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Examining spatial and socioeconomic disparities in internet resilience during extreme weather events: a case study of Hurricane Harvey and Winter Storm Uri

Yuvraj Gupta[1], Zhewei Liu[2*] and Ali Mostafavi[2]

Abstract

The resilience of internet service is crucial for ensuring consistent communication, situational awareness, facilitating emergency response in our digitally-dependent society. However, due to empirical data constraints, there has been limited research on internet service disruptions during extreme weather events. To bridge this gap, this study utilizes observational datasets on internet performance to quantitatively assess the extent of internet disruption during two recent extreme weather events. Taking Harris County in the United States as the study region, we jointly analyzed the hazard severity and the associated internet disruptions in the context of two extreme weather events. The results show that the hazard events significantly impacted regional internet connectivity. There exists a pronounced temporal synchronicity between the magnitude of disruption and hazard severity: as the severity of hazards intensifies, internet disruptions correspondingly escalate, and eventually return to baseline levels post-event. The spatial analyses show that internet service disruptions can happen even in areas that are not directly impacted by hazards, demonstrating that the repercussions of hazards extend beyond the immediate area of impact. This interplay of temporal synchronization and spatial variance underscores the complex relationships between hazard severity and Internet disruption. Furthermore, the socio-demographic analysis suggests that vulnerable communities, already grappling with myriad challenges, face exacerbated service disruptions during these hazard events, emphasizing the need for prioritized disaster mitigation strategies and interventions for improving the resilience of internet services. To the best of our knowledge, this research is among the first studies to examine the Internet disruptions during hazardous events using a quantitative observational dataset. The insights obtained hold significant implications for city administrators, guiding them towards more resilient and equitable infrastructure planning.

Keywords Urban resilience, Internet service, Infrastructure equity, Digital divide

1 Introduction

Information and communication technology (ICT) and its underlying service have become vital components of modern society, supporting daily digital activities from commerce and communication to critical services and emergency management (Wang and Hess, 2021; Yan et al., 2024). The robustness of this infrastructure, however, becomes a significant concern when faced with natural hazards (Coleman et al., 2020; Esmalian et al., 2021; Yin and Mostafavi, 2023a). As indicated in multiple

*Correspondence:
Zhewei Liu
lzwgre@gmail.com
[1] Department of Civil Engineering, Indian Institute of Technology Gandhinagar, Palaj, India
[2] UrbanResilience.AI Lab, Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX 77843, USA

studies, extreme weather and hazard events can lead to cascading impacts across critical infrastructure, the repercussions of which ripple across sectors, affecting access to these critical services and altering perceptions of recovery. (FEMA, 2017; Han et al., 2009; Hasan & Foliente, 2015; Mitsova et al., 2020; Zimmerman et al., 2017).

Historically, a multitude of disasters have exposed the vulnerabilities in our critical infrastructure systems, prompting significant research into their resilience. For instance, Hurricane Irma disrupted electricity for millions across Florida, from the Keys to the Panhandle, demonstrating how such a widespread outage can significantly strain recovery efforts (Davis et al., 2019). Meanwhile, Hurricane Michael wreaked havoc in the Mexico Beach area of Florida, damaging more than 700 structures and leaving a large number of people without electricity for nearly a month. The aftermath of Hurricane Maria in Puerto Rico was particularly devastating. The hurricane severely impacted an already fragile infrastructure system, resulting in widespread loss of services. Remarkably, almost a month post-disaster, 90% of Puerto Rico's households remained without power, and many lacked water or cell phone service, precipitating a humanitarian crisis that lingered for months (Roman, 2018; Zorrilla 2017). Similar to the complexities faced in improving internet services during extreme weather events, structural equation modeling was used to examine the factors affecting the low market share of road passenger transport based (RPTB) express services, highlighting the importance of enhancing service elements like availability and flexibility to meet user demands (Yin et al., 2018). In a further related study, FloodRisk-Net, a deep learning model, was employed to intricately map urban flood risks, demonstrating the critical need to consider diverse spatial and urban factors in disaster resilience efforts (Liu, 2020; Yin et al., 2023c).

Beyond these hurricanes, other disasters also highlighted infrastructure vulnerabilities. In the 1995 Kobe earthquake, disruptions in firefighting capabilities, primarily due to a lack of pressurized water, led to the rapid spread of urban fires causing extensive human and property losses. Furthermore, disruptions to road networks can inhibit emergency responses, restricting the movement of critical emergency services, including firefighters, ambulances, and utility repair crews (Liu, 2023; Kirsch et al., 2010; Yin and Mostafavi, 2023b). Mirroring the complexity in mapping digital disparities, Zhou et al., 2022 leveraged mobile phone location data to estimate neighborhood-level obesity by analyzing diet and physical activity patterns. This approach underscores the potential of utilizing advanced data sources to enhance understanding of public health challenges and inform targeted interventions. These examples underscore the necessity of building resilient infrastructures, emphasizing the lessons learned from hazard events (Coleman et al., 2020; Fan & Mostafavi, 2019; Zhang et al., 2020).

Despite the extensive studies and insights on infrastructure resilience during disasters, a significant research gap persists regarding the understudied resilience of internet service. Previous studies have highlighted significant disparities in internet access across various communities, with socially vulnerable groups—including racial minorities, low-income families, and rural residents—facing pronounced challenges (Graves et al., 2021; Chiou & Tucker, 2020; Ho et al., 2023). These challenges are limited not only to inadequate device ownership but extend to spotty cellular coverage and the unaffordability of data plans. These disparities in digital access have exacerbated the impaired living conditions of these vulnerable communities, causing reduced work efficiency, reduced access to news and commerce, and limited access to education during the pandemic. Such challenges further intensify existing societal inequalities (Sen & Tucker, 2020; Singh et al., 2020; Liu et al., 2023; Huang et al., 2022). While there has been considerable research on internet access disparities under normal circumstances, there has been limited investigation into these disparities during times of disaster. Emphasizing the vital role of communications during disasters, studies indicate that communication systems play pivotal roles in information sharing and protective actions during disaster response and recovery (Fan et al., 2021; Yin, et al., 2012; Zhang et al., 2019). Given the intricacies of measuring disruption, especially for communication systems, there is a dearth of data-driven approaches to assessing the resilience of internet service (Mattsson and Jenelius, 2015). With the ever-increasing reliance on internet technology, there is a pressing need to delve deeper into its vulnerabilities and to establish measures that maintain its resilience during catastrophic events, ensuring continued access and functionality even in the face of adversity.

