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Extreme Weather Events and Pandemic Threats: Analyzing the Health Impacts of Multiple Disaster Events in Puerto Rico

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Abstract

Objective: The increasing frequency and severity of climate-related disasters pose major threats to public health, particularly when they intersect with other crises like pandemics. Puerto Rico has faced multiple large-scale disasters in recent years, yet research on their cumulative health effects remains limited. This study examines associations between disaster exposure—Hurricane María and the COVID-19 pandemic—and self-reported physical, mental, and behavioral health among Puerto Rican adults using Behavioral Risk Factor Surveillance System data (2015-2021).
Methods: We used multivariable linear and log-binomial models, adjusting for key socio-demographic factors.
Results: Among 35,517 respondents, post-disaster periods were mostly linked to worse health outcomes, including more days of poor mental health, increased substance use, and more negative health perceptions. The early post-hurricane period showed the greatest harm, with participants reporting 2.47 more poor mental health days ($P < 0.002$), lower likelihood of exercise (PR = 0.65), and higher likelihood of smoking (PR = 1.20). Conversely, early and late pandemic periods showed apparent health improvements, though these findings require cautious interpretation.
Conclusions: Our results underscore the need for disaster-responsive mental health care, resilient infrastructure, and policies addressing financial inequities that heighten vulnerability. Strengthening community networks and ensuring equitable preparedness and relief efforts are essential to reducing the health impacts of future disasters.

Introduction

Over the past century, scientists, advocates, and policymakers have warned of the dangers posed by climate change to human life—an alarm that the public health community has more recently amplified by declaring the climate crisis an urgent public health emergency.[1–3] Climate change threatens health through diverse pathways—including extreme weather, disruptions to food and water systems, shifts in infectious disease patterns, and forced migration—while also increasing the frequency and severity of disasters such as hurricanes, floods, and wildfires, compounding health risks for vulnerable populations.[2–4]

Disasters can disrupt physiological functioning and exacerbate underlying health conditions, often through exposure to environmental hazards and infrastructure breakdowns. Respiratory illness, infectious disease outbreaks, and cardiovascular complications are common, particularly in the aftermath of events like Hurricane Katrina, where flood-related mold, dust, and debris were linked to widespread respiratory symptoms.[5,6] Other disasters have similarly damaged vital public health infrastructure—including food systems, electricity, sanitation, housing, and medical care—severing access to essential services and heightening the risk of illness and death.[7–9] In addition to physiologic harm, disasters often leave a profound psychological imprint, triggering mental and behavioral health challenges related to their disruptive, life-threatening, and traumatic nature. Although many individuals demonstrate resilience, research shows an elevated risk of psychological distress, including PTSD, depression, and substance use disorders.[10–12]

Despite growing recognition of these threats, critical gaps remain in understanding how climate-related disasters impact health outcomes across diverse populations. Currently, much of the existing literature focuses on a limited set of widely recognized events—such as Hurricane Katrina, 9/11, and COVID-19—leaving many individual and successive disaster events understudied.[13–15]

As climate change intensifies, the likelihood of multiple disasters occurring in close succession or overlapping increases—making it essential to understand how these converging events impact

health across diverse populations to craft targeted mitigation strategies and strengthen population resilience. While a few studies have documented some increases in substance misuse following disaster exposure in the general population, they report more substantial increases among individuals with a prior history of substance use or those who developed other mental health conditions after the event.[16,17] However, the compounded impact of multiple disasters on substance use disorders remains understudied, highlighting the need for further research into the long-term behavioral health consequences. A recent scoping review further emphasizes this concern, showing that exposure to multiple disasters can negatively affect both mental and physical health. Researchers conducting this analysis found that the cumulative risks associated with successive disasters may exceed those of singular events.[18] Particularly, emerging studies indicate that repeated climate-related disasters compound psychological distress, with ongoing exposure worsening mental health outcomes over time.[19] One recent longitudinal study reported heightened levels of stress, anxiety, and depressive symptoms among individuals affected by multiple disasters—suggesting that successive exposure intensifies mental health burdens rather than allowing for adaptation.[19] These findings reinforce the need to examine how populations facing recurrent disasters, such as those in Puerto Rico, experience long-term health consequences and whether existing response strategies adequately address these challenges.

As a U.S. territory with longstanding infrastructural vulnerabilities and unequal disaster-response funding, Puerto Rico offers a critical context for examining how systemic inequities intensify the health impacts of cumulative, successive disaster exposure. Puerto Rico's political and economic context is shaped by its status as a U.S. territory, with residents holding U.S. citizenship but facing longstanding structural limitations in political representation and access to federal resources. This colonial system has been described as a key driver of Puerto Rico's prolonged financial recession and related outcomes, leaving the island particularly vulnerable to disasters.[20,21] Understanding these dynamics is vital for informing response strategies that address social and structural determinants of resilience. Yet major knowledge gaps persist—particularly in clarifying epidemiologic pathways, quantifying health impacts, and assessing effect modification across populations. These gaps are especially acute in settings like Puerto Rico, where recurrent and overlapping disasters have deepened existing vulnerabilities. Most research to date has focused on singular disaster events, limiting insight into the cumulative toll of prolonged exposure. Additionally, few studies have fully explored how social determinants—such as pre-existing health disparities, colonial governance, and unequal access to resources—shape recovery and long-term health outcomes. Filling these gaps is essential for advancing targeted preparedness strategies, equitable resource distribution, and more inclusive recovery planning.

This study contributes to this growing body of research by examining the physical, mental, and behavioral health impacts of multiple disaster exposures on residents of Puerto Rico. Using data from 2015 to 2022, we aim to describe the relationship between disaster exposure and self-reported health outcomes and assess potential effect modifiers, including **sex, income, education, and employment status**. By incorporating these factors, our study seeks to provide a more nuanced understanding of disaster-related health disparities and inform strategies for reducing long-term health burdens.

