Well-Being and Infrastructure Disruptions during Disasters: An Empirical Analysis of Household Impact Disparities during Hurricane Harvey

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ABSTRACT

There are limited studies that empirically evaluate the interactions between households and infrastructure systems. As a result, the extent to which interruptions in infrastructure services influence different aspects of well-being for different subpopulations is still only vaguely understood. In order to address this knowledge gap, this study investigates multiple dimensions of well-being to derive an empirical relationship between sociodemographic factors of households and their subjective well-being impacts due to disruptions in various infrastructure services during and immediately after Hurricane Harvey. Statistical analysis driven by spearman-rank order correlations and fisher-z tests indicated significant disparities in well-being due to service disruptions among vulnerable population groups. The characterization of well-being is used to explain why and to what extent infrastructure service disruptions influence different subpopulations. The results show that disruptions in particular infrastructure systems are more likely to result in well-being impact disparities, in which racial minorities experience the greatest impact. Similarly, interruptions in services were more likely to evoke changes in social well-being and household's connectivity to their communities. These findings present novel insights to understanding the role of infrastructure resilience in household well-being, as well as inequalities in well-being impacts across various subpopulations. The approach of the research and its findings enable a paradigm shift towards a more human-centric approach to infrastructure resilience.

INTRODUCTION

As our infrastructure systems become "smarter" with the ability to capture more data and make decisions, resilience plans may become less in touch with the individuals and households for whom the resilience strategies exist (Falco, 2015). Infrastructure and technology-centric approaches fail to provide visibility into emergencies caused by infrastructure disruptions in disasters (Falco, 2015). Likewise, they are unable to capture the nuances of households in a community made up of diverse households and individuals (Falco, 2015). In particular, infrastructure resilience models assume communities of households to be monolithic and are unable to capture the diversity of household characteristics that influence their resilience in the face of disaster. Understanding such disparities is key to reducing impacts on the most vulnerable members of society.

From a perspective of resiliency, more focus needs to be directed towards how infrastructure systems make residents feel (*safety),* and whether or not there is an equitable provision of services to the community (*inclusive).* Having this focus is particularly important in times of disasters in which service disruptions negatively affect human well-being. However, empirical information is lacking regarding the extent to which disruptions in various infrastructure (e.g.,

transportation, power, water, and communication) would affect different aspects of human well-being (such as safety, mental and physical health) for different sub-populations. The purpose of this paper, therefore, is to use a human-centered approach to empirically analyze the relationships between households and infrastructure service disruptions and examine disparities in well-being impacts across subpopulations in the context of Hurricane Harvey.

RESEARCH SCOPE

A set of human-centric variables (i.e., *measures of well-being*) are drawn upon to derive an empirical relationship between sociodemographic factors of households and their subjective experience with disruptions in critical infrastructure services during and immediately after Hurricane Harvey. Overall, the research aims to characterize household-level disparities in impacts due to service disruptions. Accordingly, the characterization of well-being is used to explain why and to what extent infrastructure service disruptions influence different subpopulations. This research presents a novel attempt to understanding the role of infrastructure resilience in household well-being, as well as the inequalities in well-being impacts across various sub-populations. More specifically, the analysis is guided by the following research questions. (1) Do infrastructure-disruptions influence well-being impacts? If so, what services have the most impacts and on which well-being dimension? (2) Are there disparities among vulnerable populations in terms of well-being impacts caused by infrastructure service disruptions? If so, what sub-populations do experience disproportionate well-being impacts for different service disruptions?

To address these questions, a new framework for a human-centric infrastructure service model is introduced. Secondly, an approach to determining population disparities in well-being impact is discussed and demonstrated using empirical data collected from a household survey and analyzed using correlation analysis. The remainder of this section discusses the knowledge gaps to highlight the point of departure and significance of this study further.

