Preprints.org

Healthcare Access in the Aftermath: A Longitudinal Analysis of Disaster Impact on US Communities

Kevin Chang [*] , Kevin Smiley , Jana A. Hirsch , Lauren Clay , Yvonne L. Michael

Article

Healthcare Access in the Aftermath: A Longitudinal Analysis of Disaster Impact on US Communities

Kevin Chang [1,*], Kevin Smiley [2], Jana A. Hirsch [3,5], Lauren Clay [4] and Yvonne Michael [5]

[1] Deparment of Medicine, Drexel University College of Medicine, Philadelphia, PA, USA

[2] Department of Sociology, Louisiana State University, Baton Rouge, LA, USA

[3] Urban Health Collaborative, Drexel University Dornsife School of Public Health, Philadelphia, PA, USA

[4] Department of Emergency and Disaster Health Systems, University of Maryland Baltimore County, Baltimore, MD, USA

[5] Department of Epidemiology and Biostatistics, Drexel University Dornsife School of Public Health, Philadelphia, PA, USA

[*] Correspondence: kc3637@drexel.edu; Tel.: +1 516-303-4331

Abstract: Research on climate-related disasters and healthcare infrastructure has largely focused on short-term, localized impacts. This study examined the long-term association between climate-related disasters and healthcare facilities across 3,108 contiguous United States counties from 2000-2014. Utilizing databases like the National Establishment Time Series and the Spatial Hazards and Events Losses Database, we classified county-level infrastructure changes ("never had", "lost", "gained", and "always had") and disaster severity (minor, moderate, severe), respectively. Autoregressive linear models were used to estimate the total number of moderate and severe disasters (2000-2013) associated with the change in the number of healthcare establishments in 2014, after adjusting for healthcare establishments, total population, and poverty in 2000. Results demonstrate that an increase in one moderate disaster was significantly associated with increased hospital infrastructure (Count, 0.14 ;95% CI, 0.02-0.25), while severe disasters were significantly associated with a decrease (Count, -0.28; 95% CI, -0.45- -0.12). Similar but stronger associations were observed for ambulatory care (Moderate: Count, 2.49; 95% CI 0.89-4.09 and Severe: Count, -5.78; 95% CI, -8.13- -3.43, respectively). No significant associations were found among pharmacies. These findings highlight the varying impacts of climate-related disasters on healthcare accessibility. Future initiatives should prioritize strengthening existing infrastructure and enhance disaster recovery strategies.

Keywords: environmental health; disasters; healthcare accessibility; longitudinal study; United States; healthcare infrastructure

1. Introduction

Climate change threatens our world's ecosystem with more intense, frequent, and fatal weather-related disasters. In the United States (US) alone, fifteen or more billion-dollar weather-related events have occurred each year from 2015 to 2020 [1]. Approximately 24% of global deaths are due to modifiable environmental factors [2]. Climate-related disasters, such as extensive flooding or wind damage, can destroy crucial healthcare infrastructures in our communities like pharmacies, hospitals, and ambulatory care centers [3]. As a result, healthcare may be disrupted, turning away patients and interrupting access to medication or routine appointments [4]. For example, Superstorm Sandy and the aftermath of Hurricane Katrina led to short-term health system closures, destruction of medical records, and spike in medication demand, resulting in missed medical appointments and increased rates of uncontrolled hypertension [4]. Additionally, disasters obstruct continuity of care, worsening chronic health issues [5,6].

Post-disaster recovery efforts, which include the repairing or rebuilding of damaged infrastructure, require significant resources and collaboration between local and federal governments. However, communities that are of low socioeconomic status (SES) (e.g. low income) may experience greater challenges in their recovery. For example, communities have less insurance, savings, and personal resources to devote to their recovery [7]. Disaster-related losses in these communities have also been associated with worsening physical and mental health among those already at risk for poor health outcomes [7,8]. Worsening health-related conditions in low SES communities demonstrate the necessity for healthcare services that are both accessible and available post-disaster. However, an analysis examining the differences between Hurricane Katrina and Hurricane Sandy on healthcare provider availability demonstrated that access to care post-disaster remains inequitable [9]. After Katrina, researchers noted a county-level decline in primary care physicians, medical specialists, and surgeons- an effect not seen in affected counties after Sandy [9]. The median household income in counties at the time affected by Katrina ($45,800) was below the national average ($50,233), whereas the median income for counties affected by Sandy ($65,000) was well above ($56,516) [9]. These disparities underscore how county-level socioeconomic differences ultimately shape both acute disaster response and long-term recovery.

Research to date on post-disaster healthcare accessibility and availability has largely focused on single disasters and the short-term impacts of disrupted healthcare services on communities [10–12]. Additionally, past work has concentrated on the immediate effects of disasters on operations within specific healthcare facilities such as the staffing or availability of services in hospital centers [10–12]. Investigation of the long-term impact of climate-related disasters on diverse types of healthcare facilities at a larger, national scale has largely been unexplored [13]. Disasters significantly alter local healthcare infrastructure that can have lasting effects on human health. Shifting the focus beyond the immediate disaster response to the broader recovery period may reveal several crucial factors that influence health outcomes.

In our study, we address this gap by assessing the relationship between healthcare accessibility and disasters longitudinally throughout the US. To address this relationship, we focus on US counties utilizing data from three primary datasets: of healthcare infrastructure; disaster losses; and geographical polarization. We examine disaster losses over an extended period of time (2000 to 2014) and include data across various hazard types and levels of impact. In our study, we evaluate three large categories of healthcare infrastructure: (1) pharmacies; (2) hospital based inpatient care; and (3) ambulatory care. Our research examines how disasters impact the way these healthcare institutions are distributed across the continental over a 15-year time span and control for confounding by race/ethnicity and SES.