Consequently, addressing the above-mentioned research gaps, this study utilized observational data for internet performance provided by internet service provider to assess the extent of internet disruption during major weather events. Specifically, we take Harris County, in which Houston is located, as the study region and evaluate the impacts of two recent major hazard events, Hurricane Harvey (2017) and Winter Storm Uri (2021), on regional internet service. By analyzing how the internet is disrupted during these hazards, we aim to quantify the relationship between the severity of a hazard and the magnitude of internet disruption and to shed light on how different communities, especially socially vulnerable populations, are affected by these disruptions and ICT disconnectivity in the context of extreme events.

Particularly, we focus on the following research questions:

- RQ 1: To what extent is internet disruption associated with hazard intensity? Do regions that experience greater hazard severity also face more pronounced internet disruptions, leading to increased connectivity isolation?
- RQ 2: To what extent do areas with vulnerable communities have disproportional internet disruption? Will internet disruption exacerbate the precarious living conditions of vulnerable communities and hence cause new injustice?

By answering the above questions, this study investigates the effects of extreme hazards on internet connectivity and the potential emergence of social inequities that may disproportionately impact vulnerable communities. The findings of this study offer contributions across several dimensions: (1) To the best of our knowledge, this is the first study to examine internet disruptions during hazardous events using a comprehensive, quantitative observational dataset. The data provided by the internet service provider offers a distinctive view that enables us to model hazard-induced Internet disruption from a quantitative perspective, which has not been addressed by previous studies; (2) Our findings provide novel empirical evidence on the extent to which different communities (especially socially vulnerable communities) are affected by internet disruption during extreme hazard events and highlight the potential risks of emerging social injustices stemming from these disruptions; (3) The findings of study show the temporal synchronicity and spatial correlations between hazard severity and Internet disruption, which provide urban planners, city managers, and infrastructure operators with novel insights on crafting timely and effective strategies to alleviate environmental hazards and inequalities, and ultimately contribute to broader urban resilience and sustainability.

2 Dataset and methodology

2.1 Dataset

This study aims to examine the relationship between internet disruption and hazard severity during extreme weather events, as well as the effect of internet service disruptions on social disparities. This study focuses on the city of Houston, the fourth most populous city in the US, which is exposed to frequent and severe weather disturbances due to its proximity to the Gulf of Mexico. Specifically, we focus on two recent major hazard events in the regions: Winter Storm Uri and Hurricane Harvey. Winter Storm Uri hit Houston in February 2021, crippling power grids and leaving millions without electricity in freezing conditions. Hurricane Harvey, which hit in 2017, brought with it torrential rain, causing unprecedented flooding in Houston. The storm's prolonged stay and intense rainfall turned streets into rivers and inundated vast portions of the city.

To quantify the internet performance and hazard severity, the following four datasets were used for analysis, as shown in Table 1:

- *Internet Connectivity:* The dataset contains the metrics for measuring the internet access performance. Our dataset is provided by Ookla, which provides free analysis for internet performance evaluation (Ookla, 2023). The provided dataset covers information regarding cellular internet speeds, detailing metrics such as a mobile device's upload/download rates, latency, and geographically pertinent data including the locations of both the device and the server. Utilization of mobile phone data has demonstrated how advanced data collection methods can significantly enhance the understanding of urban settings (Tirabassi et al., 2024; Luo and Zhu, 2022). In this research, the upload and download speed at the client location is used as a metric for internet connection.

Table 1 Description for the used dataset

Data	Data Source	Description
Internet connectivity	Ookla	Internet upload and download speed at specific locations
Hazard severity measured by power outage	MapBox	The extent of power outage in the areas is inferred from the telemetry-based population activity
Hazard severity measured by flood extent	Federal Emergency Management Agency (FEMA)	The estimated flood extent for Hurricane Harvey
Sociodemographic	United States Census Bureau (USCB)	Statistics data for each census tract, including total population, income, minority population, etc

- *Power outage:* The magnitude of power outages during these events is extrapolated from telemetry-based population activity proffered by Mapbox. This service collects user cell phone locations from applications harnessing the Mapbox software development kit (SDK), subsequently aggregating, standardizing, and anonymizing this geographical data to estimate population activity. Numerous studies have employed Mapbox's population activity data to illuminate population dynamics during disaster events (Farahmand et al., 2022; Gao et al., 2021; Lee et al., 2022; Yuan et al., 2022). In this study, data was collected for February 2021, and the power outage used as a measurement of the hazard severity during Winter Storm Uri.
- *Flood extent:* To evaluate the spatial variation of lifestyle impacts from flooding status, we used flooding data from the estimated flood depths on August 29, 2017 (FEMA, 2018). The data had a gridded horizontal resolution of three meters, which was processed appropriately for the census block group (CBG)-scale analysis. The flood extent is used as a measurement of the hazard severity for Hurricane Harvey.
- *Sociodemographic data:* To assess the impact of internet disruption on different communities, Zip-code-level statistics data (e.g., total population, below-poverty population, minority population, etc.) is provided by the United States Census Bureau (USCB, 2023)

2.2 Methodology

2.2.1 Quantification of the degree of internet disruption and hazard severity

The quantifications of internet disruption and hazard intensity were needed to model their mutual relationships.

(1) Internet disruption

The study measures internet disruption using changes in internet speeds—both upload and download speeds. Here's how it's operationalized:

- *Baseline Calculation*: The study first establishes a baseline by calculating the average internet speed prior to the occurrence of a hazard event. This average is derived from observed internet speeds under normal conditions and serves as a reference point.
- *Disruption Measurement*: During the hazard event, internet speeds are continuously monitored. A region is considered to have experienced an internet disruption if there is a decline in internet speeds (either upload or download) that exceeds 10% compared to the pre-hazard baseline. This threshold of 10% is used to account for minor fluctuations that might not significantly impact connectivity but to identify more substantial disruptions that could affect communication and information access.

