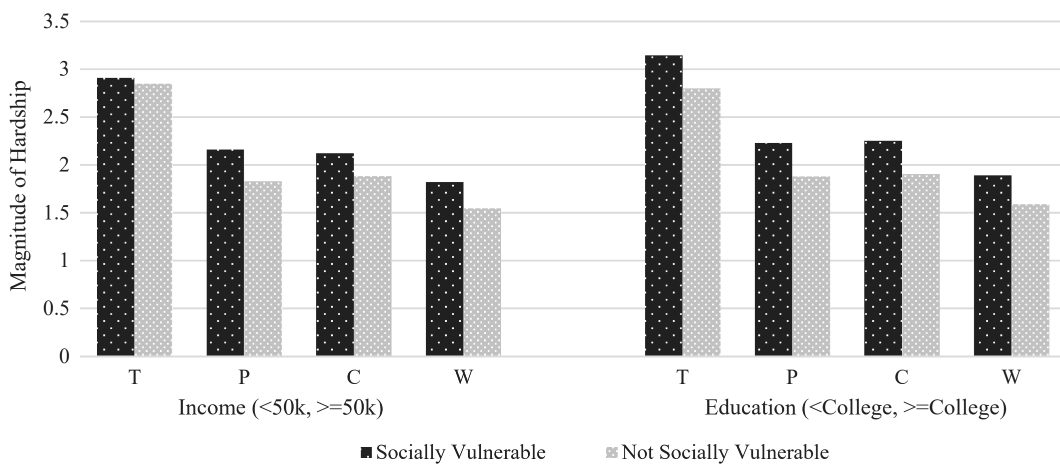

Fig. 4. Levels of self-reported hardship by income and education social subpopulations. T = transportation; P = power; C = communication; and W = water disruptions.

Household Composition

Age Groups: Based on the correlation table, households with children younger than 10 years old reported significantly higher hardship from all infrastructure service disruptions. For transportation and water quality services, this social group experienced significantly greater exposure to disruptions, but had no difference for the zones of tolerance. These households were residing in areas that were disproportionately affected by disruptions in transportation and water quality services. In regard to power service, the respondents 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 communication service, these households experienced significantly greater exposure to the disruption in 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 residents are considered a socially vulnerable group, households with residents 65 years or older reported significantly lower hardship from disruptions in transportation, communication, and water services (Table 4). This result can be explained by households experiencing significantly less exposure to transportation, water quality, and cellular disruptions, which suggests that households with elderly residents were in less impacted areas during Hurricane Harvey. In addition, these households reported a significantly higher zone of tolerance for communication service, which could have further influenced the lower reported hardship. For both age groups, Fig. 6 displays the mean values for the experienced hardship, while Table 5 displays the mean values for the exposure and the zone of tolerance.

Difficulty with Mobility: Households with residents having mobility issues experienced statistically significant greater exposure to all four infrastructure disruptions (Table 4). These households were in areas more exposed to service disruptions, which

Nat. Hazards Rev., 2020, 21(4): 04020034

Table 5. Mean values of the zone of tolerance and duration of service disruptions for sociodemographic groups

Variables	Categories	Transportation (days)		Power (days)		Communication (days)			Water (days)		
		T	D	T	D	T	D1	D2	T	D1	D2
Income	<$50,000	7.09	6.40	3.33	0.85	3.38	1.19	1.30	2.98	0.59	0.91
	> = $50,000	8.80	5.80	4.19	0.75	4.26	0.91	1.07	3.54	0.50	0.68
Education	<College	7.09	6.41	3.53	1.05	3.30	1.24	1.34	2.77	0.67	1.07
	> = College	8.46	5.92	3.96	0.73	4.10	0.96	1.11	3.48	0.50	0.70
Racial minority	Yes	7.87	6.59	3.51	0.93	3.60	1.34	1.42	3.07	0.65	1.21
	No	8.37	5.64	4.10	0.70	4.14	0.82	1.00	3.50	0.46	0.51
Children	Yes	7.92	6.64	3.71	0.82	3.42	1.46	1.30	3.43	0.73	1.18
	No	8.25	5.82	3.92	0.78	4.07	0.90	1.12	3.31	0.49	0.68
Elderly	Yes	8.00	5.20	4.04	0.77	4.23	0.70	1.13	3.50	0.50	0.57
	No	8.25	6.37	3.75	0.79	3.78	1.16	1.17	3.25	0.54	0.87
Mobility issues	Yes	7.57	7.27	3.88	1.06	4.09	1.97	2.15	3.29	0.68	0.88
	No	8.26	5.82	3.87	0.76	3.91	0.88	1.05	3.34	0.51	0.75
Chronic medical	Yes	8.40	6.31	3.79	1.03	3.98	1.39	1.48	3.29	0.68	0.71
	No	8.08	5.86	3.91	0.69	3.91	0.85	1.02	3.36	0.47	0.79
Residence type	Mobile homes/multiunits	6.54	5.36	2.86	0.77	3.24	0.99	0.87	2.53	0.73	0.77
	House	8.70	6.20	4.20	0.79	4.15	1.02	1.25	3.59	0.46	0.76
Homeownership	Renters	6.83	5.85	2.99	0.70	3.27	0.96	0.78	2.73	0.67	1.00
	Homeowners	8.73	6.06	4.24	0.82	4.21	1.04	1.30	3.58	0.47	0.67