BACKGROUND

The role of infrastructure systems in community resilience and the importance of understanding and reducing disruption impacts has been established by interdisciplinary fields (NEHRP, 2008; NRC, 2012; NIST, 2016). Measuring the impact of infrastructure services on human well-being and the extent of risk and uncertainty involved in the operations of infrastructure systems is imperative for creating both resilient infrastructure and communities (NIST 2016). More particularly, the need to know how to integrate the needs of diverse populations in planning and prioritization of resilient infrastructure. This knowledge will help to improve social inequities, and as a result, foster more resilient communities. It then becomes clear that there is a need for human-centric approaches to infrastructure resilience planning and modeling. Until now, socioeconomic measures that are typically used in studies rely on GDP, mortality rates, and patient data, which are not sufficient in capturing the differential well-being of shelter-in-place households before and during disasters. Disaster research has been able to at a high level, identify that minority groups are more prone to the impacts of disasters. However, the research does not explicitly relate these outcomes to the infrastructure systems that enable them nor specify the influence of infrastructure disruptions on the well-being of these vulnerable groups. Very few, if any, infrastructure resilience or disaster recovery models exist that represent variables of community well-being or public health (Miles, 2018; Mostafavi and Ganapati 2019). This limitation is mainly due to the lack of empirical information that specifies the relationship

between infrastructure disruptions and various elements of human well-being for different sub-populations.

CONCEPTUAL FRAMEWORK

The conceptual framework summarizes and relates households and infrastructure systems using three constructs: well-being, sociodemographic characteristics, and the services provided by the infrastructure. In this framework, household well-being (in relation with infrastructure) is determined based on two elements: (1) the extent of service disruptions (days of exposure to service outages, and (2) the extent of hardship experience due to service disruptions. The extent of hardship is used as an indicator for examining the nature of experience related to a service disruption. A household's hardship experience is influenced by various factors such the socio-economic characteristics, preparedness, and access to resources. In this study, only socio-demographic characteristics are considered since the goal of the analysis is to examine the presence and extent of disparities in well-being impacts among various sub-populations. The connection between well-being and infrastructure disruptions is supported by the capability approach framework (Sen, 1985), where well-being is defined as the ability of an individual to achieve valuable *functioning's* (Sen,1985). According to Sen's capability approach, the provision of resources enables people to develop capabilities that help them achieve 'functioning's,' or in other words, an enhanced state of well-being (Sangha et al., 2015). We use this idea to bridge the measures of hardship experience due to infrastructure disruption and well-being. In this context, the infrastructure system aims to provide households with services that enable them to develop or do specific tasks (jobs, school), with the underlying goal to maintain or improve well-being. This approach is suitable for expressing non-tangible damage caused by natural hazards and disasters, such as the subjective experiences of individuals and households**.**

Well-Being as a Measure for Minimizing Social Inequality in Disaster Risks

In the context of infrastructure resilience and disaster, measuring well-being in and of itself can draw more attention to the needs of different sub-populations within a city and towards potential action-oriented solutions (Seligman, 2011). In fact, integrating measures of well-being in infrastructure resilience assessments can shift the focus from "systems" to "people." Nevertheless, the current resilience planning and risk reduction processes in infrastructure systems have not yet adopted measures of well-being to inform investment, resource allocation, and prioritization decisions and policies.

Infrastructure Hardship Experience

In socioeconomic research, economic hardship has been shown to thwart well-being in households and individuals (Diener et. al, 2017). Based on this assumption supported by theoretical research, it is proposed that hardship experience due to infrastructure disruptions also impacts household well-being. Hence, in this study, hardship is used as a proxy variable for determining the relationship between well-being and infrastructure service disruptions. Disparities among sociodemographic groups are often studied in public health and epidemiological research in the context of health equity and are defined as occurring when a population group has a disproportionate share of health burden (CDC, 2013). The *infrastructure resilience and well-being disparity model* applies the same concept and definition of disparity: when one subgroup population has disproportionate experience in well-being impact as a result

of the exposure and experience with infrastructure service disruptions. The higher impact from infrastructure disruption experience indicates a more significantly negative well-being impact.