(2) Hazard Severity

Hazard severity is measured using different metrics tailored to the specific characteristics of each event, depending on the available data:

- *Hurricane Harvey*: For this event, the extent of flooding within each Zip code is used as the metric for hazard severity. The study likely uses geographic and hydrological data to assess how widespread and deep the flooding was in different areas.
- *Winter Storm Uri*: For this event, the metric used is the power-related parameter "activity density (DA)," which is detailed earlier in your document. A decline in DA by more than 10% from its pre-disaster average is taken as an indicator of significant disruption caused by the storm. This could reflect reductions in electricity supply, which are critical during a winter storm due to heating needs and potential risks of hypothermia.

All these metrics are assessed at the Zip code level.

2.2.2 Correlation modeling between internet disruption and hazard intensity

To understand the relationship between internet disruption and hazard intensity, we employed correlation analysis, with specific emphasis on the Pearson correlation coefficient (often represented by Pearson's R). This coefficient evaluates the linear association between two variables:

$$R = \frac{\sum (X_i - X)(Y_i - \bar{Y})}{\sqrt{\sum (X_i - X)^2 \sum (Y_i - \bar{Y})^2}}$$

where X_i and Y_i are the individual data points for the two datasets, $\bar{X}$ and $\bar{Y}$ are the means of the two datasets, the numerator is the sum of the products of the differences between each data point and its respective mean for both datasets. The denominator is the product of the square roots of the sums of the squared differences between each data point and its mean for dataset. The correlation coefficient R produced by this formula lies between -1 and 1; $r = 1$ indicates a perfect positive linear relationship;

r = -1 indicates a perfect negative linear relationship; r = 0 indicates no linear relationship. By applying Pearson's R to our data on internet disruption and hazard intensity, we can infer the strength and direction of their linear relationship.

3 Results

3.1 The association and synchronicity between internet disruption and hazard intensity

We evaluated the relationships between hazard intensity and internet disruption. For Winter Storm Uri, the extent of power outages served as a metric for hazard severity. For Hurricane Harvey, we utilized flood extent as the proxy for hazard severity. The time series analysis shows that hazard severity exhibits a strong correlation with the disruption of internet connectivity. As illustrated in Fig. 1, the temporal patterns between power outages and internet connection disruptions are significantly consistent. Specifically, the onset of power disruptions in Winter Storm Uri started in February 13, which coincides with the impact of the storm across the affected regions. The lowest point of these outages was observed on February 15, after which there was a gradual restoration of power. The internet connection's trajectory was similar to this, with a slight temporal shift. Internet connectivity began waning on February 14, a day after the initiation of managed power outages. This decline continued until February 16, at which point a revival started. Interestingly, this recovery in internet connectivity lagged the power restoration pattern by a day. This one-day delay between the two variables suggests a potential dependency of internet connectivity on hazard intensity or other intermediary factors that could be influenced by power availability. Even after primary issues (like power) are addressed, it may take additional time for secondary systems (like the internet) to regain full functionality.

The time series correlation analysis further quantifies the relationship between power outages and internet connectivity. Specifically, the correlation coefficients are 0.763 for download speeds and 0.774 for upload speeds. Both values are statistically significant at the 0.01 level. This underscores that as power outages became more pronounced, internet speeds, both download and upload, were adversely impacted. The high correlation values, combined with the temporal patterns observed in Fig. 1, clearly demonstrate that internet connectivity is inherently vulnerable to power disruptions, especially during events like Winter Storm Uri.

The intertwining synchronicity of power outages and internet disruptions during large-scale extreme weather events reveals the interdependencies between power and communication infrastructure and also underscores a pressing concern: at times when communities most require essential services for situational awareness and information dissemination, they face the most significant disruptions. This poses a substantial challenge to both individuals and emergency services, exacerbating an already challenging situation. The onset of power outages, starting from February 13, aligns closely with the dwindling of internet connectivity, which began a day later. This interdependency indicates that when large-scale events strike, crucial infrastructure systems like power and the internet are both vulnerable, responding

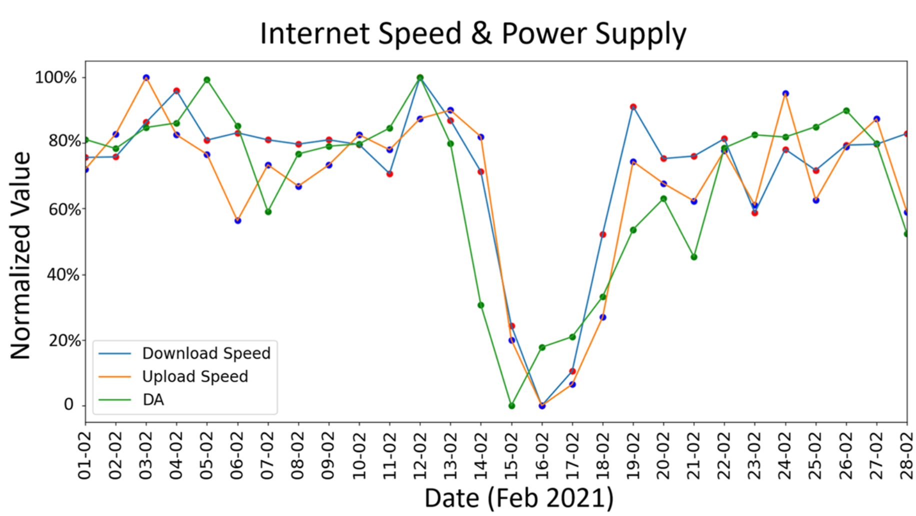

Fig. 1 Time series of average internet speed and power supply (DA) in Houston during the Winter Storm Uri series analysis. The correlation coefficient between DA and download speed is 0.763 and upload speed is 0.774 (both statistically significant at 0.01 level), demonstrating the synchronousness and interdependency between internet connectivity and power supply

in near-tandem to the external threat. This cascading effect has profound implications for situational awareness: lack of access to critical information during the most crucial times can lead to panic, misinformation, and an increased reliance on already stretched emergency services.

In addition, the slight delay observed in the restoration of internet connectivity, even after power was reinstated post-Uri, hints that restoring primary systems, such as power, does not immediately guarantee the revival of secondary systems. This lag further exacerbates the challenges faced by affected communities, prolonging their state of vulnerability and isolation.