Note: T = tolerance; and D = duration of service disruptions. D1 and D2 in Communication refer to cellular outages and wireless service outages, respectively. D1 and D2 in water refer to water availability and water boil-notices, respectively.

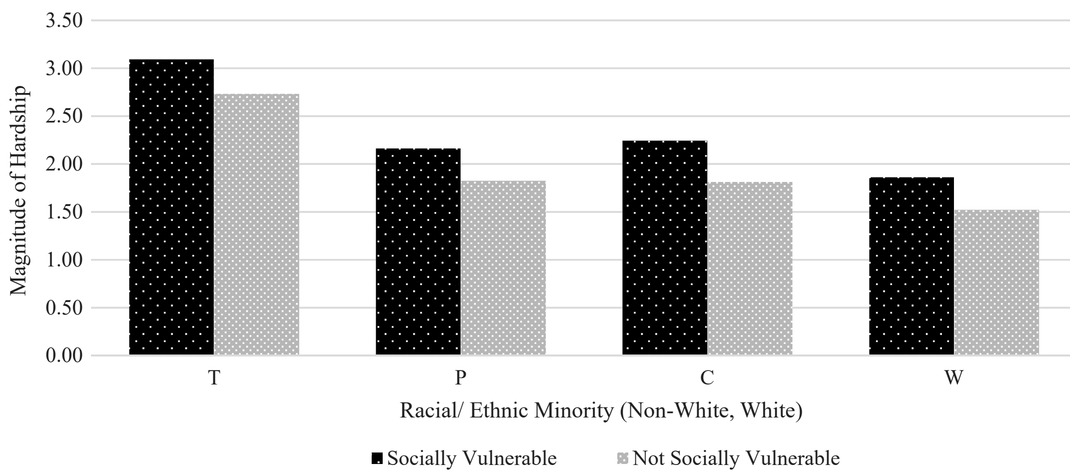

Fig. 5. Levels of self-reported hardship by racial/ethnic social subpopulations. T = transportation, P = power, C = communication, and W = water disruptions.

translated to significantly higher hardship for transportation and power services, but not for communication and water services. In this case, these households were particularly sensitive to the disruption of 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 transportation disruption, but there was no difference in either the level of exposure or zone of tolerance (Table 4). There were no other statistically significant results. The mean values for the experienced hardship are presented in Fig. 6 while the mean values for the exposure disruption and the zone of tolerance of households are presented in Table 5, specifically for the households with at least one member having a chronic medical disease and mobility issues.

Housing Type

Residence type: According to the statistical correlation analysis, residents living in mobile homes/apartments reported significantly higher hardship from power and water disruptions in comparison to residents living in standard homes (Table 4). These households experienced significantly greater exposure to a disruption in the water availability along with lower zones of tolerance for both power and water services, and both the exposure and zone of tolerance explains the disparity in hardship. Residents living in mobile homes/apartments also reported significantly lower zones of tolerance for transportation and communication services, but these did not correlate to significant differences in hardship. These results show that the residential type of household is more sensitive to power and water disruptions.

Home Ownership: Based on the correlation table, renters reported significantly higher hardship from water disruption. They also experienced significantly greater exposure to disruption in water availability, along with a lower zone of tolerance. Similarly, the residence type social group also reported significantly lower zones of tolerance for the remaining services, but these did not correlate to significant differences in hardship. The results suggest that