2. Materials and Methods

2.1. Study Sample

This study linked data from three primary data sources to create an annual panel dataset of counties in the contiguous US from 2000 to 2014 totaling 46,620 county-years, including longitudinal data on disasters losses and healthcare infrastructure. The study had a total of 3,108 continental nonwater US counties. To establish consistency over time, the 2000 US Census geographies were utilized for the demographic and socioeconomic measurements.

2.2. Measures

Health and Healthcare Institutions. The presence of healthcare facilities was measured using 2000 to 2014 business data from the National Establishment Time Series (NETS) database, licensed from Walls & Associates (Denver, Colorado) in January 2017 [14]. From the NETS, records were categorized as ambulatory care or as pharmacies using 8-digit Standard Industrial Classification (SIC) codes (Table S1) according to methods published elsewhere [15]. Healthcare facilities were geocoded

and aggregated to county for each year in which a business was open, focused on 2000 and 2014. Using this information, we assessed counts of healthcare facilities per county and change over time. Categories of change of healthcare facilities were divided as: (1) Never (counties having no facilities at both time points (2000-2014)), (2) Lose (counties going from having at least one facility in 2000 to having none in 2014), (2) Gain (counties going from having no facilities in 2000 to having at least one in 2014) and (4) Always present (counties having at least one at both time points (2000-2014)). Due to the distribution of the NETS resource, ambulatory care values were measured using a threshold value of 10 facilities per county per year, rather than the initial threshold of one facility.

Disaster impact. Disaster impact losses were measured using 2000 to 2014 data from Spatial Hazards and Events Losses Database for the United States (SHELDUS™), a national database of eighteen different hazard types at county level resolution for all 50 states [16]. SHELDUS™ consolidates multiple disaster databases, including data from the National Climatic Data Center, US Geological Survey, and others. For every event with any measured loss, SHELDUS™ provides: location (county), time (begin and end date), inflation-adjusted direct losses (property and crop damage, fatalities, injuries), and type of hazard (peril). SHELDUS™ is a leading data set relating to disasters and is used across dozens of studies [17–19]. We created a three-level typology: severe, moderate, and minor impact. For each county during 2000-2014, a severe disaster month was classified as greater than $50 property damage per capita and/or three or more fatalities, a moderate disaster month as between $10 and $50 of property damage per capita and/or 2 fatalities, and a minor disaster month occurs as fewer than $10 property damage per capita and/or has one fatality from disasters [20]. The disaster impact variable was created by totaling up the number of months in a year for each category for each county.

Geographical Polarization Data. Geographical polarization data was reported as a single metric value named the Index of Concentration at the Extremes (ICE). The ICE value represents the extent to which a county's population are organized into the extremes of deprivation and privilege utilizing 2018 household income. The ICE value is a commonly used measure to assess disparities utilizing a geographical perspective [21]. Values range from -1 to +1, with a value of -1 indicating the most deprived county and a value of +1 indicating the most privileged county. For this project we compared non-Hispanic white high-income groups versus person of color low-income groups. High-income counties were defined as populations that were part of the top quintile of household income and low-income counties were defined as populations that were part of the bottom quintile of household income [21].

Covariates. Covariate data was assessed using data from the Longitudinal Tract Database provided by Brown University, including decennial census data from 2000 and 2010 and data from the National Historical Geographic Information Systems [22]. Longitudinal Tract Database data were produced at the census tract-level and were aggregated to the county-level. Using these data for each county, the annual community-level social and demographic characteristics were obtained: (1) proportion of white residents, (2) owner-occupied homes, measured as the proportion of owner-occupied housing units (compared to renters), and (3) proportion college educated, measured as the proportion of residents aged 25 or older who have completed a bachelor's degree.

2.3. Statistical Analysis

We calculated descriptive statistics of healthcare infrastructure, demographic, socioeconomic, and geographical polarization characteristics for 2000, 2014 (healthcare infrastructure only), and 2018 (geographical polarization data only). Total counts of healthcare infrastructure were calculated for each county during the time period as well as the average proportion of such counties living below poverty, unemployed, college educated, or residing in owner-occupied housing units (Table 1). In addition, average ICE values of each county were calculated (Table 1). Because minor disasters encompassed a broad range of event hazards and were overrepresented in our dataset, they introduced considerable variability, making systematic analysis more challenging (Table 2). Given

the study's focus on more intense disasters with significant public health consequences, we limited our analyses to moderate and severe events to enhance clarity.

Table 1. Demographic and Socioeconomic Characteristics (2000) and Climate-related Disasters (2000) Across Categories of Change (2000-2014) in Healthcare Facilities for 3108 Continental Nonwater US Counties.