We then looked into the spatial patterns of internet disruptions and power outages. When assessing the data between February 15 and February 18, 2021 (the timeframe impacted by Winter Storm Uri), we calculated the average degree of both power outage and internet disruption. These averages were then plotted at the ZIP code-level (Fig. 2). The visual interpretation suggests that the regions most significantly affected by internet disruptions and power outages do not exhibit considerable overlap. This observation is quantitatively reinforced by a Pearson's correlation coefficient of only 0.028, which is not statistically significant.

A similar pattern was also observed for Hurricane Harvey. When comparing the average flood extent with internet disruption at the Zip code-level (Fig. 3), distinct disparities arise. Specifically, the northeast regions of Houston experienced a more significant flood extent relative to other regions. Yet, the internet connections in these heavily flooded areas were less disrupted. The quantitative correlation analysis further supports this observation, with a Pearson's R value of 0.189, also proving to be not significant.

These spatial analyses underscore the phenomenon that regions with severe power outages or flooding may not always coincide with areas of significant internet disruption. This suggests the presence of other mitigating factors or service characteristics that safeguard internet connectivity despite surrounding hazards. For example, certain areas might be equipped with underground cabling systems that are less vulnerable to external hazards. Alternatively, some regions might have access to redundant internet service providers, ensuring that if one provider faces downtime, another can continue to offer service. Furthermore, localized service characteristics could play a pivotal role. Regions with advanced network services, such as modern data centers or state-of-the-art routing systems, might be better poised to withstand

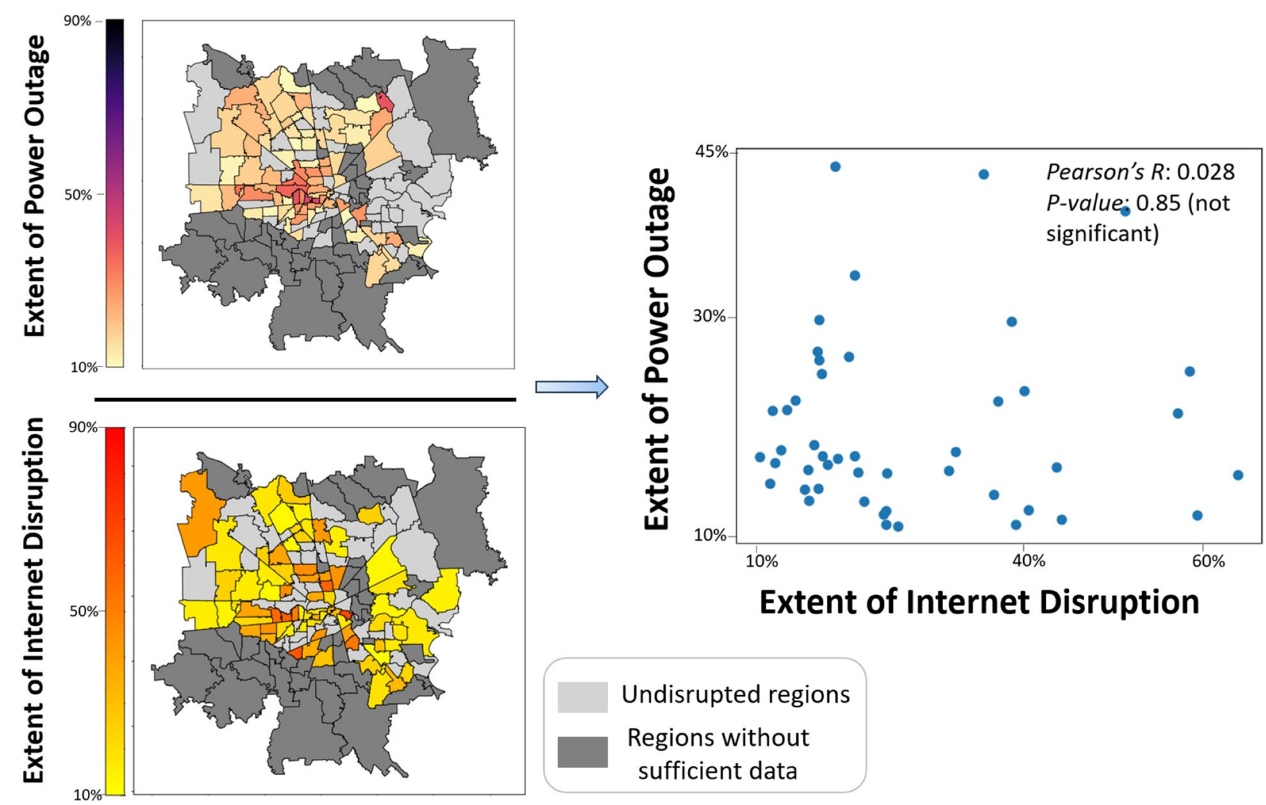

Fig. 2 Spatial comparison between regions' extent of power outage and internet disruption during Winter Storm Uri