Materials and Methods

Data Source

This study draws on data from the Behavioral Risk Factor Surveillance System (BRFSS), a nationwide health survey conducted by the U.S. Centers for Disease Control and Prevention (CDC) that uses random-digit dialing of landlines and cell phones across all U.S. states and territories.[22] We used a repeated cross-sectional design with data from 2015 to 2021, covering responses collected between January 1, 2015, and March 15, 2022. The analytic sample was restricted to adult respondents from Puerto Rico; all others were excluded. Data collection in Puerto Rico was conducted in Spanish. Analyses were conducted using SAS OnDemand for Academics, with BRFSS survey weights applied to account for the complex sampling design and ensure consistency across survey years.

Weighting

To improve representativeness, BRFSS applies sampling weights that adjust for selection probability, non-response, and coverage errors.[22] These weights incorporate geographic strata, household phone type, and the number of adults per household. BRFSS uses ranking—a post-stratification method—to align sample demographics with the broader population.[23] For this study, weights were applied to all analyses to ensure estimates accurately reflect the adult population in Puerto Rico.

Exposure Measurement

Disaster exposure was classified based on interview dates relative to major events in Puerto Rico. Because BRFSS lacks geographic detail, we focused on island-wide disasters: Hurricane María (September 20, 2017) and the COVID-19 pandemic. We defined 5 disaster periods: pre-disaster (referent), early post-hurricane (0-6 months), late post-hurricane (6+ months until March 11, 2020), early pandemic (March 12, 2020-April 14, 2021, pre-vaccine), and late pandemic (April 15, 2021, onward). These periods reflect key phases of disaster impact and recovery, with the early post-hurricane phase marked by severe service disruptions and psychological distress.[24,25] Additionally, Hurricane Irma occurred approximately 2 weeks before Hurricane María and caused localized disruptions in parts of Puerto Rico. However, Hurricane María was the primary driver of widespread infrastructure failure across the island, and the post-hurricane period reflects the population-level impacts following María within the context of sequential storm events. Moreover, the late post-hurricane period overlaps with the known 2019-2020 earthquake sequence in Puerto Rico. Due to the lack of geographic identifiers in BRFSS data, it was not possible to distinguish individuals directly affected by the earthquakes or to isolate earthquake-related impacts. Since the earthquakes were geographically concentrated, with the most severe effects in the island's southwestern region, they did not have the same widespread impact as the pandemic or the hurricane. Therefore, defining a distinct earthquake exposure period at the population level could introduce substantial exposure misclassification. Given these constraints, the defined time periods reflect broader island-wide phases of disruption, although estimates from this period may capture overlapping influences from multiple events. Due to the cross-sectional nature of BRFSS data, cumulative exposure to multiple disasters could not be directly measured at the individual level. Instead, disaster exposure was operationalized using mutually exclusive time periods corresponding to key phases following the hurricane and during the COVID-19 pandemic.

Outcome Variables of Interest

Due to limitations in the BRFSS dataset—including the absence of diagnosis dates and potential issues with temporality—we analyzed

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self-reported health measures rather than clinical diagnoses. To reduce bias, we focused on 3 outcome categories: (1) self-reported days of poor physical and mental health in the past 30 days, (2) self-perceived general health status, and (3) health-related behaviors. The first category was assessed using questions that asked how many days in the past 30 participants experienced poor physical or mental health, with responses ranging from 0 to 30. The second question asked participants to rate their general health on a 5-point scale; for analysis, responses were dichotomized into positive (excellent to good) vs. negative (fair or poor) health perception. The third category included smoking (current vs. non-smokers), alcohol use (any drinking and binge drinking in the past 30 days), and physical activity (any exercise outside of work in the past 30 days). Specific outcome selection was guided by the availability and consistency of BRFSS variables across survey years in Puerto Rico. Variables such as nutrition, food insecurity, and sleep were considered but were not consistently collected across the study period and were therefore excluded to preserve comparability across time.

Covariates

Age, sex, income, education, marital status, and employment status were included as covariates in our regression models. These variables were selected based on epidemiologic principles, where we included variables that may confound the relationship between disaster exposure (as proxied by time period) and health outcomes. These methodological and theoretical decisions were informed by prior research and population characteristics. Specific covariate categories are presented in Table 1.

Analytic Approach

We calculated descriptive statistics for all outcome variables and covariates, reporting categorical variables as frequencies and percentages, and continuous variables as means with standard deviations. The study hypotheses were developed before data analysis as part of the first author's doctoral dissertation proposal. They were informed by existing literature on disaster-related health impacts in Puerto Rico and globally. Health outcomes were initially examined across disaster periods without adjustment. To assess associations between disaster periods and self-reported health, we used multivariable linear regression for continuous outcomes (e.g., days of poor health) and log-binomial models for categorical outcomes (e.g., health perception and behaviors), adjusting for relevant covariates. Effect modification was tested across sex, income, education, and employment, using the most socioeconomically advantaged group as the reference (men, highest income/education, employed). Missing data were assessed, and multiple imputation was applied for variables with >10% missingness to reduce bias. All analyses incorporated BRFSS sampling weights and were conducted in SAS OnDemand for Academics using PROC SURVEY procedures to account for the complex survey design. Statistical significance was set at $P < 0.05$, but findings were interpreted in light of both significance and the direction and magnitude of associations.[26] The disaster periods analyzed in this paper are based on publicly available information and BRFSS data which are publicly available. Code used to model and clean data is available from the corresponding author on reasonable request.

Ethical Approval

This study was deemed exempt by the University of Michigan's Institutional Review Board (HUM00230376), as it relied on publicly available datasets that do not contain sensitive or identifiable participant information.