Table 1. Select Well-Being Measures and Their Dimension

Well-being Measure	Dimension
Helplessness	*Social*
Anxiousness	*Emotional*
Upsetting thoughts	*Emotional*
Safety	*Social*
Depression	*Emotional*
Daily life tasks	*Social*
Feeling Distant	*Social*

Days of Exposure

In Esmalian et al. (2019), the authors found no significant disparity in days of exposure to hardship experience across various subgroups for electricity services in Hurricane Harvey. This finding indicates that exposure to service disruptions was not significant for different socio-demographic groups. For that reason, we do not link days of exposure to sociodemographic factors. Furthermore, the study found a positive correlation between days of exposure to hardship experience.

Household Factors Influencing Disparity

The household influencing factors only focus on sociodemographic groups so that the role of sociodemographic well-being experience can be analyzed. Sociodemographic characteristics are hypothesized to influence the extent of hardship experienced, which is also determined by the days of exposure. We hypothesize that the sensitivity of hardship experience (and the subsequent well-being impacts) to the duration of service disruption varies for different sub-populations and various infrastructure services. In disaster events, infrastructure disruptions frequently cause or exacerbate many types of socioeconomic impacts, including health, social, economic, and environmental consequences (Cheng, 2016). Vulnerable populations referred to in this framework have been derived from the Social Vulnerability Index (SVI) and include households who are racial or ethnic minorities, children, elderly, socioeconomically disadvantaged, underinsured or those with certain medical conditions. While sociodemographic factors influence the extent of hardship, and ultimately the well-being experienced, life events (i.e., disasters and changes to critical infrastructure services) have the potential to be detrimental to health and well-being (Cleland et al., 2016).

METHODOLOGY

Survey Design

This study is centered around the critical infrastructure outages affecting Harris County residents during Hurricane Harvey. The proposed well-being framework is used to identify areas of risk disparity due to infrastructure service disruptions within a population. We utilize empirical data from Hurricane Harvey to test the framework in answering the proposed research questions in the context of critical infrastructure system disruptions due to disaster. The survey

design, data measures, and analytical approach are described. This study is centered around the empirical data on household exposures to infrastructure gaps, hardship experiences due to infrastructure service disruptions, and changes to household well-being as a result of Hurricane Harvey, which made landfall in Houston, Texas in late August 2018. A total of 1081 samples across 140 of 145 total zip codes in Harris County were collected through Qualtrics using stratified sampling from a census represented panel. Incomplete responses and those that had evacuated their households before Hurricane Harvey landed were eliminated from the analysis, resulting in 837 household samples. The rationale for this selection is that for evacuated households, 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).

Data and Measures

Subjective indicators of household well-being are derived from seven survey questions that focus on the mental and social levels of households within one month after the experience of Hurricane event (Table 2). They are self-reported, measured in a five-point Likert-scale ranging from None at all (=1) to A great deal (=5). The well-being components have been categorized by their respective domain (OECD, 2013) for more straightforward interpretability of their meaning and role in the overall well-being of a household. Measures for well-being were determined from a literature review on post-disaster physical and mental well-being impact surveys (WHO, 2003; Weathers, et al., 1991).

Table 2: Survey Questions Measuring Well-Being Impact of Households 1-Month Post-Harvey

Well-being measure	Survey Question
Q1: *Helplessness*	How often did you find yourself or a household member helpless?
Q2: *Anxiousness*	How often did you or a household member feel anxious, worried or nervous?
Q3: *Upsetting thoughts*	How often did you or a household member have upsetting thoughts and feelings related to the storm or the damage it caused?
Q4: *Safety*	How much did your household experience with Hurricane Harvey make you or members of your household feel less safe and protected in your daily life?
Q5: *Depression*	How much did your household experience with Hurricane Harvey make you or members of your household feel depressed or restless?
Q6: *Daily life tasks*	How much did your household experience with Hurricane Harvey lower your ability to do your daily life tasks such as working or dealing with others?
Q7: *Feeling distant*	How much did your household experience with Hurricane Harvey make you or members of your household feel distant or cut off from other people?