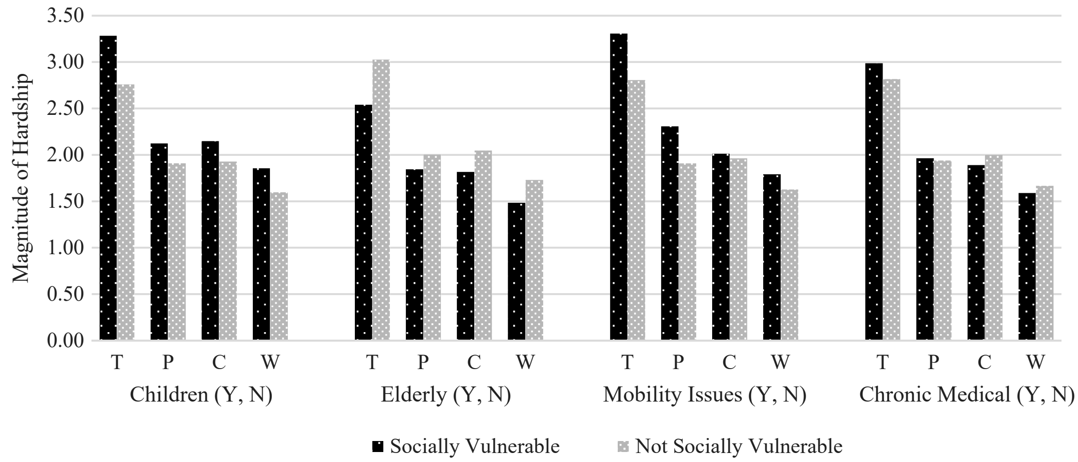

Fig. 6. Levels of self-reported hardship by age and medical social subpopulations. T = transportation; P = power; C = communication; and W = water disruptions.

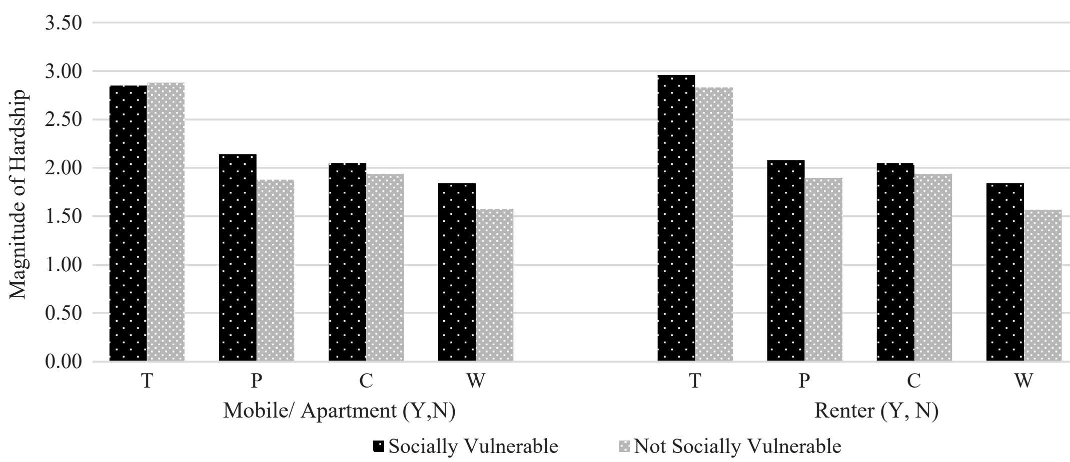

Fig. 7. Levels of self-reported hardship by residence type and home ownership status. T = transportation; P = power; C = communication; and W = water disruptions.

renters were more sensitive to water disruptions and had a lower ability to withstand all service disruptions. The mean values for the experienced hardship are displayed in Fig. 7 while the mean values for the duration of the service disruptions and the zone of tolerance are displayed in Table 5, specifically for the housing type social subpopulations.

Years of Residency: Households with new residents correlated with significantly greater hardship to transportation service due to greater exposure to flooded roads (Table 4). A common pattern is that the housing style section (e.g., mobile homes/apartments, renters, and newer residents) often reported statistically significant lower zones of tolerance.

Discussion

Fig. 8 is a visual representation of the overall correlation results for the sociodemographic characteristics' exposure to the disruptions and zone of tolerance. Referring to all sociodemographic characteristics (except households with elderly residents), the connection through the dotted lines indicates a significantly lower zone of tolerance to the particular service, and the connection through the solid lines indicates significantly greater exposure of the service outages; households that experienced both a lower zone of tolerance and greater exposure of the service loss are connected by double lines. For households with elderly residents, the definition is reversed, meaning lower hardship, a higher zone of tolerance, and less exposure. For example, low-income households had a lower zone of tolerance for transportation and power services and a coupling effect for communication and water services. Highfield et al. (2014) concluded that both physical and social vulnerabilities accounted for significant housing damage from Hurricane Ike. By extension, the findings from this research study are able to interpret the integration of physical and social vulnerabilities directly to infrastructure service losses. As a result, identifying the specific needs and expectations that these subpopulations have on infrastructure services is required in planning and designing an equitable approach for the resilience of infrastructure systems. This figure is primarily tailored to the findings of Harris County following the impact of Hurricane Harvey. Therefore local organizations in Harris County can utilize these findings to determine the risk disparity of households with certain sociodemographic characteristics as well as the investments on infrastructure service improvements.