Results

The dataset includes 35,517 BRFSS participants from Puerto Rico (2015-2022). Most respondents were women (53.2%), over 45 years old (49.0%), employed (42.0%), married/partnered (45.6%), had some college education (48.1%), and earned <$25,000 annually (74.2%). Most identified as non-smokers (90.0%), reported good health (67.0%), did not consume alcohol (69.9%), and did not binge drink (87.1%). On average, participants experienced 4.8 days of poor physical health and 3.7 days of poor mental health in the past 30 days. Due to 18.4% missing income data (18-22% across disaster periods), multiple imputation was used in the regression models. Complete-case analyses yielded similar results (data not shown).

Main Effects: Days of Poor Health

Disaster periods were linked to variations in self-reported poor health (Table 2). The early post-hurricane period was associated with 2.47 additional days of poor mental health and 0.80 additional days of poor physical health, while the late post-hurricane period was associated with 1.17 additional days of poor physical health. In contrast, both pandemic periods saw reductions in poor health days: early-pandemic participants reported 0.55 fewer days of poor mental health and 0.72 fewer days of poor physical health; the late-pandemic period showed a similar but weaker trend.

Main Effects: Current General Health Status and Health-Modifying Behaviors

Self-reported negative general health perceptions increased in the early (prevalence ratio (PR) = 1.32) and late (PR = 1.18) post-hurricane periods but decreased during the early (PR = 0.73) and late (PR = 0.76) pandemic periods. The early post-hurricane period saw declines in exercise (PR = 0.65), increased smoking (PR = 1.20), and a slight rise in alcohol consumption (PR = 1.06). The late post-hurricane period showed minimal behavioral changes. Conversely, the early and late pandemic periods were associated with increased exercise (PR = 1.15 and PR = 1.14, respectively), reduced smoking (PR = 0.88), and lower binge drinking (PR = 0.91).

Effect Modification: Days of Poor Health

Modification effects varied by sociodemographic factors (Table 3). Women experienced more poor mental health days during the early (0.43) and late (0.53) pandemic but had fewer poor physical health days across all disaster periods. Lower-income participants (<$15K) consistently reported more days of poor mental and physical health, particularly in the early post-hurricane period (1.24 days) and the early pandemic period (0.80 days). The $15K-$25K income group showed similar trends. Lower education levels were also associated with more poor health days, with the strongest association observed among those with some college education during the early post-hurricane period (1.83 days). Employment status effects were mixed. Unemployed participants had more poor physical health days in the early pandemic (0.78 days), while those unable to work reported worse physical health during the early (4.36 days) and late (1.59 days) post-hurricane periods. Homemakers had higher poor health days in the late pandemic (1.45 mental; 0.94 physical).

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Table 1. Weighted sociodemographic characteristics and distribution of key covariates by disaster period. Behavioral Risk Factor Surveillance System. Respondents from Puerto Rico, 2017–2022

	Pre-disaster	Early post-hurricane	Late post-hurricane	Early pandemic	Late pandemic	*P* value*
	n = 14,837	*n* = 1,083	*n* = 10,533	*n* = 5,055	*n* = 4,009	
Age groups						<0.0001
18–24	13.1%	13.0%	12.5%	12.6%	12.7%	
25–34	16.4%	17.7%	16.1%	15.9%	15.8%	
35–44	16.2%	20.1%	16.1%	16.0%	16.1%	
45–54	16.7%	19.6%	16.6%	16.7%	16.6%	
55–64	15.8%	14.1%	15.8%	15.8%	15.8%	
65+	21.7%	15.5%	23.0%	23.0%	23.0%	
Income						<0.0001
<15k	49.9%	41.4%	43.2%	42.8%	38.1%	
15k–25k	28.8%	30.9%	30.2%	30.0%	26.4%	
25k–35k	9.0%	11.7%	10.5%	9.3%	12.3%	
35k–50k	6.2%	5.9%	7.1%	7.4%	10.5%	
>50k	6.1%	10.3%	9.0%	10.5%	12.8%	
Sex						<0.0001
Female	53.1%	54.6%	53.3%	53.1%	53.4%	
Education						<0.0001
Less than HS	25.9%	18.2%	23.4%	23.6%	23.5%	
HS graduate	27.2%	25.9%	27.9%	27.5%	27.5%	
Some college	25.5%	27.2%	16.5%	16.5%	16.7%	
College grad	21.3%	28.8%	32.2%	32.4%	32.3%	
Children						<0.0001
Has children	28.9%	35.8%	29.9%	27.8%	27.6%	
Marital status						<0.0001
Single	23.9%	20.8%	17.6%	17.2%	16.9%	
Married or living with partner	48.8%	46.8%	42.7%	43.5%	43.8%	
Separated or divorced	18.3%	24.4%	28.5%	29.0%	27.8%	
Widowed	9.0%	8.0%	11.3%	10.3%	11.5%	
Employment status						<0.0001
Employed	36.5	47.0%	44.3%	44.5%	50.1%	
Unemployed	10.9%	8.2%	7.7%	11.2%	6.3%	
Homemaker/Housewife	19.5%	18.8%	16.6%	14.1%	15.0%	
Student	7.2%	6.4%	5.5%	4.5%	4.4%	
Retired	18.6%	13.0%	18.8%	19.6%	16.9%	
Unable to work/Disabled	7.3%	6.5%	7.1%	6.1%	7.5%	

**P* values represent chi-square values for differences between subgroups by disaster periods.

Effect Modification: Current General Health Status and Health-Modifying Behaviors