2000 Characteristic[a]	No. (%) All counties (N= 3108)
Race/ethnicity[b]	
Predominantly NH white	2671 (85.9)
Predominantly NH black	45 (1.4)
Predominantly Hispanic/Latino	33 (1.1)
Other or Racially/ethnically mixed	359 (11.6)
Living below poverty, mean (SD), %	14.2 (6.5)
Unemployed, mean (SD), %	6.2 (3.4)
College Educated, mean (SD), %	16.5 (7.8)
Ownership-Occupied Housing Units, mean (SD), %	74.1 (7.6)
Total Population, mean (SD)	89956.1 (293542.8)
Index of Concentration at the Extremes (ICE)	
ICEwnhinc[c], mean (SD)	0.10 (0.13)
Climate-related Disaster (total number)[d]	
Minor Disaster	5355
Moderate Disaster	603
Severe Disaster	305

2000 Characteristic	No. (%) Pharmacies			
	Never[e] (n= 116)	Lose (n=66)	Gain (n=28)	Always (n=2898)
Race/ethnicity				
Predominantly NH white	96 (82.8)	51 (77.3)	24 (85.7)	2500 (86.3)
Predominantly NH black	2 (1.7)	2 (3.0)	0	41 (1.4)
Predominantly Hispanic/Latino	4 (3.4)	2 (3.0)	0	27 (0.9)
Other or Racially/ethnically mixed	14 (12.1)	11 (16.7)	4 (14.3)	330 (11.4)
Living below poverty, mean (SD), %	16.6 (8.9)	17.4 (8.5)	15.3 (8.8)	14.0 (6.3)
Unemployed, mean (SD), %	6.0 (6.6)	5.9 (4.2)	6.2 (4.2)	6.2 (3.1)
College Educated, mean (SD), %	16.4 (6.0)	15.6 (6.3)	15.6 (7.8)	16.5 (7.9)
Ownership-Occupied Housing Units, mean (SD), %	73.2 (10.4)	74.8 (5.8)	76.2 (6.0)	74.1 (7.5)
Total Population, mean (SD)	3058.1 (2892.6)	6659.0 (4560.4)	8853.4 (7253.6)	96115.0 (303068.1)
Index of Concentration at the Extremes (ICE)				
ICEwnhinc, mean (SD)	0.09 (0.18)	0.07 (0.09)	0.11 (0.19)	0.11 (0.13)
Climate-related Disaster (total number)				
Minor Disaster	42	55	19	5239
Moderate Disaster	36	14	5	548
Severe Disaster	18	11	4	272

2000 Characteristic	No. (%) Hospitals			
	Never (n= 307)	Lose (n=86)	Gain (n=150)	Always (n=2565)
Race/ethnicity				
Predominantly NH white	267 (87.0)	63 (73.3)	129 (86.0)	2212 (86.2)
Predominantly NH black	5 (1.6)	5 (5.8)	3 (2.0)	32 (1.2)

	Predominantly Hispanic/Latino	4 (1.3)	2 (2.3)	5 (2.7)	23 (0.9)
	Other or Racially/ethnically mixed	37 (10.1)	16 (18.6)	14 (9.3)	298 (11.6)
Living below poverty, mean (SD), %		16.1 (7.4)	17.6 (7.5)	15.0 (7.6)	13.8 (6.2)
Unemployed, mean (SD), %		5.7 (3.8)	6.9 (3.4)	6.2 (3.2)	6.2 (3.3)
College Educated, mean (SD), %		14.0 (5.6)	12.3 (3.9)	13.8 (7.7)	17.1 (8.1)
Ownership-Occupied Housing Units, mean (SD), %		77.0 (6.8)	76.0 (8.4)	77.9 (6.1)	73.5 (7.5)
Total Population, mean (SD)		7433.3 (6428.5)	10635.9 (6740.9)	17713.2 (12661.53)	106717.2 (320604.4)
Index of Concentration at the Extremes (ICE)					
	ICEwnhinc, mean (SD)	0.10 (0.07)	0.02 (0.11)	0.09 (0.11)	0.11 (0.10)
Climate-related Disaster (total number)					
	Minor Disaster	267	72	203	4813
	Moderate Disaster	66	15	19	503
	Severe Disaster	39	6	11	249

	No. (%)			
	Ambulatory Care[e]			
2000 Characteristic	**Never (n= 495)**	**Lost (n=21)**	**Gain (n=201)**	**Always (n=2391)**
Race/ethnicity				
Predominantly NH white	403 (81.4)	15 (71.4)	172 (85.6)	2081 (87.0)
Predominantly NH black	14 (2.8)	2 (9.5)	6 (3.0)	23 (1.0)
Predominantly Hispanic/Latino	12 (2.4)	1 (4.8)	1 (0.5)	19 (0.8)
Other or Racially/ethnically mixed	66 (13.3)	3 (14.3)	22 (10.9)	268 (11.2)
Living below poverty, mean (SD), %	17.3 (7.7)	17.2 (8.7)	15.7 (7.1)	13.4 (6.0)
Unemployed, mean (SD), %	5.9 (4.4)	7.8 (4.5)	6.3 (3.6)	6.2 (3.1)
College Educated, mean (SD), %	13.3 (4.7)	13.0 (3.4)	13.0 (4.6)	17.5 (8.3)
Ownership-Occupied Housing Units, mean (SD), %	76.2 (7.0)	77.5 (5.3)	78.0 (4.8)	73.3 (7.5)
Total Population, mean (SD)	5585.2 (3751.8)	9285.9 (3415.9)	10466.9 (4657.25)	114813.9 (330653.4)
Index of Concentration at the Extremes (ICE)				
ICEwnhinc, mean (SD)	0.07 (0.09)	0.04 (0.08)	0.08 (0.13)	0.12 (0.09)
Climate-related Disaster (total number)				
Minor Disasters	354	30	246	4725
Moderate Disasters	110	4	50	439
Severe Disasters	66	6	22	211

[a] Data are from the 2000 US Census report unless otherwise indicated. [b] Racial/ethnic composition was assessed by predominant (>60%) racial/ethnic group. Places with no predominant group were classified as racially/ethnically mixed areas. [c] Index of Concentration at the Extremes (ICE) for non-Hispanic white high-income vs. person of color low-income 2018 value. High-income defined as counties that were part of the top quintile of household income and low-income defined as counties that were part of bottom quintile of household income. The ICE variable ranges from -1 (least privileged) to +1 (most privileged). [d] Data are from the SHELDUS™ national database unless otherwise indicated. [e] Due to the distribution of the NETS resource, ambulatory care values were defined as: (1) Never (counties having less than 10 facilities at both time points (2000-2014)), (2) Lost (counties that had at least 10 facilities in 2000 to less than 10 in 2014), (3) Gain (counties that had less than 10 facilities in 2000 to at least 10 in 2014), and (4) Always (counties always having at least 10 facilities at both time points (2000-2014)).