Although Harris County has made redevelopment in its disaster mitigation plans, especially after Hurricane Harvey, these changes

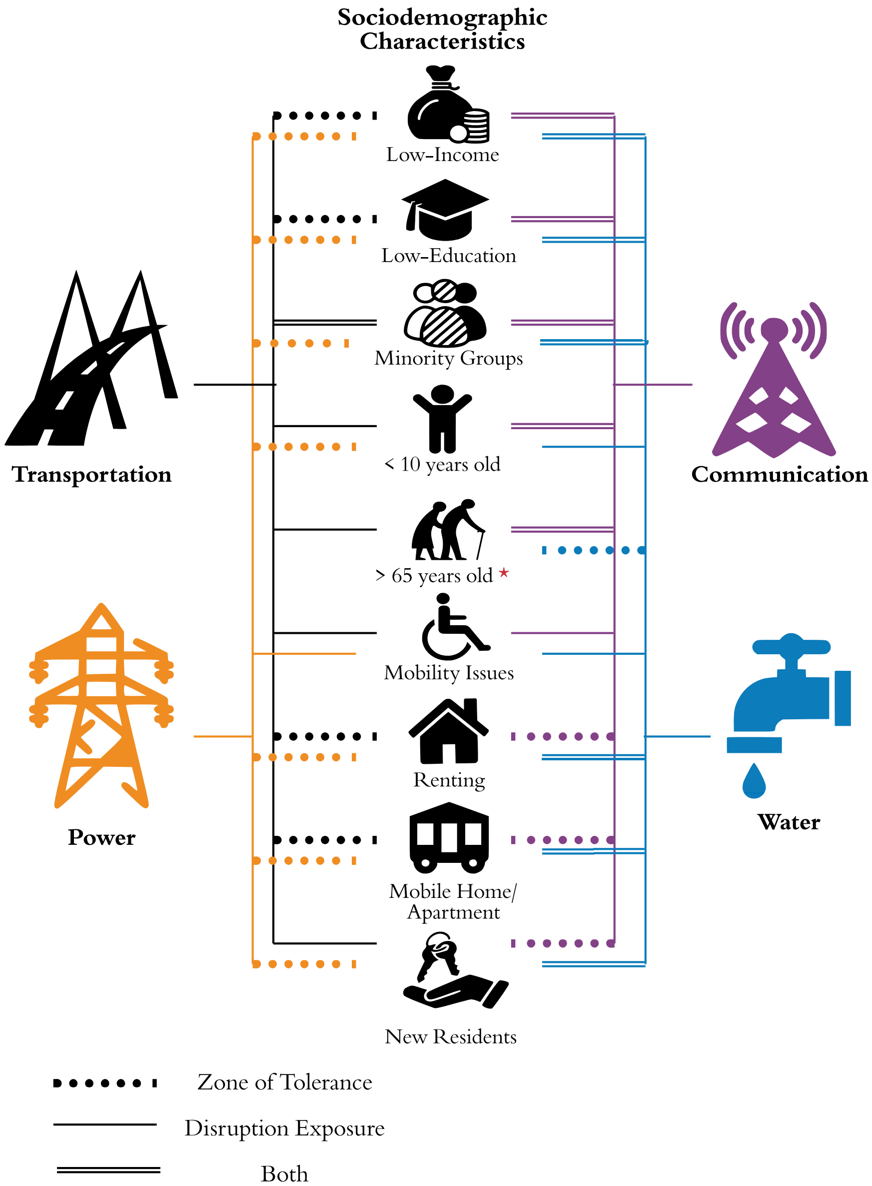

Fig. 8. Disparities in exposure and zone of tolerance to infrastructure service disruptions of households in Harris County during Hurricane Harvey. *Relationship for elderly group is reversed as this group experienced a lower duration of disruption and higher zone of tolerance to disruptions. Solid lines indicate disparity in experienced duration of disruptions. Dotted lines indicate disparities in zone of tolerance of households to service disruptions, and double lines display condition in which both duration and zone of tolerance are significant for sociodemographic characteristics.

have primarily focused on the physical characteristics of the area such as updating the flood maps. The results of this research will guide local agencies in considering the social dimension in disaster preparedness and mitigation plans to address the preexisting social inequities in the area. Local agencies can use the findings of this research to identify vulnerable populations in a community and then develop mitigation plans that promote equitable resilience design in infrastructure systems. In addition, agencies should establish proper communication channels with these vulnerable populations to ensure that they are aware of any coping strategies for the service outages. Literature has shown that vulnerable groups are often unable to receive information about protective actions due to political boundaries and language barriers (Fothergill et al. 1999; Fothergill and Peek 2004). As such, the local agencies should target these vulnerable populations for risk communication.