Sociodemographic factors modified general health and behavior outcomes (Table 4 and Supplemental Table 1). Women showed minimal adverse modification effects but had higher smoking rates in the late post-hurricane period (PR = 1.07) and increased heavy drinking in the early post-hurricane period (PR = 1.12). Lower-income participants reported less exercise, increased smoking, worse general health, and higher drinking levels. Smoking rates were particularly high in the early pandemic period for the <$15K group (PR = 1.28) and in the early post-hurricane period for the $15K-$25K group (PR = 1.48). Heavy drinking was also elevated among the lowest-income group in the early post-hurricane (PR = 1.13) and early pandemic (PR = 1.16). Lower education levels were linked to increased smoking, negative general health perceptions, and heavy drinking. Those without a high school diploma had

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Table 2. Results of multivariate regression models for main outcomes of interest. Behavioral Risk Factor Surveillance System; respondents from Puerto Rico, 2017–2022

Outcome	Disaster period	Estimate
Linear regression models		
Days of poor mental health in the 30 days prior to the interview		β (SE)
	Early post-hurricane	2.47 (0.24)**
	Late post-hurricane	−0.06 (0.08)
	Early pandemic	−0.55 (0.10)**
	Late pandemic	−0.32 (0.11)**
Days of poor physical health in the 30 days prior to the interview		β (SE)
	Early post-hurricane	0.80 (0.19)**
	Late post-hurricane	1.17 (0.08)**
	Early pandemic	−0.72 (0.16)**
	Late pandemic	0.38 (0.14)**
Log-binomial regression models		**Prevalence ratios**
Exercised in the 30 days prior to the interview		*PR (95% CI)*
	Early post-hurricane	0.65 (0.61, 0.70)**
	Late post-hurricane	1.02 (0.99, 1.04)
	Early pandemic	1.15 (1.10, 1.20)**
	Late pandemic	1.14 (1.09, 1.20)**
Smoked in the 30 days prior to the interview		*PR (95% CI)*
	Early post-hurricane	1.20 (1.07, 1.34)**
	Late post-hurricane	0.94 (0.88, 0.99)**
	Early pandemic	0.97 (0.90, 1.05)**
	Late pandemic	0.88 (0.81, 0.95)**
Consumed alcoholic drinks in the 30 days prior to the interview		*PR (95% CI)*
	Early post-hurricane	1.06 (0.98, 1.15)
	Late post-hurricane	1.01 (0.98, 1.13)
	Early pandemic	0.98 (0.93, 1.03)
	Late pandemic	1.02 (0.97, 1.07)
Binge drinking in the 30 days prior to the interview		*PR (95% CI)*
	Early post-hurricane	0.96 (0.85, 1.07)
	Late post-hurricane	1.08 (1.02, 1.14)**
	Early pandemic	1.00 (0.93, 1.08)
	Late pandemic	0.91 (0.84, 0.97)**
Current perception of their health as negative		*PR (95% CI)*
	Early post-hurricane	1.32 (1.22, 1.43)**
	Late post-hurricane	1.18 (1.14, 1.23)**
	Early pandemic	0.73 (0.69, 0.78)**
	Late pandemic	0.76 (0.70, 0.82)**

*All models were controlled for age, income, sex, education, marital status, and employment status. The pre-disaster period was used as the reference point for all analyses.
***P* value < 0.05.

worse general health in the early post-hurricane period (PR = 1.20) and in the early pandemic period (PR = 1.10), while heavy drinking increased during the early pandemic period (PR = 1.27). Employment status yielded varied results. Those unable to work had lower smoking rates in the early post-hurricane (PR = 0.42) but higher rates in the early (PR = 2.08) and late (PR = 1.50) pandemic. They also reported worse general health in the late post-hurricane (PR = 1.16) but better health in the early pandemic (PR = 0.68). Heavy drinking decreased in the early post-hurricane period (PR = 0.23) but increased in the late post-hurricane period (PR = 1.72) and in

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Table 3. Effect modification in linear regression models by outcome and disaster periods. Behavioral Risk Factor Surveillance System; respondents from Puerto Rico, 2017–2022

	Outcomes							
	Mental health				Physical health			
Effect modifier	Early post-hurricane	Late post-hurricane	Early pandemic	Late pandemic	Early post-hurricane	Late post-hurricane	Early pandemic	Late pandemic
Sex	Estimate (days of poor health)				Estimate (days of poor health)			
Male	ref	ref	ref	ref	ref	ref	ref	ref
Female	−0.39	0.00	0.43*	0.53*	−0.95*	−0.14	−0.30	−0.22
Income	Estimate (days of poor health)				Estimate (days of poor health)			
$50k or more	ref	ref	ref	ref	ref	ref	ref	ref
$35k – $50k	−2.28*	−0.13	0.59	−0.76*	−0.23	−0.63*	−0.09	0.25
$25k – $35k	−0.18	−0.36	0.82*	0.16	0.18	−0.36	0.06	−0.02
$15k –$25k	1.18	0.36	0.48	0.17	1.20*	0.53*	0.62	0.38
$15K or less	1.24	0.18	0.80*	0.06	0.36	0.69*	0.66*	1.33*
Education	Estimate (days of poor health)				Estimate (days of poor health)			
College grad	ref	ref	ref	ref	ref	ref	ref	ref
Some college	1.83*	0.17	−0.35	0.85*	0.28	0.71*	0.39	0.34
High school	−1.44*	0.36*	−0.07	0.39	−0.61	0.97*	0.98*	0.49
Less than HS	0.93*	0.00	−0.70*	0.12	1.20*	1.15*	1.79*	0.61
Employment	Estimate (days of poor health)				Estimate (days of poor health)			
Employed	ref	ref	ref	ref	ref	ref	ref	ref
Unemployed	−0.67	0.46	−0.41	−0.19	−2.02*	0.04	0.78*	0.16
Homemaker	0.10	0.32	0.27	1.45*	0.31	0.94*	1.12*	0.97*
Student	−0.50	0.17	0.05	1.92*	0.24	−0.33	0.16	1.72*
Retired	0.67	0.22	0.21	0.39	−0.72	0.54*	1.31*	1.33*
Unable to work	1.56	−1.45*	−1.76*	−1.18	4.36*	1.59*	−1.66*	0.72