Table 2. Change in Climate-related Disaster Occurrences (2000-2014) Across Categories of Change in Healthcare Facilities (2000-2014) for 3108 Continental Nonwater US Counties.

	No. (%)				
		Pharmacies			
Change in Characteristic (2000-2014)	**All counties (N= 3108)**	**Never (n= 116)**	**Lose (n=66)**	**Gain (n=28)**	**Always (n=2898)**
Climate-related Disaster, mean (SD),%:					
Minor Disaster	7.5 (221.1)	-13.8 (105.4)	19.7 (129.2)	-21.4 (87.6)	-7.7 (227.0)
Moderate Disaster	-5.8 (7.5)	18.1 (61.3)	10.6 (43.4)	17.9 (39.0)	5.1 (58.7)
Severe Disaster	-2.1 (42.5)	1.7 (47.5)	3.0 (58.1)	-3.6 (57.6)	2.1 (41.7)
		Hospitals			
Change in Characteristic (2000-2014)		**Never (n= 307)**	**Lose (n=86)**	**Gain (n=150)**	**Always (n=2565)**
Climate-related Disaster, mean (SD),%:					
Minor Disaster		9.4 (146.0)	33.7 (192.0)	2.5 (208.8)	5.3 (230.0)
Moderate Disaster		-7.5 (60.3)	4.6 (59.2)	-.7 (53.7)	-6.2 (58.4)
Severe Disaster		-2.3 (49.5)	3.5 (38.9)	-1.3 (30.6)	-2.3 (42.3)
		Ambulatory Care			
Change in Characteristic (2000-2014)		**Never (n= 495)**	**Lose (n=21)**	**Gain (n=201)**	**Always (n=2391)**
Climate-related Disaster, mean (SD),%:					
Minor Disaster		13.1 (138.0)	-47.6 (143.6)	-.50 (165.4)	7.4 (239.0)
Moderate Disaster		-5.9 (62.6)	4.6 (63.2)	-6.0 (75.3)	-5.8 (55.8)
Severe Disaster		-1.2 (49.7)	3.5 (53.9)	0 (40.0)	-2.2 (41.0)

We fit multivariable linear models to estimate the change in the number of medical establishments in 2014 associated with a 1-unit increase in the number of years exposed to each type of moderate and severe disaster from 2000 to 2013 (Table 3). To avoid over-controlling, we identified *a priori* the most important confounding variables to include in the analysis, drawing on previous disaster research and empirical evidence. A review of current literature has indicated that healthcare establishment, population density, and SES influence post-disaster outcomes [7,8,23]. By adjusting for these factors, we aim to minimize residual confounding and isolate the specific effects of disaster exposure on healthcare infrastructure over time and across space.

Table 3. Adjusted Autoregressive Models Measuring Change in Total Number of Healthcare Establishments in 2014 With Total Number of Moderate and Severe Climate-related Disasters for 3108 Nonwater US Counties.

	Pharmacies		**Hospitals**		**Ambulatory Care**	
	Count	**95 % CI**	**Count**	**95 % CI**	**Count**	**95 % CI**
Climate-related Disasters						
Moderate Disaster	0.09	(-0.06, 0.24)	0.14*	(0.02, 0.25)	2.49**	(0.89, 4.09)
Severe Disaster	0.10	(-0.09, 0.35)	-0.28***	(-0.45, -0.12)	-5.78***	(-8.13, -3.43)

*$p < 0.05$; ** $p < 0.01$; *** $p < 0.001$. Counts were adjusted for poverty rates in 2000, the total number of healthcare establishments in 2000, and total population in 2014.

3. Results

3.1. Differences in Counties by Changes in Healthcare Facilities (2000-2014)

Across all types of healthcare categories, pharmacies experienced the least change (n=94). Counties that went from having at least one type of healthcare facility from 2000 to having none in 2014, had a higher proportion of residents living below poverty. Counties that lost hospitals had the highest proportion of individuals living below poverty (17.6%). We observed similar levels of poverty among counties that never had a type of healthcare facility at both time points. (Table 1)

Counties that *lost* healthcare facilities had higher levels of segregation (lower ICE scores) compared to counties that consistently had healthcare facilities at both time points, across all categories of healthcare facilities. (Table 1)

3.2. Changes in Disasters (2000-2014) by Changes in Healthcare Facilities (2000-2014)

Counties that lost their pharmacies (n=66), hospitals (n=86), and ambulatory care (n=21), 2000 to 2014, experienced more moderate and severe disasters. The patterns were less consistent for minor disasters (Table 2)

3.3. Change in Total Number of Healthcare Establishments in 2014 with Total Number of Moderate and Severe Disasters

While an increase in one moderate disaster was associated with a statistically significant increase in hospital infrastructure over the time period (Count, 0.14; 95% CI, 0.02-0.25), we observed a significant decrease in hospital infrastructure (Count, -0.28; 95% CI, -0.45- -0.12) associated with severe disaster. We observed a similar pattern of association for ambulatory care (Moderate: Count, 2.49; 95% CI, 0.89-4.09 and Severe: Count, -5.78; 95% CI, -8.13- -3.43, respectively). We observed no significant association between moderate or severe disasters in relation to pharmacies. (Table 3)

4. Discussion

This study describes changes in healthcare availability associated with climate-related disasters across the contiguous US between 2000 and 2014. Few prior studies have evaluated post-disaster changes in different types of healthcare facilities at the national level.