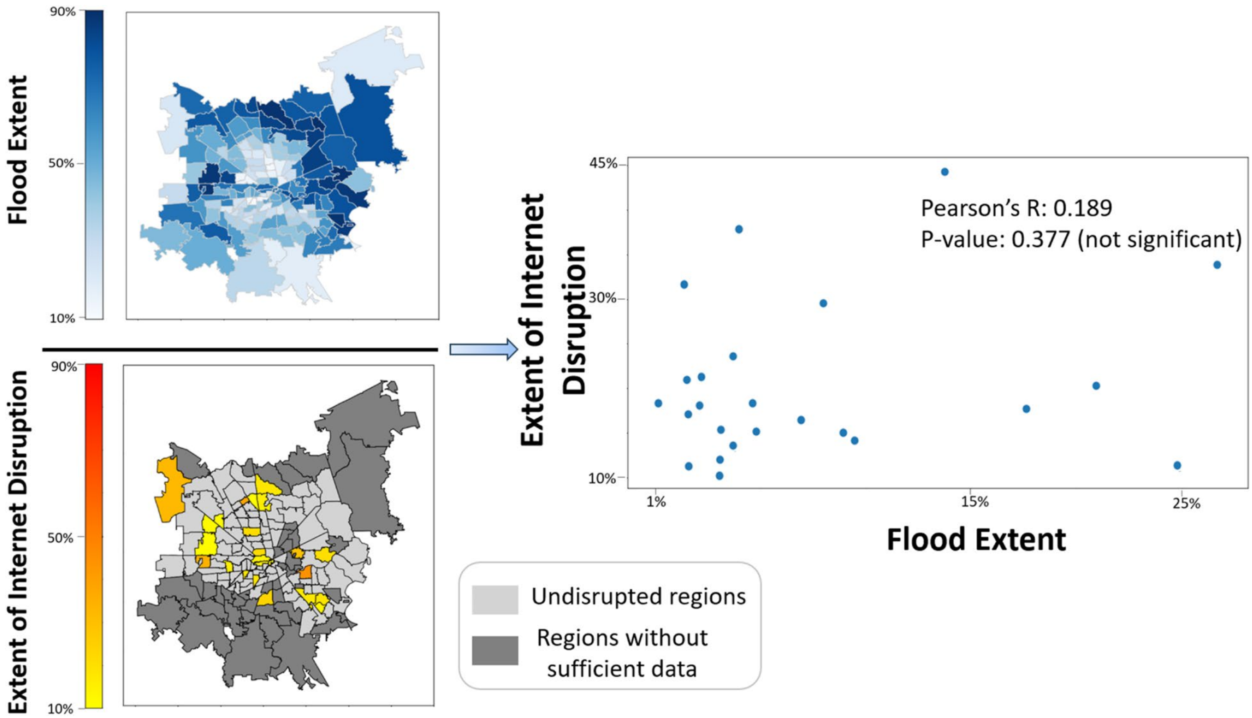

Fig. 3 Spatial comparison between regions' extent of power outage and internet disruption during Hurricane Harvey

disruptions or to reroute traffic effectively during power outages or other hazards. There could also be localized backup power solutions, such as generators or battery reserves, specifically dedicated to maintaining internet service, ensuring a consistent online presence even when broader electrical grids are compromised.

The spatial disconnect between hazard intensity and internet disruption emphasizes the importance of not viewing internet connectivity in isolation. It is crucial to recognize that internet service disruptions can happen even in areas that are not directly impacted by hazards, which means that the repercussions of hazards extend beyond the immediate area of impact, affecting regions that might seem safe or untouched at first glance. Internet disruptions in areas not directly affected by hazards can occur due to several factors. Centralized network infrastructures like data centers or main cable routes, if impacted, can disrupt service widely. Interruptions in the power grid, which internet services heavily rely on, can also extend disruptions beyond the immediate hazard area. Additionally, internet service providers may reroute or manage traffic in ways that strain the infrastructure in unaffected areas. Indirect physical damage from cascading effects like flooding or falling debris, as well as increased internet demand during emergencies, can further stress the system. These factors highlight the complex interdependencies and operational challenges that contribute to spatial variance in internet disruptions during hazard events. This phenomenon underscores the broader implications of such hazards, as areas without direct hazard impacts can still experience disruptions in essential internet services. Disruptions of internet services in areas not impacted directly by the hazards can slow down the response and relief efforts to impacted areas due to the disrupted information dissemination and situational awareness.

While the temporal alignment between power outages and internet disruptions is evident, our spatial analyses offer a contrasting picture. The spatial patterns observed during both Winter Storm Uri and Hurricane Harvey exhibit a significant disconnect. Regions heavily affected by power outages or flooding did not necessarily overlap with areas facing the most internet disruptions. This spatial incongruence underscores the complexity of the infrastructure networks and their interdependencies (Liu et at, 2024; Rajput et at, 2024). A potential explanation for this spatial inconsistency could be rooted in the spatial distribution of internet infrastructure (e.g., cell towers). Furthermore, the presence of redundant systems, be it in the form of multiple internet providers or backup power solutions, can greatly enhance a region's resilience, acting as a buffer against widespread disruptions x. While the temporal consistency between hazard intensity and internet disruptions sheds light on the immediacy of the effects of large-scale events on infrastructural systems, the spatial inconsistency points towards a set of local factors, from infrastructure resilience to historical preparedness, that can mediate these effects. The findings call for a nuanced approach in disaster management, focusing not just on immediate responses but also on strengthening spatially diverse infrastructural systems, making them more resilient in the face of future hazards.

3.2 Environmental injustice: social demographic analysis

We further explored the matter of environmental injustice issues regarding internet disruption during hazard events. Particularly, the grouping of regions is made based on the residents' income level (Sect. 2.1): The calculation of the median of percentage of the population living below the poverty line was performed. Regions where this percentage exceeds the median are classified as low-income groups, whereas those with percentages below the median are designated as high-income groups. After grouping, the pre-hazard internet connectivity and the internet disruption of each income group during the hazard in each group is calculated.

As illustrated in Fig. 4, during the events of Winter Storm Uri and Hurricane Harvey, low-income communities experienced reduced internet speeds and heightened internet disruptions (quantified by the percentage decrease in internet speed during these events) compared to high-income communities. Notably, this disparity was particularly pronounced during Winter Storm Uri. In this instance, the decline in internet speed for high-income communities was approximately 25% to 30%, while it exceeded 40% for low-income communities. This substantial difference underscores a marked disparity faced