*All models were controlled for age, income, sex, education, marital status, and employment status. The pre-disaster period was used as the reference point for all analyses.
**P value < 0.05.

both pandemic periods. Unemployed participants had higher smoking rates in the early (PR = 1.20) and late (PR = 1.18) post-hurricane periods, with increased alcohol consumption during the early post-hurricane (PR = 1.48) and heavy drinking episodes (PR = 2.07). However, drinking declined in the late post-hurricane (PR = 0.89), along with heavy drinking (PR = 0.74).

Discussion

Summary of Research Findings

This study examined the impact of multiple disasters on the physical, mental, and behavioral health of 35,517 Puerto Rican adults (2015-2022 BRFSS). Following Hurricane María, all outcomes—except drinking behaviors—worsened compared to pre-disaster levels. In contrast, post-COVID-19 outcomes showed contrasting patterns, with fewer poor mental health days, reduced heavy drinking (late pandemic), fewer poor physical health days (early pandemic), lower smoking rates (late pandemic), and a more positive perception of their general health as good or excellent. The effects of disaster exposure varied by sex, income, education, and employment, with differences in strength and direction across disasters and outcomes.

Main Discussion and Contextualization of Results

Disaster exposure was associated with more reports of poorer mental health, particularly in the early post-hurricane period, which was associated with 2.47 additional poor mental health days, increased smoking (PR = 1.20), more negative health perceptions (PR = 1.32), and potentially increased alcohol consumption (PR = 1.06). These patterns suggest that stress and anxiety may have driven substance use as a coping mechanism, aligning with prior studies linking disasters to PTSD, depression, and increased substance use.[27] While the adverse effects of disaster exposure were not sustained across all periods, alcohol consumption consistently showed harmful associations. Additionally, sex, income, and education significantly modified the relationship between disaster exposure and mental health and substance use behaviors. Participants with less than a high school education had higher smoking rates post-hurricane, were more likely to drink during the late post-hurricane and early pandemic, and had increased binge drinking in the early pandemic. This suggests that disasters disproportionately impact more vulnerable subgroups, even if they do not lead to widespread mental health crises.

The type of disaster may also influence health behaviors. Notably, the pandemic period was associated with fewer days of poor

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Table 4. Effect modification in log-binomial models by outcome and disaster periods. Behavioral Risk Factor Surveillance System; respondents from Puerto Rico, 2017–2022