Our research found that over the 15-year period, counties that always lacked access to healthcare services or lost their facilities were more likely to have high poverty levels and racial segregation. Especially in rural areas, the closure of healthcare facilities often worsens economic instability [24–26]. As care is delayed, chronic conditions like cardiovascular disease and cognitive decline become more difficult to manage [5,27–29]. On the other hand, counties that gained or maintained their facilities were predominantly non-Hispanic White and had higher education levels. These communities often have economic and political influence that enable them to secure resources/policies that maintain their healthcare infrastructure. ([25], [30–32]). Interestingly, we observed that among all categories of facilities, pharmacies experienced the most stability during the period. Prior work supports that despite the reported overall growth of pharmacies in the US between 2007 and 2015, the number of them per capita remain relatively unchanged [33]. However, variation was found across counties with areas experiencing greater access to pharmacies than others, widening disparities to medication access and adherence [33].

The association between disasters and changes in availability of healthcare facilities also varies by the intensity of disaster and the category of healthcare facility. Counties that experienced a loss of healthcare facilities across all types from 2000-2014 also experienced the greatest increase in moderate and severe climate-related disasters. Even after adjusting for potential confounders, a significant decrease in healthcare facilities -- particularly hospitals and ambulatory care– was observed in these counties following each *severe* climate-related disaster. As the severity of Hurricane Katrina demonstrated, many facilities were either not rebuilt or their services reduced, leading to disruptions to necessary medical care [34].

Rebuilding facilities after severe climate-related disasters is further complicated by financial constraints and coordination among governmental agencies [35]. In low-income communities and

communities of color, recovery efforts are often systematically excluded from access to rebuilding resources [36]. Thus, among communities that are already afflicted with pre-existing healthcare accessibility challenges, the destructive impact of disasters may widen existing disparities [37–39]. A study among Hurricane Ike survivors found that those with a lower annual income and a high school degree or equivalent were more likely to experience depression post-climate-related disaster compared to wealthier, more educated survivors [7,8]. In another case, the aftermath of Hurricane Katrina led to disruptions to access to care for those with chronic diseases. Medical records were lost due to water damage, and one of the most frequently cited challenge was medication procurement, specifically its availability, due to the spike in demand post-disaster [40].

In contrast to our finding with severe disasters, moderate disasters were associated with a significant increase in hospitals and ambulatory care throughout the time period. This idea fits the notion that disasters can, in some cases, lead to (possibly unequal) redevelopment [41–43]. Moderate disasters may provide governing agencies with an opportunity to learn and develop policies that prioritize investment in and the construction of resilient infrastructure, proactively addressing the risks of future, more severe climate-related events. For instance, traditional "build-back-better" efforts and disaster response protocols often leave communities vulnerable to future hazards due to the tendency to rebuild to prior, inadequate engineering standards [44–46]. Novel initiatives, like Alternative Project Delivery Methods, a process involving earlier collaboration between designers and contractors, can leverage stakeholders in the community to develop more robust and resilient infrastructure reconstruction [47].

Finally, we observed the absence of an association between the presence of pharmacies and moderate or severe disasters over time. We presume that the absence is largely due to the already existing low number of pharmacies within parts of the US, termed "pharmacy deserts" [48,49]. Especially as online pharmacies become more prevalent, communities become increasingly reliant on delivery infrastructure rather than the physical presence of pharmacies. The frequent closures over the past decade driven by the growing role of pharmacy benefit managers (PBMs), have also reduced access, leading to poorer health outcomes and increased costs from hospitalizations and emergency room visits [50,51]. Therefore, the shifting dynamics of pharmacy accessibility demonstrate nuances in how healthcare systems are impacted by disasters, influencing health outcomes and community recovery.

Strengths and Limitations

This study utilized a longitudinal dataset to analyze healthcare infrastructure in association with climate-related disasters. Linking four national datasets consisting of demographic, social stratification, healthcare infrastructure, and climate-related disaster events between 2000 to 2014, the findings provide relevant information to inform the development of resilient communities with robust healthcare infrastructure.

There are some limitations within this study. First, data licensing agreements limited the healthcare infrastructure data available after 2014. However, the relations we examined between disaster and access to healthcare infrastructure may be conservative given the increasing intensifying effect of climate-related disasters [52–54]. Second, our operationalization of demographic, healthcare infrastructure, or climate-related disaster variables may have resulted in misclassification. However, we used datasets and variables that have been validated in previous research [21,55–58]. Third, there may be unmeasured confounders that we did not account for with our autoregressive model such as the effects of systemic racism along with preexisting geographic vulnerability. For example, historical redlining is associated with communities having poor health outcomes lacking access to healthcare facilities from practices like the systemic closures of hospitals or the inaccessibility of pharmacies [59–61]. Such communities are often located in areas prone to flooding or other environmental hazards [62,63]. As a result, delayed or even absent recovery efforts can further discourage trust in the medical system and potentially delay necessary medical care [64,65]. Controlling for or exploring these effects

may involve incorporating redlining maps and additional geospatial data and is a focus for future research. Fourth, counties are heterogenous. While we studied effects at the county level due to data limitations from SHELDUS™, there may be inter- and intra-county differences in SES and healthcare facility disaster impact that we could not capture. A more detailed analysis, however, is beyond the scope of this study.