Self-reported hardship due to disruptions in infrastructure services was measured in a five-point Likert-scale ranging from None at all (=1) to A great deal (=5) for the following question: Households were asked: "What was the extent of overall hardship experienced due to [infrastructure] outages/interruptions posed by Hurricane Harvey?" Self-reported hardship is used as a proxy for examining the experience of households due to service disruptions. Greater exposure to hardship experiences would lead to more significant well-being impacts. Hence, the combined effects of the extent of hardship experience and the duration of exposure are used to examine well-being impacts on households.

For this analysis and to maintain consistency with the elements of social vulnerability index (SVI), households have been classified into subgroups according to the reported age groups in the household, ethnic identity, health status, and income level. The survey did not differentiate between white Hispanic and non-white Hispanics. Additionally, the '*Other*' racial category represents households that identified as mixed-race or ethnicity in addition to Pacific Islanders and Native Americans. Pacific Islanders and Native American households were grouped into the *Other* category because of the low population samples. Most statistical analyses require sample sizes to be greater than or equal to 10. The income group levels were divided into three brackets (low, middle, high), according to recent census data on median household income in Texas (US Census Bureau, 2018). Sub-categories were combined, as shown in Table 3.

Table 3. Measurement of The Influencing Sociodemographic Factors of Household Well-Being Disparities

Subgroup domain	Subgroups
Age	*Under ten years, between 11-17, Over 65;* *Reference group = between 18-64 years*
Income	*Low (<$25K - $50K), Middle ($55K-$100K),* *High($100K+); Reference group = High ($100K+)*
Racial/Ethnic Identity	*Minorities (=1), Black, Hispanic/Latino, Asian, Other;* *Reference group = White (=0)*
Health: Chronic	*Yes (=1) or No (=0);* *Reference group = no health condition reported*
Health: Disability	*Yes (=1) or No (=0);* *Reference group = no health condition reported*

Statistical Analysis

Statistical analysis using R programming was performed on the filtered dataset to determine well-being risk disparity, with the level of significance set at $p < 0.05$. Spearman rank-order correlation analyses were performed between each well-being dimension and each critical infrastructure service disruption experience across 15 different sociodemographic subgroups. Disparities among the identified household influencing factors, as presented in Table 1, were determined by comparing the *rho* values of the subgroups and their respective reference groups using Fisher z-tests. Given that the p-value is less than 0.05, results from the Fisher z-tests would signify the presence of well-being impact disparity associated with the household's sociodemographic characteristic(s). Tests for significance were conducted using the R *cocor package* (Diedenhofen & Musch, 2015). Based on the recommendations of literature (Hinkle, 2003), coefficient values below 0.35 were classified as weak. Correlation coefficients above .35 were considered to have moderate to high correlation. Trends are identified to characterize

services by well-being dimension, and also to identify which subgroup was associated most with which well-being component due to associations with which infrastructure service. A disparity is determined when there is a significant difference between the coefficient of the vulnerable group and the reference population, and the coefficient is greater than or equal to 0.35 an p<0.05, indicating a moderate (either positive or negative) association between well-being impact and infrastructure service disruption

Table 4. Subgroup Populations Experiencing Disparity by Well-Being Dimension and Infrastructure Service