	Exercising				Smoking				Negative general health			
Effect modifier	Early post-hurricane	Late post-hurricane	Early pandemic	Late pandemic	Early post-hurricane	Late post-hurricane	Early pandemic	Late pandemic	Early post-hurricane	Late post-hurricane	Early pandemic	Late pandemic
Sex	Prevalence ratio (95% confidence interval)				Prevalence ratio (95% confidence interval)				Prevalence ratio (95% confidence interval)			
Male	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref
Female	1.04 (0.97, 1.12)	1.05 (1.00, 1.10)	0.97 (0.92, 1.01)	0.97 (0.94, 1.00)	0.95 (0.85, 1.07)	1.07 (1.01, 1.13)	1.00 (0.93, 1.08)	0.95 (0.87, 1.03)	0.90 (0.83, 0.98)	0.98 (0.94, 1.02)	1.06 (1.00, 1.14)	1.01 (0.95, 1.07)
Income	Prevalence ratio (95% confidence interval)				Prevalence ratio (95% confidence interval)				Prevalence ratio (95% confidence interval)			
$50k or more	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref
$35k – $50k	0.94 (0.77, 1.16)	1.19 (1.08, 1.31)	0.93 (0.83, 1.05)	0.92 (0.82, 1.05)	0.44 (0.24, 0.80)	1.11 (0.89, 1.39)	1.41 (1.11, 1.80)	1.14 (0.86, 1.51)	0.85 (0.64, 1.13)	0.99 (0.87, 1.13)	0.97 (0.82, 1.15	1.14 (0.96, 1.34)
$25k – $35k	1.04 (0.88, 1.24)	0.89 (0.82, 0.96)	1.06 (0.96, 1.18)	1.02 (0.92, 1.14)	1.09 (0.80, 1.50)	1.05 (0.90, 1.23)	0.70 (0.57, 0.86)	1.08 (0.87, 1.34)	1.39 (1.10, 1.75)	0.98 (0.88, 1.09)	0.97 (0.83, 1.13)	0.86 (0.75, 0.99)
$15k –$25k	0.96 (0.84, 1.09)	0.98 (0.92, 1.04)	1.02 (0.94, 1.10)	0.99 (0.91, 1.08)	1.48 (1.17, 1.87)	0.86 (0.76, 0.96)	0.98 (0.85, 1.12)	0.99 (0.84, 1.16)	1.17 (0.99, 1.37)	1.00 (0.93, 1.07)	1.02 (0.92, 1.14)	0.88 (0.80, 0.98)
$15K or less	1.17 (1.04, 1.32)	0.95 (0.90, 1.01)	0.95 (0.88, 1.03)	0.94 (0.89, 0.99)	1.14 (0.91, 1.43)	0.98 (0.88, 1.08)	1.28 (1.12, 1.46)	0.82 (0.71, 0.95)	1.14 (0.99, 1.33)	0.95 (0.89, 1.02)	1.07 (0.97, 1.18)	0.94 (0.86, 1.03)
Education	Prevalence ratio (95% confidence interval)				Prevalence ratio (95% confidence interval)				Prevalence ratio (95% confidence interval)			
College grad	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref
Some college	0.92 (0.82, 1.04)	1.04 (0.99, 1.11)	0.96 (0.89, 1.03)	1.04 (0.96, 1.13)	1.01 (0.85, 1.22)	0.96 (0.87, 1.05)	0.94 (0.83, 1.06)	1.14 (1.00, 1.31)	0.94 (0.82, 1.08)	1.07 (1.01, 1.15)	0.83 (0.76, 0.91)	1.10 (1.00, 1.20)
High school	0.95 (0.84, 1.08)	0.97 (0.91, 1.02)	1.07 (0.99, 1.15)	1.02 (0.94, 1.10)	0.92 (0.77, 1.10)	0.91 (0.83, 1.00	1.04 (0.91, 1.19)	1.32 (1.15, 1.51)	0.99 (0.86, 1.14)	1.06 (1.00, 1.13)	1.07 (0.97, 1.18)	0.93 (0.85, 1.01)
Less than HS	1.08 (0.93, 1.26)	1.07 (1.00, 1.15)	0.92 (0.83, 1.01)	0.94 (0.85, 1.03)	1.33 (1.08, 1.64)	1.08 (0.97, 1.20)	1.04 (0.90, 1.19)	0.66 (0.57, 0.79)	1.20 (1.01, 1.42)	0.84 (0.78, 0.90)	1.10 (0.98, 1.23)	0.99 (0.89, 1.09)
Employment	Prevalence ratio (95% confidence interval)				Prevalence ratio (95% confidence interval)				Prevalence ratio (95% confidence interval)			
Employed	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref	ref
Unemployed	0.87 (0.70, 1.08)	1.17 (1.05, 1.30)	1.02 (0.89, 1.17)	1.01 (0.87, 1.17)	1.20 (0.89, 1.63)	1.18 (1.00, 1.38)	0.95 (0.77, 1.17)	0.80 (0.63, 1.03)	1.16 (0.90, 1.50)	0.95 (0.84, 1.08)	1.16 (0.98, 1.38)	0.87 (0.72, 1.05)
Homemaker	1.22 (1.04, 1.43)	0.83 (0.77, 0.90)	0.99 (0.88, 1.12)	1.05 (0.93, 1.18)	1.30 (1.00, 1.70)	1.01 (0.87, 1.17)	0.84 (0.68, 1.04)	0.85 (0.68, 1.06)	1.24 (1.04, 1.49)	0.90 (0.82, 0.98)	0.98 (0.86, 1.13)	0.97 (0.85, 1.10)
Student	0.85 (0.65, 1.10)	1.04 (0.91, 1.19)	1.05 (0.87, 1.25)	0.88 (0.71, 1.10)	1.04 (0.59, 1.84)	0.88 (0.66, 1.18)	0.95 (0.65, 1.38)	0.83 (0.53, 1.31)	0.47 (0.29, 0.77)	1.25 (1.02, 1.54)	1.19 (0.88, 1.60)	1.14 (0.83, 1.55)
Retired	1.34 (1.14, 1.57)	0.89 (0.83, 0.96)	0.87 (0.78, 0.98)	1.04 (0.93, 1.15)	1.21 (0.90, 1.61)	1.09 (0.95, 1.25)	0.71 (0.59, 0.86)	1.13 (0.92, 1.39)	1.14 (0.95, 1.36)	0.83 (0.77, 0.90)	1.21 (1.07, 1.39)	1.00 (0.89, 1.13)
Unable to work	0.87 (0.67, 1.13)	1.16 (1.03, 1.30)	0.98 (0.82, 1.18)	1.03 (0.87, 1.21)	0.42 (0.28, 0.64)	0.90 (0.74, 1.08)	2.08 (1.59, 2.72)	1.50 (1.16, 1.93)	1.06 (0.79, 1.41)	1.16 (1.01, 1.33)	0.68 (0.54, 0.85)	1.13 (0.94, 1.37)

*All models were controlled for age, income, sex, education, marital status, and employment status. The pre-disaster period was used as the reference point for all analyses.

mental health and reduced smoking, findings that contradict expectations of worsening health under cumulative stress. Several mechanisms may help explain these patterns. The pandemic, with its respiratory risks, may have deterred smoking and drinking due to concerns over viral complications. In addition, pandemic-related social policies, such as expanded unemployment benefits, economic stimulus payments, and eviction moratoriums, may have provided temporary financial relief that protected against some negative health effects. At the same time, these findings must be interpreted with important threats to validity in mind. Due to the limitations of BRFSS data, which may be sensitive to shifts in respondent profiles during the pandemic, including differential participation among individuals with varying levels of health and socioeconomic stability, selection bias (such as participants with better mental health choosing to answer the survey) could contribute to an apparent improvement in population-level health outcomes. Importantly, these behavioral changes could also reflect structural constraints and shifts in daily life during the pandemic, such as changes in employment, mobility, finances, or access to usual activities, rather than intentional health-promoting choices. Reporting bias may also play a role, since stigma surrounding mental and behavioral health could lead to underreporting, particularly during a period of widespread social disruption.[28–30] Thus, these findings of reduced smoking and better mental health during the pandemic period may reflect a combination of behavioral adaptations, short-term economic supports, and methodological factors. Importantly, prior studies suggest that individuals with greater social vulnerability are more likely to adopt potentially harmful coping strategies post-disaster.[31,32] Further research is needed to disentangle these mechanisms and assess whether these patterns persist over time.