Greater Exposure to Transportation Disruptions

In Hurricane Harvey, Harris County households experienced greater days of exposure to transportation disruption compared to the power, communication, and water disruptions (Table 5). Based on the results related to the transportation service from Fig. 8, the following subpopulations faced higher risk disparity due to greater exposure to the service loss, or in this case, the number of days roads were flooded: racial minority groups, children younger than 10 years old, mobility issues, and fewer years of residence. Here, these households are living in areas that are vulnerable to floods and overrun. Retrofits such as road elevation could be taken in these locations populated by socially vulnerable groups to reduce the impact of future events on these vulnerable households. Furthermore, the results concerning households with mobility issues align with the findings of Stough et al. (2015), which studied the experiences of people with disabilities following Hurricane Katrina. People with disabilities stated their inability to access transportation systems to be a personal hardship, which further impacted the well-being and recovery of these individuals. For this research study, households with mobility issues were more exposed to transportation disruption during Hurricane Harvey, which resulted in significantly higher hardship.

The findings stress the importance of further investment in transportation services with high levels of disruption disproportionately impacting socially vulnerable communities. Harris County is highly aware of the tremendous flooding issues in the transportation system following major events, and as such, has already made strides to mitigate this impact. However, the findings of the research highlight the disproportionate impact of transportation disruption on socially vulnerable households. Therefore, the equity standards must be considered by identifying those vulnerable populations and including their needs into the planning and resource allocation of the mitigation practices.

Lower Zone of Tolerance for the Power Disruption

As shown in the power service section from Fig. 8, residents of lower income levels, lower education levels, racial minority groups, children younger than 10 years, and mobile homes/apartments reported significantly higher hardship due to a significantly lower zone of tolerance but not a difference in exposure. This indicates that exposure disparity alone cannot explain disaster impact and that the ability to tolerate service loss must also be considered. For example, households with power generators would have a sense of stability throughout the duration of the power disruption since their needs and expectations related to power service were to a certain degree being met. This could have allowed the household to withstand a disruption in a more secure environment and/or for a longer period of time, resulting in the higher zone of tolerance and lower experienced hardship. Similarly, Baker (2011) concluded that households designated as low-income, noncollege graduate, racial minority, and/or mobile homes/multiunits had lower preparedness scores for recent hurricanes. These subpopulations were unable to adjust to a service disruption because they did not have the proper resources.

The identified vulnerable populations are less likely to take protective actions for the power outages. Protective actions for withstanding the prolonged power outages, such as buying a generator, can be expensive, and the limited resources that these households have would prevent them from obtaining such necessary supplies. In addition, in order for the household to take protective actions, they should also be aware of the potential threat and available options for conducting protective actions. Groups such as minorities might have some barriers in receiving proper risk communication.

Coupling Effects for Communication and Water Disruptions

From communication and water services in Fig. 8, households with lower income levels, lower education levels, and racial minority groups were disproportionately impacted because of significantly greater exposure and a lower zone of tolerance. In addition, households with young children experienced a coupling effect for communication disruption, while renters and mobile home/apartment dwellers had a coupling effect for water disruption. In the literature review, it was discussed that the physical location of these households was an important indicator for the intensity of the exposure, and the findings support the limited literature. For instance, when investigating the impact of Superstorm Sandy, Faber (2015) found that households living below the poverty line were in more flooded tracts than dry tracts, at statistically significant levels. Furthermore, Peacock et al. (2014) consistently found that low-income, multiunit, and rented households lost more of their initial property values, indicating greater net damage to the residences. However, the coupling effect demonstrates that not only were the subpopulations unable to avoid service losses, but they were also less able to withstand outages. Households with low-income are often unable to afford to move out of flooding-prone areas or to purchase expensive preparations for the disaster. The results also show the increased vulnerability of households with children. Families may have a greater need to protect the overall well-being of their children, particularly the ability to call for help, which decreases their ability to withstand a communication disruption. This need is further interrupted by a longer exposure period.

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

In particular, having access to reliable communication services allows residents to stay informed in the middle of the disaster setting. It is imperative that public safety agencies establish communication systems that would enable them to withstand outages. The findings indicate that socially vulnerable populations are least able to stay involved in conversations about disaster due to a greater period of exposure and lower ability to tolerate such disruptions.

Conclusion

This study advances the understanding of social inequalities in exposure and hardship experienced due to infrastructure service disruptions in disasters. In particular, the findings provide the much-needed empirical information necessary to uncover the extent to which subpopulations in a community experience varying levels of the disaster impact due to infrastructure system disruptions. Hence, the study contributes to establishing the fundamental knowledge needed for a paradigm shift toward a more equitable resilience approach in infrastructure systems. The results of this study have concluded that certain socially vulnerable subpopulations are disproportionately impacted by infrastructure service disruptions, and thus, have demonstrated the importance of integrating both physical and social vulnerabilities into a resilience model.