5. Conclusion

Our findings describe the differential impact of climate-related disasters on disruptions to healthcare facilities in the contiguous US. Hospital and ambulatory care are less accessible in counties that experienced greater number of severe climate related disasters. Given the US' diversity in geography, population, and policy, it is important to examine the factors that influence how communities respond and recover from disaster. Developing innovative strategies to enhance resilience within healthcare infrastructure can protect public health and reduce healthcare disparities during increasingly severe disasters.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author(s).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters. Secondary NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters 2024. https://www.ncei.noaa.gov/access/billions/.
2. Prüss-Üstün A, Wolf J, Corvalán C, Bos R, Neira M. *Preventing disease through healthy environments: a global assessment of the burden of disease from environmental risks*: World Health Organization, 2016.
3. Centers for Disease Control and Prevention. Guidance for Reopening Healthcare Facilities After Water and Wind Damage. Updated October 24 AN, 2024. https://www.cdc.gov/infection-control/hcp/reopen-health-facilities/water-wind-damage.html.
4. Baum A, Barnett ML, Wisnivesky J, Schwartz MD. Association Between a Temporary Reduction in Access to Health Care and Long-term Changes in Hypertension Control Among Veterans After a Natural Disaster. JAMA Netw Open 2019;**2**(11):e1915111 doi: 10.1001/jamanetworkopen.2019.15111 [published Online First: 20191101].

5. Mokdad AH, Mensah GA, Posner SF, Reed E, Simoes EJ, Engelgau MM. When chronic conditions become acute: prevention and control of chronic diseases and adverse health outcomes during natural disasters. Prev Chronic Dis 2005;**2 Spec no**(Spec No):A04 [published Online First: 20051101].

6. Hikichi H, Tsuboya T, Aida J, et al. Social capital and cognitive decline in the aftermath of a natural disaster: a natural experiment from the 2011 Great East Japan Earthquake and Tsunami. The Lancet Planetary Health 2017;**1**(3):e105-e13 doi: 10.1016/S2542-5196(17)30041-4.

7. Fothergill A, Peek LA. Poverty and Disasters in the United States: A Review of Recent Sociological Findings. Natural Hazards 2004;**32**(1):89-110 doi: 10.1023/b:nhaz.0000026792.76181.d9.

8. Tracy M, Norris FH, Galea S. Differences in the determinants of posttraumatic stress disorder and depression after a mass traumatic event. Depress Anxiety 2011;**28**(8):666-75 doi: 10.1002/da.20838 [published Online First: 20110526].

9. Bell SA, Klasa K, Iwashyna TJ, Norton EC, Davis MA. Long-term healthcare provider availability following large-scale hurricanes: A difference-in-differences study. PLoS One 2020;**15**(11):e0242823 doi: 10.1371/journal.pone.0242823 [published Online First: 20201124].

10. Chambers KA, Husain I, Chathampally Y, et al. Impact of Hurricane Harvey on Healthcare Utilization and Emergency Department Operations. West J Emerg Med 2020;**21**(3):586-94 doi: 10.5811/westjem.2020.1.41055 [published Online First: 20200413].

11. Davidow AL, Thomas P, Kim S, Passannante M, Tsai S, Tan C. Access to Care in the Wake of Hurricane Sandy, New Jersey, 2012. Disaster Med Public Health Prep 2016;**10**(3):485-91 doi: 10.1017/dmp.2016.79.

12. Stehling-Ariza T, Park YS, Sury JJ, Abramson D. Measuring the impact of Hurricane Katrina on access to a personal healthcare provider: the use of the National Survey of Children's Health for an external comparison group. Matern Child Health J 2012;**16 Suppl 1**:S170-7 doi: 10.1007/s10995-012-1006-y.

13. Davis JR, Wilson S, Brock-Martin A, Glover S, Svendsen ER. The Impact of Disasters on Populations With Health and Health Care Disparities. Disaster Medicine and Public Health Preparedness 2010;**4**(1):30-38 doi: 10.1017/s1935789300002391.

14. Walls D. National establishment time-series (NETS) database: 2013 database description. 2015. Denver C.

15. Hirsch JA, Moore KA, Cahill J, et al. Business Data Categorization and Refinement for Application in Longitudinal Neighborhood Health Research: a Methodology. J Urban Health 2021;**98**(2):271-84 doi: 10.1007/s11524-020-00482-2 [published Online First: 20201001].

16. CEMHS SHEaLDftUS, Version 22.0. [Online Database]. Phoenix, AZ: Center for Emergency Management and Homeland Security, Arizona State University.

17. Schultz J, Elliott JR. Natural disasters and local demographic change in the United States. Population and Environment 2013;**34**:293-312.

18. Borden KA, Cutter SL. Spatial patterns of natural hazards mortality in the United States. Int J Health Geogr 2008;**7**:64 doi: 10.1186/1476-072X-7-64 [published Online First: 20081217].

19. Gall M, Borden KA, Emrich CT, Cutter SL. The Unsustainable Trend of Natural Hazard Losses in the United States. Sustainability 2011;**3**(11):2157-81 doi: 10.3390/su3112157.