Unlike previous research that consistently reports worsened health post-disaster,[14,33] our study, contrary to hypothesized associations, found variability in self-reported health depending on the type and stage of disaster. Participants were more likely to report worse health after Hurricane María (PR = 1.32) but better health during the pandemic (early: PR = 0.73; late: PR = 0.76). One possible explanation for this perceived improvement during the pandemic is that self-rated health may be influenced by shifting reference points during a widespread crisis. For example, individuals may evaluate their health relative to those who were hospitalized or severely ill with COVID-19. However, we found no existing research directly supporting this interpretation, and it should be considered a hypothesis requiring further investigation. In contrast, Hurricane María caused immediate disruptions in food, water, and medication access, which likely had a more direct and tangible impact on participants' health. This highlights how disaster characteristics influence health outcomes—where slow-moving crises like pandemics may affect perceptions differently than acute disasters like hurricanes.

Income and employment status significantly modified disaster-related health impacts. Lower-income groups had higher smoking rates in the early post-hurricane (PR = 1.14–1.48) and early pandemic (PR = 1.28) compared to higher-income individuals. Similarly, those who were unemployed, retired, or homemakers were significantly more likely to smoke post-hurricane (PR = 1.20-1.38) and drink heavily post-hurricane (PR = 1.48-2.07). These patterns likely reflect a combination of structural and contextual factors. Socioeconomic inequities may have shaped access to essential resources post-disaster, aligning with studies showing how wealthier populations are better equipped to mitigate disaster impacts.[34–36] Previous research suggests that lower-income populations face greater barriers to disaster relief programs, such as delays in Federal Emergency Management Agency (FEMA) aid processing, lower homeownership rates that limit eligibility for rebuilding grants, and inconsistent health care access post-disaster.[37,38] At the same time, differences in daily routines and time spent at home among unemployed, retired, or homemakers may also influence health behaviors, potentially increasing opportunities for substance use due to reduced structure, social isolation, or the absence of workplace constraints. Together, these findings highlight the need to consider both structural inequities and behavioral contexts when interpreting post-disaster health behaviors.

Women reported significantly more poor mental health days in both the early (0.43) and late (0.53) pandemic periods, particularly among homemakers. This aligns with studies showing that women experienced greater burnout and mental distress during COVID-19, likely due to increased caregiving responsibilities.[39–41] Interestingly, women were not consistently more likely to drink, binge drink, or smoke post-disaster, except for increased heavy drinking in the early post-hurricane period. This suggests gender differences in coping mechanisms, warranting further research.

The early post-hurricane period had the most widespread negative health effects, with worsened mental and physical health, reduced exercise, increased smoking and drinking, and more negative health perceptions. While some of these patterns may be attributed to the storm's severity, they may also be shaped by broader structural factors influencing disaster response and recovery. For example, prior research has documented disparities in response time and federal aid allocation between Puerto Rico and U.S. states experiencing similar disasters, such as Hurricanes Harvey and Irma in Texas and Florida.[20,37,42–44] Although our study does not directly assess these structural dynamics, such contextual factors may contribute to differences in recovery trajectories and population health following disasters. Additionally, limitations in public health surveillance infrastructure may further constrain the ability to fully capture these dynamics. For example, BRFSS data collection in Puerto Rico has been inconsistent across years, limiting the availability of key variables (e.g., nutrition and sleep and restricting comparability across time.[45] Together, these factors highlight how broader structural conditions may shape not only disaster recovery, but also the measurement and interpretation of population health outcomes. Further research is needed to better understand how these broader structural conditions (e.g., colonialism and exclusion from health surveillance systems) influence post-disaster health disparities and long-term recovery.

Strengths and Limitations

This study has several strengths. Limited research has examined multiple disaster exposures in epidemiologic literature, making our approach using pre-existing data innovative and valuable. Unlike traditional cross-sectional studies, which struggle with temporal ambiguity, our study mitigates this issue by focusing on participants' health perceptions at the time of the interview and in the 30 days prior. Additionally, given the ethical and logistical challenges of studying disasters through experimental designs, leveraging survey data allows for hypothesis generation that can inform future cohort or case-control studies.

Another key strength is that, given the widespread impact of Hurricane María and the COVID-19 pandemic in Puerto Rico, it is reasonable to assume that most participants interviewed during the designated disaster periods were affected in some capacity. This reduces the risk of significant exposure misclassification, though individual disaster experiences likely varied. Furthermore, using

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BRFSS data allowed for the examination of a broad range of health outcomes, including physical, mental, and behavioral health, providing a comprehensive assessment of disaster-related health effects. Finally, BRFSS is a large, publicly available, and nationally representative dataset with over 300 variables, making it an important tool for exploring disaster-related health patterns and generating hypotheses for future research and policy interventions.

Several limitations should be considered. The study's repeated cross-sectional design does not track individuals over time, preventing direct assessment of long-term health trajectories. While this study is framed within the context of multiple and overlapping disasters, the analytic approach captures population-level health patterns across sequential time periods, rather than cumulative exposure at the individual level. As such, the interpretation of findings, particularly those that diverge from expected patterns, should consider the range of potential biases inherent to repeated cross-sectional survey data collected during periods of disasters. Future research could incorporate longitudinal cohort studies or case-control designs to better understand causal relationships and cumulative disaster effects.

Our findings should be interpreted considering the initial hypothesis that overlapping disaster conditions, such as incomplete recovery from Hurricane María intersecting with the COVID-19 pandemic, would exacerbate adverse health outcomes. However, the interpretation of counterintuitive findings in our study (e.g., pandemic period associated with apparent health improvements) should consider the range of potential biases inherent to repeated cross-sectional survey collection during periods of large-scale disruption. These may include selection bias, changes in survey response patterns, differential access to telephone-based surveys, and shifts in population composition due to displacement. These factors may influence who is captured in the sample and how health outcomes are reported during periods of crisis. Nonetheless, the observed pattern may also indicate that our initial hypothesis regarding worsening health outcomes during overlapping disaster periods was not supported in these data.