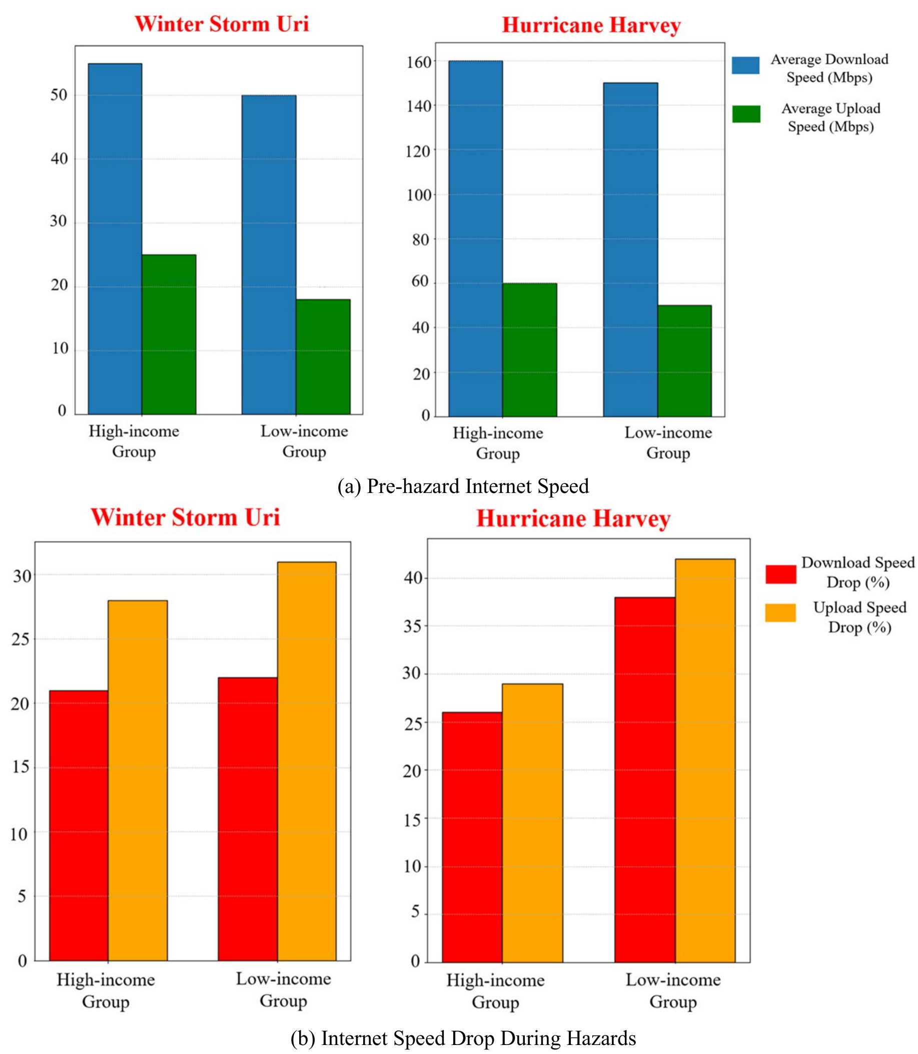

Fig. 4 Pre-hazard internet connectivity and the internet disruption during the hazards. **a** Pre-hazard Internet Speed. **b** Internet Speed Drop During Hazards

by low-income communities in terms of internet connectivity during such hazard events.

The patterns uncovered from the data, specifically during Winter Storm Uri and Hurricane Harvey, bring forth an unsettling realization about the intricacies of internet disruptions in vulnerable communities. In times of crises, the internet serves as a lifeline for many, providing essential information on safety measures, weather updates, emergency services, and more. Situational awareness is crucial during such events, and the internet plays a pivotal role in disseminating real-time information. Vulnerable communities, often already grappling with socio-economic challenges, find themselves in an even more precarious situation when they cannot access critical information due to internet outages. Moreover, the internet is also a primary tool for information sharing. Communities use it to organize relief efforts, and individuals use it to seek help or provide updates about their safety. When internet services are disrupted, especially in areas with a high concentration of vulnerable populations, the effects can be detrimental to life and health.

The findings from Winter Storm Uri and Hurricane Harvey highlight that at times and in places where vulnerable communities most require these services for situational awareness and information sharing, they might encounter even more significant disruptions than other groups. This paradox emphasizes the need for targeted interventions and strategies. Ensuring that these vulnerable communities have access to reliable internet services during disasters should be a priority. Vulnerable communities may lack robust internet infrastructure or the economic means to access reliable services, which can lead to greater isolation during emergencies. To mitigate these disparities and enhance resilience, strategic interventions could include investing in more robust and redundant internet infrastructure in these areas, such as installing backup power solutions or diversifying internet service providers to ensure service continuity during power outages or infrastructure damage. Additionally, government and service providers could implement subsidized internet programs that ensure affordable access for low-income households. Community-based approaches, like local mesh networks that operate independently of large service providers, could also empower communities to maintain connectivity autonomously. These strategies not only aim to improve the resilience of internet services but also ensure that vulnerable populations remain connected and supported during critical times.

These findings bring into focus a pressing need for policymakers, city planners, and internet service providers to re-evaluate infrastructure strategies. Enhancing the robustness of internet service in vulnerable areas, developing contingency plans for rapid response to outages, and perhaps even considering localized, community-based internet solutions could be potential steps forward.

4 Concluding remarks

Evaluating the impact of hazards on infrastructure is critical for hazard monitoring and enhancing urban resilience. However, the disruption of information and communication technology (ICT) service—a crucial component of contemporary communication and urban operations—has long been overlooked by previous research (Liu et at, 2022; Wang, 2020). To address these gaps, this study innovatively utilized observational data on internet performance to delve into the impacts of hazard severity on internet disruption during two major US hazard events: Hurricane Harvey and Winter Storm Uri.

Our findings show that the hazard events caused significant disruptions of regional internet connectivity. Time series analysis indicates a strong correlation between the magnitude of disruption and hazard severity. Internet disruptions worsen with intensifying hazard severity and eventually return to baseline levels post-hazard. However, spatial analyses highlight that regions with pronounced hazard severity don't necessarily coincide with zones experiencing the highest internet disruptions. Areas not directly impacted by hazards can also experience severe disruption, demonstrating the repercussions of hazards extend beyond the immediate area of impact, affecting regions that might seem safe or untouched at first glance. Our findings resonate with previous studies on environmental justice and the digital divide, demonstrating that socio-economic disparities significantly influence internet accessibility during disasters. This study substantiates theories suggesting that economically marginalized communities face compounded challenges during environmental crises due to infrastructural inequities, as these communities typically experience more severe internet disruptions. By providing empirical data linking income levels to internet service resilience, our research contributes new insights to the existing knowledge, emphasizing the need for equitable infrastructure development. These contributions are crucial for policymakers and planners aiming to bridge the digital divide and ensure environmental justice, ensuring that all communities have equitable access to critical information and communication technologies during emergencies.