20. Michael YL, Smiley KT, Clay L, Hirsch JA, Lovasi GS. Uneven Growth in Social Capital Organizations After Disasters by Pre-Disaster Conditions in the United States 2000–2014. *Disaster Med. Public Health Prep.* 2023;**17**:1-8 doi: 10.1017/dmp.2022.230.

21. Krieger N WP, Chen JT, Rehkopf DH, Subramanian SV. Boston, MA: Harvard School of Public Health; Geocoding and monitoring US socioeconomic inequalities in health: an introduction to using area-based socioeconomic measures—The Public Health Disparities Geocoding Project monograph. Available at: http://www.hsph.harvard.edu/thegeocodingproject. Accessed December 6, 2023. .

22. Logan JR XZ, Stults B. Interpolating US decennial census tract data from as early as 1970 to 2010: a longitudinal tract database. Prof Geogr. 2012;66(3):412-420. doi:10.1080/00330124.2014.905156.

23. Yabe T, Tsubouchi K, Fujiwara N, Sekimoto Y, Ukkusuri SV. Understanding post-disaster population recovery patterns. Journal of The Royal Society Interface 2020;**17**(163):20190532 doi: 10.1098/rsif.2019.0532.

24. U.S. Government Accountability Office. Rural Hospital Closures: Affected Residents Had Reduced Access to Health Care Services. GAO-21-93. Published December 22 AN, 2024. https://www.gao.gov/assets/gao-21-93.pdf.

25. Kaufman BG, Thomas SR, Randolph RK, et al. The Rising Rate of Rural Hospital Closures. J Rural Health 2016;**32**(1):35-43 doi: 10.1111/jrh.12128 [published Online First: 20150714].

26. McCarthy S, Moore D, Smedley WA, et al. Impact of Rural Hospital Closures on Health-Care Access. J Surg Res 2021;**258**:170-78 doi: 10.1016/j.jss.2020.08.055 [published Online First: 20201001].

27. Wald A. Emergency department visits and costs for heat-related illness due to extreme heat or heat waves in the United States: an integrated review. Nursing Economics 2019;**37**(1):35-48.

28. U.S. Environmental Protection Agency. Climate Change Impacts on Health: Environmental Justice and Equity. EPA. Published 2023. Accessed November 8 Afhwe. Secondary.

29. Arrieta M, Foreman R, Crook E, et al. A network approach to facilitating continuity of care for patients with chronic diseases in the aftermath of a natural disaster. Mobile, AL: Center for Healthy Communities Research Office, University of South Alabama 2007.

30. Guo J, Dickson S, Berenbrok LA, Tang S, Essien UR, Hernandez I. Racial disparities in access to health care infrastructure across US counties: A geographic information systems analysis. Front Public Health 2023;**11**:897007 doi: 10.3389/fpubh.2023.897007 [published Online First: 20230411].

31. Caldwell JT, Ford CL, Wallace SP, Wang MC, Takahashi LM. Racial and ethnic residential segregation and access to health care in rural areas. Health & Place 2017;**43**:104-12 doi: 10.1016/j.healthplace.2016.11.015.

32. Muñoz C, Tate E. Unequal Recovery? Federal Resource Distribution after a Midwest Flood Disaster. International Journal of Environmental Research and Public Health 2016;**13**(5):507 doi: 10.3390/ijerph13050507.

33. Qato DM, Zenk S, Wilder J, Harrington R, Gaskin D, Alexander GC. The availability of pharmacies in the United States: 2007-2015. PLoS One 2017;**12**(8):e0183172 doi: 10.1371/journal.pone.0183172 [published Online First: 20170816].

34. Griffies WS. Health Care Infrastructure Post-Katrina: Disaster Planning to Return Health Care Workers to Their Home Communities. Psychiatric Services 2010;**61**(1):70-73 doi: 10.1176/ps.2010.61.1.70.

35. Vigdor J. The Economic Aftermath of Hurricane Katrina. Journal of Economic Perspectives 2008;**22**(4):135–54 doi: 10.1257/jep.22.4.135.

36. Ferreira R, Davidson T, Buttell F, et al. Barriers to equitable disaster recovery: A scoping literature review. International Journal of Disaster Risk Reduction 2024;**110**:104628 doi: 10.1016/j.ijdrr.2024.104628.

37. Stough LM, Sharp AN, Resch JA, Decker C, Wilker N. Barriers to the long-term recovery of individuals with disabilities following a disaster. Disasters 2016;**40**(3):387-410 doi: 10.1111/disa.12161 [published Online First: 20151117].

38. Policy BoHS, Health CoP-DRoaCsP, Medical, Services S. Healthy, resilient, and sustainable communities after disasters: strategies, opportunities, and planning for recovery. 2015.

39. Straker H, Finister S. Not business as usual. Journal of Health Care for the Poor and Underserved 2007;**18**(2):241-45.

40. Arrieta MI, Foreman RD, Crook ED, Icenogle ML. Providing continuity of care for chronic diseases in the aftermath of Katrina: from field experience to policy recommendations. Disaster Med Public Health Prep 2009;**3**(3):174-82 doi: 10.1097/DMP.0b013e3181b66ae4.

41. Elliott JR, Clement MT. Natural Hazards and Local Development: The Successive Nature of Landscape Transformation in the United States. Social Forces 2017;**96**(2):851-76 doi: 10.1093/sf/sox054.

42. Fox Gotham K, Greenberg M. *Crisis Cities: Disaster and Redevelopment in New York and New Orleans*: Oxford University Press, 2014.

43. Pais JF, Elliott JR. Places as Recovery Machines: Vulnerability and Neighborhood Change After Major Hurricanes. Social Forces 2008;**86**(4):1415-53 doi: 10.1353/sof.0.0047.