As well, our findings indicated that certain socially vulnerable subpopulations have unique needs and expectations from each infrastructure service, all of which must be factored into an equitable resilience model. Specifically, social groups with low socioeconomic status, racial minority groups, and/or children younger than 10 years old reported significantly higher hardship from the four service disruptions (transportation, power, communication, and water). These social groups were most prone to the coupling effect, which refers to significantly greater exposure and significantly lower zone of tolerance. For example, lower-income households are generally unable to afford adjustments such as power generators

Nat. Hazards Rev., 2020, 21(4): 04020034

and water tanks to lessen the impact of infrastructure service disruptions. Also, racial minority groups reported significantly lower zone tolerance to the four infrastructure services and greater exposure to transportation, communication, and water services, which indicates that racial minority groups are less able to withstand or avoid a service disruption. Additionally, households with children younger than 10 years old may experience greater hardship because of the inherent social vulnerability of children, and therefore may have a greater need to be able to access water and call for help. Households with mobility issues also reported significantly greater exposure to disruption of the four services, meaning that these households were residing in areas with more service disruptions. Further research is needed to understand the exact connection between mobility issues and exposure disparity. Surprisingly, households with residents 65 years or older experienced lower hardship; however, this could be attributed to more years of experience and familiarity with the services, both of which could override the vulnerability associated with the elderly. Finally, nondetached households including mobile homes and apartments reported a lower zone of tolerance. Although this research examined the disparities among the detached and nondetached housing types, future studies could further investigate the disparities faced by residents of different types of housing types such as mobile homes, apartments, and high-rise buildings.

The application of the equitable infrastructure resilience model can enhance infrastructure investment prioritizations based on considering the societal needs and expectations of infrastructure systems. The disparities in subpopulation exposure to service disruptions indicate a need for structural investments in more vulnerable areas. Meanwhile, a lower zone of tolerance indicates the need for the capability to withstand infrastructure service disruptions, that is, one that enhances adjustments, increases preparation support, and rapidly restores services for vulnerable households. In the case of Harris County in the aftermath of Hurricane Harvey, significantly higher hardship was associated with greater exposure from transportation disruption, the lower zone of tolerance to power disruption, and a coupling effect for communication and water services. Because of the significantly greater exposure to service disruption, investment should be allocated to the structural components of transportation systems in which vulnerable populations reside. In contrast, there was no difference in exposure to power outages; however, areas with low income and racial minority populations would benefit from prioritization in service restorations during and after future disasters. For communication and water services, both structural investments and prioritization in service restoration would decrease risk disparity among the subpopulations.

The findings of this research indicate the need for a more equitable resilience approach to infrastructure systems. The practical contributions of this study are to apply the integration of physical and social vulnerabilities to guide the allocation of limited resources in the disaster setting and to prioritize the restoration and investment of infrastructure systems. The findings can assist influential stakeholders such as policymakers, emergency management planners, community leaders, and engineers in creating more sustainable and disaster-resilient infrastructure systems, which are catered to the specific needs of the representative community. Policymakers, for instance, should be aware of the social disparities in a community and how this relates to the disaster experience. As such, they should support plans that address issues related to disparities in risk. Additionally, engineers should also be aware of the consequences of their infrastructure designs and implement equity consideration for the maintenance, restoration, and future of these infrastructure systems. By being proactive in designing and delivering sustainable systems, instead of being just a direct problem solver, engineers can ensure that residents with different sociodemographic characteristics and from different locations have equitable access to infrastructure services.

Future research should investigate the spatial distribution of the societal impacts of such losses so as to provide a better understanding of the community level risk disparities of infrastructure service disruptions. In addition, future studies should also examine the underlying factors associated with the zone of tolerance, such as preparedness, previous experience, and adjustment factors to better understand and enhance individual household's ability to deal with service disruptions.

Data Availability Statement

Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions. The household survey data used in this research received Institutional Review Board (IRB) for the human subject. As a part of the IRB data protection requirement, only the research team have access to the data, and the data cannot be shared with others.

Acknowledgments

The authors would like to acknowledge the funding support from the National Science Foundation under Grant No. 1846069 and National Academies' Gulf Research Program Early-Career Research Fellowship. Any opinions, findings, conclusions, or recommendations expressed in this research are those of the authors and do not necessarily reflect the view of the funding agencies.

References

Aptekar, L., and J. Boore. 1990. "The emotional effects of disaster on children: A review of literature." *Int. J. Mental Health* 19 (2): 77–90. https://doi.org/10.1080/00207411.1990.11449164.

ATC (Applied Technology Council). 2016. *Critical assessment of lifeline system performance: Understanding societal needs in disaster recovery*. Redwood City, CA: ATC.