This temporal synchronization, juxtaposed with spatial discrepancies, underscores the complex relationships between hazard severity and internet disruption. Additionally, our sociodemographic inquiry sheds light on the disparate impacts of hazards across communities. The data reveals that the living conditions of the vulnerable communities may be further aggravated due to their already challenging situations, which call for special attention for prioritized strategies for disaster mitigation and interventions (Zhou et at, 2024). Our research contributes to the body of knowledge in disaster prevention and urban resilience. It harnesses a quantitative observational dataset to elucidate the repercussions of hazards on the stability of ICT service. To the best of our knowledge, ours is the first study where the nexus between internet disruption and hazard severity is empirically and quantitatively examined. Our sociodemographic investigations further underscore the multifaceted relationship between vulnerable communities and the extent of internet disruption. The findings confirm the prevalent notion that vulnerable groups endure the worst of internet disruptions during significant events, offering insights into environmental inequities in disaster contexts. Practically, our discoveries provide invaluable perspectives on the disruptions, connectivity lapses, and recovery trajectories of internet performance in relation to hazard severity, which are pivotal for urban planners and infrastructure operators, aiding in the formulation of timely and effective strategies to mitigate hazard impacts and strengthen urban resilience.

The findings of this research point to several promising avenues for future exploration. While the current study was confined to two events pertaining to hurricanes and winter storms, restricted by data availability, future endeavors could seek to broaden the dataset. This expanded study would encompass a more varied range of hazard events, offering a comprehensive view of internet disruptions across different disaster contexts. Besides, this study's generalizability is limited by the specific data sources used and the narrow focus on particular dates and events. The reliance on data from distinct incidents such as Hurricane Harvey and Winter Storm Uri means the findings may not be directly applicable to other types of disasters or different geographical locations. This specificity in data and context restricts the broader applicability of the study's methods and conclusions to other hazard scenarios. Furthermore, deeper analysis should be undertaken to uncover the regional determinants that account for the spatial variances in internet resilience. Such insights would be instrumental in understanding why certain regions exhibit greater resilience compared to others, with the objective of identifying protective or mitigating factors.

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Availability of data and materials
The authors have no right to share the data.

Declarations

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References

Chiou, L., & Tucker, C. (2020). *Social distancing, internet access and inequality (No. w26982)*. National Bureau of Economic Research.

Coleman, N., Esmalian, A., & Mostafavi, A. (2020). Equitable resilience in infrastructure systems: Empirical assessment of disparities in hardship experiences of vulnerable populations during service disruptions. *Natural Hazards Review,21*(4), 04020034.

Davis, J., Mitsova, D., Briggs, T., & Briggs, T. (2019). Post-hurricane Michael damage assessment using ADCIRC storm surge hindcast, image classification, and LiDAR. *Shore & Beach,87*(4).

Esmalian, A., Dong, S., Coleman, N., & Mostafavi, A. (2021). Determinants of risk disparity due to infrastructure service losses in disasters: a household service gap model. *Risk Analysis,41*(12), 2336–2355.

Fan, C., & Mostafavi, A. (2019). A graph-based method for social sensing of infrastructure disruptions in disasters. *Computer-Aided Civil and Infrastructure Engineering,34*, 1055–70.

Fan, C., Zhang, C., Yahja, A., & Mostafavi, A. (2021). Disaster City Digital Twin: a vision for integrating artificial and human intelligence for disaster management. *International Journal of Information Management,56*, 102049.

Farahmand, H., Wang, W., Mostafavi, A., Maron, M., & M,. (2022). Anomalous human activity fluctuations from digital trace data signal flood inundation status. *Environment and Planning B: Urban Analytics and City Science,* 23998083211069990.

Federal Emergency Management Administration (FEMA). (2018). FEMA - Harvey Flood Depths Grid. *HydroShare*. https://doi.org/10.4211/hs.165e2c3e335d40949dbf501c97827837

FEMA. (2017). Power outage incident annex to the response and recovery federal interagency operational plans: Managing the cascading impacts from a long-term power outage. https://www.fema.gov/media-library/assets/documents/154058. Accessed 15 June 2023.

Gao, X., Fan, C., Yang, Y., Lee, S., Li, Q., Maron, M., & Mostafavi, A. (2021). Early indicators of human activity during covid-19 period using digital trace data of population activities. *Frontiers in Built Environment,6*, 607961.

Graves, J. M., Abshire, D. A., Amiri, S., & Mackelprang, J. L. (2021). Disparities in technology and broadband internet access across rurality: implications for health and education. *Family & Community Health,44*(4), 257.

Han, S. R., Guikema, S. D., Quiring, S. M., Lee, K. H., Rosowsky, D., & Davidson, R. A. (2009). Estimating the spatial distribution of power outages during hurricanes in the Gulf coast region. *Reliability Engineering & System Safety,94*(2), 199–210.

Hasan, S., & Foliente, G. (2015). Modeling infrastructure system interdependencies and socioeconomic impacts of failure in extreme events: emerging R&D challenges. *Natural Hazards,78*(3), 2143–2168.