44. Hayes S, Desha C, Burke M, Gibbs M, Chester M. Leveraging socio-ecological resilience theory to build climate resilience in transport infrastructure. Transport Reviews 2019;**39**(5):677-99.

45. Ingram JC, Franco G, Rumbaitis-del Rio C, Khazai B. Post-disaster recovery dilemmas: challenges in balancing short-term and long-term needs for vulnerability reduction. Environmental science & policy 2006;**9**(7-8):607-13.

46. Comfort LK. Risk, security, and disaster management. Annu. Rev. Polit. Sci. 2005;**8**(1):335-56.

47. Chester M, El Asmar M, Hayes S, Desha C. Post-Disaster Infrastructure Delivery for Resilience. Sustainability 2021;**13**(6):3458.

48. Guadamuz JS, Alexander GC, Zenk SN, Kanter GP, Wilder JR, Qato DM. Access to pharmacies and pharmacy services in New York City, Los Angeles, Chicago, and Houston, 2015-2020. J Am Pharm Assoc (2003) 2021;**61**(6):e32-e41 doi: 10.1016/j.japh.2021.07.009 [published Online First: 20210719].

49. Guadamuz JS, Wilder JR, Mouslim MC, Zenk SN, Alexander GC, Qato DM. Fewer Pharmacies In Black And Hispanic/Latino Neighborhoods Compared With White Or Diverse Neighborhoods, 2007-15. Health Aff (Millwood) 2021;**40**(5):802-11 doi: 10.1377/hlthaff.2020.01699.

50. University of California BSoPHNirphcsBPHPS, 2022. Accessed January 7, 2025. https://publichealth.berkeley.edu/news-media/research-highlights/nearly-1-in-3-retail-pharmacies-have-closed-since-2010. Secondary.

51. Qato DM, Alexander GC, Chakraborty A, Guadamuz JS, Jackson JW. Association Between Pharmacy Closures and Adherence to Cardiovascular Medications Among Older US Adults. JAMA Netw Open 2019;**2**(4):e192606 doi: 10.1001/jamanetworkopen.2019.2606 [published Online First: 20190405].

52. Smith AB. 2023: A historic year of U.S. billion-dollar weather and climate disasters. NOAA Climate.gov. January 8 AN, 2024. https://www.climate.gov/news-features/blogs/beyond-data/2023-historic-year-us-billion-dollar-weather-and-climate-disasters.

53. Bhatia KT, Vecchi GA, Knutson TR, et al. Recent increases in tropical cyclone intensification rates. Nature Communications 2019;**10**(1) doi: 10.1038/s41467-019-08471-z.

54. Alfieri L, Bisselink B, Dottori F, et al. Global projections of river flood risk in a warmer world. Earth's Future 2017;**5**(2):171-82 doi: 10.1002/2016ef000485.

55. Smiley KT, Howell J, Elliott JR. Disasters, local organizations, and poverty in the USA, 1998 to 2015. Population and Environment 2018;**40**(2):115-35 doi: 10.1007/s11111-018-0304-8.

56. Tsui J, Hirsch JA, Bayer FJ, et al. Patterns in Geographic Access to Health Care Facilities Across Neighborhoods in the United States Based on Data From the National Establishment Time-Series Between 2000 and 2014. JAMA Netw Open 2020;**3**(5):e205105 doi: 10.1001/jamanetworkopen.2020.5105 [published Online First: 20200501].

57. Howell J, Elliott JR. Damages done: The longitudinal impacts of natural hazards on wealth inequality in the United States. Social problems 2019;**66**(3):448-67.

58. Krieger N, Waterman PD, Spasojevic J, Li W, Maduro G, Van Wye G. Public Health Monitoring of Privilege and Deprivation With the Index of Concentration at the Extremes. Am J Public Health 2016;**106**(2):256-63 doi: 10.2105/AJPH.2015.302955 [published Online First: 20151221].

59. Appolon G, Tang S, Gabriel N, et al. Association Between Redlining and Spatial Access to Pharmacies. JAMA Network Open 2023;**6**(8):e2327315 doi: 10.1001/jamanetworkopen.2023.27315.

60. Nardone A, Chiang J, Corburn J. Historic Redlining and Urban Health Today in U.S. Cities. Environmental Justice 2020;**13**(4):109-19 doi: 10.1089/env.2020.0011.

61. King CJ, Buckley BO, Maheshwari R, Griffith DM. Race, Place, And Structural Racism: A Review Of Health And History In Washington, D.C. Health Aff (Millwood) 2022;**41**(2):273-80 doi: 10.1377/hlthaff.2021.01805.

62. Berberian AG, Gonzalez DJX, Cushing LJ. Racial Disparities in Climate Change-Related Health Effects in the United States. Current Environmental Health Reports 2022;**9**(3):451-64 doi: 10.1007/s40572-022-00360-w.

63. Gutierrez KS, LePrevost CE. Climate justice in rural southeastern United States: a review of climate change impacts and effects on human health. International journal of environmental research and public health 2016;**13**(2):189.

64. LaVeist TA, Isaac LA, Williams KP. Mistrust of health care organizations is associated with underutilization of health services. Health services research 2009;**44**(6):2093-105.

65. Raker EJ, Arcaya MC, Lowe SR, Zacher M, Rhodes J, Waters MC. Mitigating Health Disparities After Natural Disasters: Lessons From The RISK Project. Health Affairs 2020;**39**(12):2128-35 doi: 10.1377/hlthaff.2020.01161.

13