Subgroup	Well-being Dimension	Infrastructure Service	Rho	Reference Group Rho	Fisher z-score
Black/African American	Upset	Transportation	0.502***	0.323***	2.28
	Helplessness	Solid Waste	0.451***	0.293***	1.93*
	Depression	Food	0.513***	0.224***	3.56*
	Anxiety	Food	0.425***	0.248***	2.12*
	Upset	Food	0.420***	0.212***	2.45*
	Safety	Food	0.470***	0.232***	2.86*
	Helplessness	Food	0.502***	0.236***	3.27*
	Daily tasks	Solid Waste	0.420***	0.241***	2.07*
	Daily tasks	Food	0.500***	0.224***	3.38*
	Distance	Food	0.460***	0.285***	2.09*
Asian	Anxiety	Food	- 0.352*	0.285***	3.23*
	Safety	Water	- 0.243	0.319***	3.18*
Other	Safety	Solid Waste	0.645***	0.351***	2.57*
	Anxiety	Solid waste	0.597***	0.319***	2.31*
	Daily Tasks	Solid Waste	0.612***	0.241***	3.00*
	Upset	Solid	0.528***	0.312***	1.70*
	Depression	Solid	0.579***	0.308***	2.20*
	Distance	Solid	0.573***	0.338***	1.93*
	Helplessness	Solid	0.563***	0.293***	2.16*
Low-income	Distance	Transportation	0.398***	0.243***	2.00*
	Daily tasks	Solid Waste	0.328***	0.158**	2.09*
	Distance	Solid Waste	0.369***	0.198***	2.16*
Middle Income	Daily tasks	Solid Waste	0.348***	0.158**	2.35*
	Distance	Solid Waste	0.454***	0.198***	3.32**
Children (11-17 years)	Safety	Water	0.445***	0.281**	1.87*
Chronic Health	Depression	Solid Waste	0.425***	0.270**	2.30*
Disability	Distance	Water	0.489***	0.330***	1.97*
	Distance	Food	0.462	0.285***	2.12*

*p ≤ 0.05, **p ≤ 0.01, *** p ≤ 0.001

RESULTS

This study analyzed the relationship between humans and infrastructure from three-dimensions: 1) a household's sociodemographic characteristics, 2) reported hardship due to infrastructure disruptions, 3) reported household well-being. Statistically significant disparities in well-being experience across all household subgroups were found concerning all infrastructure service disruptions apart from Electricity (this is probably because of the non-extensive power outage in Harris County during Harvey). The Spearman correlation coefficients associating well-being dimensions with infrastructure disruption experience were statistically significant for groups across all racial, age, health, and income subpopulations ($p<0.01$) apart from Asian households. This finding alone implies that the association between well-being and service disruptions is not due to an experimental-wise error. The claim that certain population groups experience higher risks in disasters and service disruptions are empirically backed by the results of this study's correlation analysis: the identified vulnerable population groups tend to have stronger correlations to well-being impact due to infrastructure disruptions compared to their reference group. However, not all of the differences were proven to be statistically significant. Table 4 presents sociodemographic groups that experienced statistically significant disparity in well-being impact due to infrastructure disruption. It includes the dimension of well-being and the infrastructure service in which disparity was prevalent, the Spearman correlation coefficient of the association for the sociodemographic group and reference group, as well as the z-score resulting from the Fisher z-score coefficient difference tests. All coefficient values represented in this table are significant at $p > 0.01$.

Based on the rho values alone, well-being dimensions measured by the *"Ability to do daily life tasks"* and *"Feeling distant or cut off"* appear to be more strongly associated with well-being impact as compared to the other dimensions considered in this study. *"Feeling depressed"* or *"feeling upset"* did not have as significant or influential associations with infrastructure disruptions. The association between well-being and infrastructure disruptions was disproportionately stronger for Black and African American households compared to both the reference group (White) and other racial groups. On the other hand, infrastructure service disruptions did not have a significant impact on the well-being of Asian households, for which most rho coefficients were below 0.20 and or negative. For example, a negative correlation between disruptions in Food services and *"feeling anxious"* was found (rho = -0.352, $p<0.01$). The association between *"difficulty doing daily tasks"* and disruptions in electricity services is the only significant positive rho coefficient found in Asian households (0.336, $p<0.01$).