Ho, Y. H., Liu, Z., Lee, C. C., & Mostafavi, A. (2023). ML4EJ: Decoding the Role of Urban Features in Shaping Environmental Injustice Using Interpretable Machine Learning. arXiv preprint arXiv:2310.02476
Huang, X., Lu, J., Gao, S., Wang, S., Liu, Z., & Wei, H. (2022). Staying at home is a privilege: Evidence from fine-grained mobile phone location data in the United States during the COVID-19 pandemic. *Annals of the American Association of Geographers,112*(1), 286–305.
Kirsch, T. D., Mitrani-Reiser, J., Bissell, R., Sauer, L. M., Mahoney, M., Holmes, W. T., ... & De La Maza, F. (2010). Impact on hospital functions following the 2010 Chilean earthquake. *Disaster medicine and public health preparedness*, *4*(2), 122–128.
Lee, C. C., Maron, M., & Mostafavi, A. (2022). Community-scale big data reveals disparate impacts of the Texas winter storm of 2021 and its managed power outage. *Humanities and Social Sciences Communications,9*(1), 1–12.
Liu, Z., Wang, A., Weber, K., Chan, E. H., & Shi, W. (2022). Categorisation of cultural tourism attractions by tourist preference using location-based social network data: The case of Central. *Hong Kong. Tourism Management,90*, 104488.
Liu, Z., Felton, T., & Mostafavi, A. (2024). Interpretable machine learning for predicting urban flash flood hotspots using intertwined land and built-environment features. *Computers Environment and Urban Systems,110*, 102096.
Liu, Z., Liu, C., & Mostafavi, A. (2023). Beyond Residence: A Mobility-based Approach for Improved Evaluation of Human Exposure to Environmental Hazards. arXiv preprint arXiv:2306.10197
Luo, P., & Zhu, D. (2022). Sensing overlapping geospatial communities from human movements using graph affiliation generation models. In Proceedings of the 5th ACM SIGSPATIAL International Workshop on AI for Geographic Knowledge Discovery (pp. 1–9).
Mattsson, L. G., & Jenelius, E. (2015). Vulnerability and resilience of transport systems–A discussion of recent research. *Transportation Research Part a: Policy and Practice,81*, 16–34.
Mitsova, D., Sapat, A., Esnard, A. M., & Lamadrid, A. J. (2020). Evaluating the impact of infrastructure interdependencies on the emergency services sector and critical support functions using an expert opinion survey. *Journal of Infrastructure Systems,26*(2), 04020015.
Ookla (2023). Speedtest by Ookla. https://www.speedtest.net/
Rajput, A. A., Liu, C., Liu, Z., & Mostafavi, A. (2024). Human-centric characterization of life activity flood exposure shifts focus from places to people. Nature Cities, 1–11.
Roman, J. (2018). Hurricane Maria: A preventable humanitarian and health care crisis unveiling the Puerto Rican dilemma. *Annals of the American Thoracic Society,15*(3), 293–295.
Sen, A., & Tucker, C. E. (2020). Social distancing and school closures: documenting disparity in internet access among school children. Available at SSRN 3572922.
Singh, G. K., Girmay, M., Allender, M., & Christine, R. T. (2020). Digital divide: Marked disparities in computer and broadband internet use and associated health inequalities in the United States. *International Journal of Translational Medical Research and Public Health,4*(1), 64–79.
Tirabassi, J. N., Wang, J., Zhou, R. Z., & Hu, Y. (2024). *Human mobility data demonstrates increase in park visitation since start of COVID-19 pandemic in Buffalo* (p. 102650). Preventive Medicine Reports.
USCB (2023). Explore Census Data. https://data.census.gov/
Wang, C., & Hess, D. B. (2021). Role of urban big data in travel behavior research. *Transportation Research Record,2675*(4), 222–233.
Wang, A., Zhang, A., Chan, E. H., Shi, W., Zhou, X., & Liu, Z. (2020). A review of human mobility research based on big data and its implication for smart city development. *ISPRS International Journal of Geo-Information,10*(1), 13.
Yan, Z., Guo, X., Zhao, Z., & Tang, L. (2024). Achieving fine-grained urban flood perception and spatio-temporal evolution analysis based on social media. *Sustainable Cities and Society,101*, 105077.
Yin, J., et al. (2012). Using social media to enhance emergency situation awareness. *IEEE Intelligent Systems,27*(06), 52–59.
Yin, K., Li, X., Chen, Q., & Lu, J. (2018). Examining the Reasons for the Low Market Share of Road Passenger Transport Based Express Using Structural Equation Modeling. *18th COTA International Conference of Transportation Professionals* (pp. 459–471). American Society of Civil Engineers.
Yin, K., & Mostafavi, A. (2023a). Deep Learning-driven Community Resilience Rating based on Intertwined Socio-Technical Systems Features. arXiv preprint arXiv:2311.01661.
Yin, K., Wu, J., Wang, W., Lee, D. H., & Wei, Y. (2023b). An integrated resilience assessment model of urban transportation network: A case study of 40 cities in China. *Transportation Research Part a: Policy and Practice,173*, 103687.
Yin, K., & Mostafavi, A. (2023c). Unsupervised Graph Deep Learning Reveals Emergent Flood Risk Profile of Urban Areas. arXiv e-prints, arXiv-2309.
Yuan, F., Yang, Y., Li, Q., & Mostafavi, A. (2022). Unraveling the temporal importance of community-scale human activity features for rapid assessment of flood impacts. *IEEE Access,10*, 1138–1150.
Zhang, C., Fan, C., Yao, W., Hu, X., & Mostafavi, A. (2019). Social media for intelligent public information and warning in disasters: An interdisciplinary review. *International Journal of Information Management,49*, 190–207.
Zhang, C., Yao, W., Yang, Y., Huang, R., & Mostafavi, A. (2020). Semiautomated social media analytics for sensing societal impacts due to community disruptions during disasters. *Computer-Aided Civil and Infrastructure Engineering,35*(12), 1331–1348.
Zhou, R. Z., Hu, Y., Tirabassi, J. N., Ma, Y., & Xu, Z. (2022). Deriving neighborhood-level diet and physical activity measurements from anonymized mobile phone location data for enhancing obesity estimation. *International Journal of Health Geographics,21*(1), 22.
Zhou, R. Z., Hu, Y., Zou, L., Cai, H., & Zhou, B. (2024). Understanding the disparate impacts of the 2021 Texas winter storm and power outages through mobile phone location data and nighttime light images. International Journal of Disaster Risk Reduction, 104339.
Zimmerman, R., Zhu, Q., de Leon, F., & Guo, Z. (2017). Conceptual modeling framework to integrate resilient and interdependent infrastructure in extreme weather. *Journal of Infrastructure Systems,23*(4), 04017034.
Zorrilla, C. D. (2017). The view from Puerto Rico—Hurricane Maria and its aftermath. *New England Journal of Medicine,377*(19), 1801–1803.
Liu, J., Chau, K. W., & Bao, Z. (2023). Multiscale spatial analysis of metro usage and its determinants for sustainable urban development in Shenzhen, China. *Tunnelling and Underground Space Technology, 133*, 104912.
Liu, J., Bi, H., & Wang, M. (2020). Using multi-source data to assess livability in Hong Kong at the community-based level: A combined subjective-objective approach. *Geography and sustainability, 1*(4), 284–294.

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