Baker, E. J. 2011. "Household preparedness for the aftermath of Hurricanes in Florida." *Appl. Geogr.* 31 (1): 46–52. https://doi.org/10.1016/j.apgeog.2010.05.002.

Berkeley, A. R., III, and M. Wallace. 2010. *A framework for establishing critical infrastructure resilience goals: Final report and recommendations by the council*. Washington, DC: National Infrastructure Advisory Council.

Blake, E. S., and D. A. Zelinsky. 2018. *National Hurricane Center tropical cyclone report: Hurricane Harvey*. Washington, DC: National Oceanic and Atmospheric Administration; National Weather Service.

Burton, C. G. 2010. "Social vulnerability and hurricane impact modeling." *Nat. Hazards Rev.* 11 (2): 58–68. https://doi.org/10.1061/(ASCE)1527-6988(2010)11:2(58).

CBS/AP (CBS News/Associated Press). 2017. "Hurricane Harvey: Texas power outages affect more than quarter million." Accessed September 1, 2018. www.cbsnews.com/news/hurricane-harvey-texas-power-outages-affect-more-than-255000.

Chakraborty, J., T. W. Collins, M. C. Montgomery, and S. E. Grineski. 2014. "Social and spatial inequities in exposure to flood risk in Miami, Florida." *Nat. Hazards Rev.* 15 (3): 04014006. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000140.

Chang, S. 2016. "Socioeconomic impacts of infrastructure disruptions." In *Oxford research encyclopedia of natural hazard science*. Oxford, UK: Oxford University Press.

Chang, S. E., and N. Nojima. 2001. "Measuring post-disaster transportation system performance: The 1995 Kobe earthquake in comparative perspective." *Transp. Res. Part A: Policy Pract.* 35 (6): 475–494. https://doi.org/10.1016/S0965-8564(00)00003-3.

Clark, S. S., T. P. Seager, and M. V. Chester. 2018. "A capabilities approach to the prioritization of critical infrastructure." *Environ. Syst. Decis.* 38: 339–352. https://doi.org/10.1007/s10669-018-9691-8.

Davis, S. 2018. *Hurricane Harvey: Impact of Harvey on Houston MUDs*. Austin, TX: Meyers Research and Municipal Information Services.

Doorn, N., P. Gardoni, and C. Murphy. 2018. "A multidisciplinary definition and evaluation of resilience: The role of social justice in defining resilience." *Sustainable Resilient Infrastruct*. 4 (3): 112–123. https://doi.org/10.1080/23789689.2018.1428162.

Esmalian, A., S. Dong, N. Coleman, and A. Mostafavi. Forthcoming. "Determinants of risk disparity due to infrastructure service losses in disasters: A household service gap model." *Risk Anal.*

Faber, J. W. 2015. "Superstorm Sandy and the demographics of flood risk in New York City." *Hum. Ecol.* 43 (3): 363–378. https://doi.org/10.1007/s10745-015-9757-x.

Flanagan, B. E., E. W. Gregory, E. J. Hallisey, J. L. Heitgerd, and B. Lewis. 2011. "A social vulnerability index for disaster management." *J. Homeland Secur. Emergency Manage.* 8 (1): Article 3. https://doi.org/10.2202/1547-7355.1792.

Fothergill, A., J. A. DeRouen Darlington, and E. G. M. Maestas. 1999. "Race, ethnicity and disasters in the United States: A review of the literature." *Disasters* 23 (2): 156–173. https://doi.org/10.1111/1467-7717.00111.

Fothergill, A., and L. A. Peek. 2004. "Poverty and disasters in the United States: A review of recent sociological findings." *Nat. Hazards* 32 (1): 89–110. https://doi.org/10.1023/B:NHAZ.0000026792.76181.d9.

Gomez, C., and J. W. Baker. 2019. "An optimization-based decision support framework for coupled pre- and post-earthquake infrastructure risk management." *Struct. Saf.* 77 (Mar): 1–9. https://doi.org/10.1016/j.strusafe.2018.10.002.

Highfield, W. E., W. G. Peacock, and S. Van Zandt. 2014. "Mitigation planning: Why hazard exposure, structural vulnerability, and social vulnerability matter." *J. Plann. Educ. Res.* 34 (3): 287–300. https://doi.org/10.1177/0739456X14531828.

Horney, J. 2008. "Factors associated with hurricane preparedness: Results of a pre-hurricane assessment." *J. Disaster Res.* 3 (2): 143–149. https://doi.org/10.20965/jdr.2008.p0143.

Lindell, M. K., and S. N. Hwang. 2008. "Households' perceived personal risk and responses in a multihazard environment." *Risk Anal.* 28 (2): 539–556. https://doi.org/10.1111/j.1539-6924.2008.01032.x.