Selection bias is another potential limitation, as individuals most affected by disasters—such as those who lost their homes, lacked electricity, or migrated off the island—may be underrepresented in the data. Those with severe disaster experiences may have been unreachable for phone interviews, incapacitated, or deceased, leading to possible underestimation of disaster-related health impacts. Additionally, post-disaster migration, particularly among those with resources or those most impacted, may contribute to selection bias. However, if present, this bias would imply that the observed findings are likely an underestimate and that there may be even greater impact if those who are missing have a higher risk of poor health outcomes.

Measurement bias regarding exposure classification should be considered. We defined disaster exposure based on the time of the interview relative to the disaster rather than individual-level exposure severity. This assumes uniform exposure, despite significant variability in disaster impacts such as wind speeds, community mortality, and power outages across Puerto Rico, as well as potential variation in recovery trajectories over time.[46–48] For example, as defined the late post-hurricane period spans multiple phases of recovery, which may not be fully captured by the aggregated time classification we used. Future studies using more granular data are needed to better characterize how disaster-related health effects evolve over time.

It is also important to consider that Hurricane María occurred shortly after Hurricane Irma, which caused initial disruptions in parts of Puerto Rico. Although Hurricane María was the primary driver of widespread infrastructure collapse, the close temporal proximity of these events may have contributed to the severity of post-hurricane conditions, making it difficult to fully isolate the effects of a single storm. Moreover, the late post-hurricane period overlaps with the 2019-2020 earthquakes, which had geographically concentrated impacts, mainly affecting the southwestern region of the island. Due to the lack of geographic identifiers in BRFSS data, it was not possible to distinguish individuals directly affected by the earthquakes, and defining a separate earthquake exposure period would likely introduce substantial exposure misclassification. As a result, estimates for the late post-hurricane and early pandemic periods may partially reflect unmeasured earthquake-related confounding, particularly among affected populations in Southwest Puerto Rico, complicating the interpretation of these time periods as representing distinct phases of recovery or disruption. Our analysis also relies on self-reported outcomes through the BFRSS, which may be impacted by social desirability, stigma, and respondent bias. Latinx populations have historically reported higher levels of distrust in research,[49,50] potentially influencing disclosure of health status. Additionally, disaster survivors may perceive their health more favorably when comparing themselves to others who experienced more severe losses, such as the complete destruction of their homes. This pattern of downward social comparison has been noted in previous disaster studies, where individuals report improved well-being when they perceive others as having suffered more significantly.[51,52] While our research team has also observed this tendency, further empirical studies are needed to substantiate this phenomenon.

Importantly, Hurricane María and the COVID-19 pandemic represented widespread, near-universal disruptions in Puerto Rico, including prolonged power outages, mobility restrictions, and economic impacts. However, even under such population-wide exposures, estimates derived from repeated cross-sectional surveys may still be influenced by shifts in sample composition, migration, differential access to telephone-based surveys, and changes in response patterns over time. As a result, observed differences across periods may reflect both true changes in population health and these underlying survey-related dynamics. While the pre-disaster period was used as a reference, observed differences across time periods may reflect underlying temporal trends or shifts in population composition, rather than the direct effects of disaster exposure alone. Future studies could incorporate approaches such as placebo or time-shift analyses to further assess the extent to which observed patterns are attributable to disaster-related events versus broader temporal dynamics.

Lastly, the interaction analyses involved multiple comparisons across categorical variables (e.g., age, income, education, marital status, employment, and disaster period), increasing the likelihood of Type I errors or chance findings.[53–55] Although a Bonferroni correction could be used to adjust for multiple comparisons, it may be overly conservative, increasing the risk of Type II errors. Future studies may benefit from applying false discovery rate approaches, such as the Benjamini-Hochberg procedure, to better balance error control with statistical power.[56]

Conclusion

Our findings provide important insights into the association between multiple disaster exposures and public health outcomes. Consistent with prior research on post-disaster mental health, we observed adverse effects on self-reported mental health, smoking,

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and alcohol consumption, with the first 6 months post-hurricane being particularly harmful. In contrast, the pandemic period appeared to have a protective effect on self-reported health outcomes. These associations varied by sex, income, education, and employment, highlighting the need for a more nuanced understanding of how disasters affect different populations. Overall, our results suggest that disasters can negatively impact health and that recovery efforts should prioritize targeted interventions for vulnerable groups. Policymakers should examine the differential effects of hurricanes and pandemics and consider whether more rapid response measures or widespread financial assistance following catastrophic hurricanes could help mitigate mental health consequences. In addition to short-term financial assistance, disaster recovery strategies should prioritize sustained mental health interventions. Given the disproportionate burden of poor mental health and substance use among lower-income and unemployed groups, integrating community-based mental health services into disaster response plans could mitigate long-term consequences. Expanding mobile or electronic (tele-health) mental health units, increasing accessibility to culturally competent care, and ensuring long-term Medicaid coverage for disaster-affected populations may help reduce disparities in post-disaster health outcomes. Future research could benefit from retrospective designs that better account for individual-level disaster exposure across multiple events.

Supplementary material. The supplementary material for this article can be found at http://doi.org/10.1017/dmp.2026.10410.

Data availability statement. The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

Author contribution. Mislael A. Valentín-Cortés: Conceptualization, methodology, formal analysis, data curation, investigation, software, writing—original draft.

Marie S. O'Neill: Supervision, conceptualization, writing—review and editing. Michael R. Elliott: Supervision, methodology, writing—review and editing. Paul J. Fleming: Supervision, writing—review and editing. Carlos E. Rodriguez-Diaz: Supervision, writing—review and editing. Alexis J. Handal: Supervision, conceptualization, writing—review and editing.

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