CONCLUSION

This effort is among the first studies to systemically and empirically evaluate the social inequalities related to well-being risks in the context of infrastructure resilience. The results of this study provide empirical grounding and evidence of the inequitable state of risks due to infrastructure disruptions. In the context of this study area and Harris County in Harvey, disruptions in *transportation, solid waste, food, and water* infrastructure services resulted in more significant well-being impact disparities as compared to *electricity and communication services.* It is likely that the planning and preparation efforts taken by communication service companies led to limited disruption and rapid restoration that buffered the impact of disruptions on households during the storm. Furthermore, the average reported days of electricity disruptions in the sample households is 0.790 days, while the average duration of wireless and internet

service outages were 1.18 and 0.845 days, respectively. This is in contrast to the average five days of household reported duration in transportation service interruptions. This can be an example of how strategic resilience planning, as well as retrofit and mitigation investments for disaster, can improve the resiliency of infrastructure systems and minimize the impact on households during a disaster, contributing to the household and community resiliency.

Factors such as ethnicity and household income affect the amount of tolerance that a household can emotionally and mentally withhold when experiencing hardships due to service disruptions. Using the correlation analysis, this study discovered disparities in well-being experience due to disruptions in infrastructure services, primarily among racial or ethnic groups. The future studies of the authors will investigate the influence of other factors such as preparedness, previous experience, expectations, and social capital on the well-being impacts of infrastructure disruptions.

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REFERENCES

Centers for Disease Control and Prevention (2013). CDC Health Disparities and Inequalities Report. MMWR; 62:3.

Diedenhofen, B., Musch, J. (2015). cocor: A Comprehensive Solution for the Statistical Comparison of Correlations. PLOS ONE;10(4):e0121945.

Diener, E., Pressman, S.D., Hunter, J., Delgadillo-Chase, D. (2017). If, Why, and When Subjective Well-Being Influences Health, and Future Needed Research. Applied Psychology: Health and Well-Being; 9(2):133-67.

Esmalian A, Ramaswamy,M., Rasoulkhani, K. Mostafavi, A. (2019). Agent-Based Modeling Framework for Simulation of Societal Impacts of Infrastructure Service Disruptions during Disasters. Computing in Civil Engineering 2019. p. 16-23.

Falco, G.J (2015). City Resilience through Data Analytics: A Human-centric Approach. Procedia Engineering;118:1008-14.

Miles, S.B. (2015). Foundations of community disaster resilience: well-being, identity, services, and capitals. Environmental Hazards ;14(2):103-21.

Mostafavi, A. and Ganapati, N. E. (2019), Toward Convergence Disaster Research: Building Integrative Theories Using Simulation. Risk Analysis. doi:10.1111/risa.13303.

NEHRP (2008). Annual report of the National Earthquake Hazards Reduction Program. 2008 NEHRP Annual Report.

NIST (2016). Community Resilience Planning Guide for Buildings and Infrastructure Systems. Gaithersburg, MD.: National Institute of Standards and Technology;

NRC (2012). Disaster Resilience: A National Imperative. Washington, DC: The National Academies Press; 260 p.

Organization for Economic Co-operation and Development (2013). OECD Guidelines on Measuring Subjective Well-being. Paris.

Sangha,K.K., Le Brocque, A., Costanza, R., Cadet-James, Y. (2015). Application of capability

approach to assess the role of ecosystem services in the well-being of Indigenous Australians. Global Ecology and Conservation. 4:445-58.

Sen, A. K. (1985), Well-being, Agency and Freedom: the Dewey Lectures, Journal of Philosophy, 82(4), 169ñ221.

Weathers, F.W., Litz, B.T., Herman, D.S., Huska, J.A., Keane, T.M (1991). The PTSD Checklist—Civilian Version (PCL-C) Available from F.W. Weathers National Center for PTSD, Boston Veterans Affairs Medical Center 150 S. Huntington Avenue; Boston, MA 02130.