Lindell, M. K., and C. S. Prater. 2003. "Assessing community impacts of natural disasters." *Nat. Hazards Rev.* 4 (4): 176–185. https://doi.org/10.1061/(ASCE)1527-6988(2003)4:4(176).

Marsh, B., A. M. Parnell, and A. M. Joyner. 2010. "Institutionalization of racial inequality in local political geographies." *Urban Geogr.* 31 (5): 691–709. https://doi.org/10.2747/0272-3638.31.5.691.

Masozera, M., M. Bailey, and C. Kerchner. 2007. "Distribution of impacts of natural disasters across income groups: A case study of New Orleans." *Ecol. Econ.* 63 (2–3): 299–306. https://doi.org/10.1016/j.ecolecon.2006.06.013.

McDaniels, T., S. Chang, K. Peterson, J. Mikawoz, and D. Reed. 2007. "Empirical framework for characterizing infrastructure failure interdependencies." *J. Infrastruct. Syst.* 13 (3): 175–184. https://doi.org/10.1061/(ASCE)1076-0342(2007)13:3(175).

Mostafavi, A. 2018. "A system-of-systems framework for exploratory analysis of climate change impacts on civil infrastructure resilience." *Sustainable Resilient Infrastruct.* 3 (4): 175–192. https://doi.org/10.1080/23789689.2017.1416845.

Mostafavi, A., N. E. Ganapati, H. Nazarnia, N. Pradhananga, and R. Khanal. 2018. "Adaptive capacity under chronic stressors: Assessment of water infrastructure resilience in 2015 Nepalese Earthquake using a system approach." *Nat. Hazards Rev.* 19 (1). https://doi.org/10.1061/(ASCE)NH.1527-6996.0000263.

Murphy, C., and P. Gardoni. 2006. "The role of society in engineering risk analysis: A capabilities-based approach." *Risk Anal.* 26 (4): 1073–1083. https://doi.org/10.1111/j.1539-6924.2006.00801.x.

National Research Council. 2012. *Disaster resilience: A national imperative*. Washington, DC: The National Academies Press.

Ott, L., and M. Longnecker. 2010. *An introduction to statistical methods and data analysis*. Pacific Grove, CA: Duxbury.

Paton, D., J. McClure, and P. T. Büergelt. 2006. "Natural hazard resilience: The role of individual and household preparedness." In *Disaster resilience: An integrated approach*, 105–127. Springfield, IL: Charles C Thomas Publisher.

Peacock, W. G., S. Van Zandt, Y. Zhang, and W. E. Highfield. 2014. "Inequities in long-term housing recovery after disasters." *J. Am. Plann. Assoc.* 80 (4): 356–371. https://doi.org/10.1080/01944363.2014.980440.

Rasoulkhani, K., and A. Mostafavi. 2018. "Resilience as an emergent property of human-infrastructure dynamics: A multi-agent simulation model for characterizing regime shifts and tipping point behaviors in infrastructure systems." *PLoS One* 13 (11): e0207674. https://doi.org/10.1371/journal.pone.0207674.

Rufat, S., E. Tate, C. G. Burton, and A. S. Maroof. 2015. "Social vulnerability to floods: Review of case studies and implications for measurement." *Int. J. Disaster Risk Reduct.* 14 (Dec): 470–486. https://doi.org/10.1016/j.ijdrr.2015.09.013.

Stough, L. M., A. N. Sharp, A. J. Resch, C. Decker, and N. Wilker. 2015. "Barriers to the long-term recovery of individuals with disabilities following a disaster." *Disasters* 40 (3): 387–410. https://doi.org/10.1111/disa.12161.

Sutley, E. J., J. W. van de Lindt, and L. Peek. 2017. "Community-level framework for seismic resilience. II: Multiobjective optimization and illustrative examples." *Nat. Hazards Rev.* 18 (3): 04016015. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000230.

Trump, B. D., K. Poinsatte-Jones, M. Elran, C. Allen, B. Srdjevic, M. Merad, D. M. Vasovic, and J. M. P. Palma-Olivera. 2017. "Social resilience and critical infrastructure systems." In *Resilience and risk*, 289–299. Dordrecht, Netherlands: Springer.

UNISDR (United Nations Office for Disaster Risk Reduction). 2009. *2009 UNISDR terminology on disaster risk reduction*. Geneva: UNISDR.

Westbrook Lauten, A., and K. Lietz. 2008. "A look at the standards gap: Comparing child protection responses in the aftermath of Hurricane Katrina and the Indian Ocean tsunami." *Children Youth Environ.* 18 (1): 158–201.

Yoon, D. K. 2012. "Assessment of social vulnerability to natural disasters: A comparative study." *Nat. Hazards* 63 (2): 823–843. https://doi.org/10.1007/s11069-012-0189-2.