Published in final edited form as:

Int J Disaster Risk Reduct. 2022 June 15; 76: . doi:10.1016/j.ijdrr.2022.102986.

Flooding and emergency department visits: Effect modification by the CDC/ATSDR Social Vulnerability Index

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Abstract

The Centers for Disease Control and Prevention (CDC)/Agency for Toxic Substances and Disease Registry (ATSDR) Social Vulnerability Index (SVI) is a census-based metric that includes 15 socioeconomic and demographic factors split into four themes relevant to disaster planning, response, and recovery. Using CDC/ATSDR SVI, health outcomes, and remote sensing data, we sought to understand the differences in the occurrence of overall and cause-specific emergency department (ED) visits before and after a 2017 flood event in Texas following Hurricane Harvey, modified by different levels of social vulnerability. We used a controlled before-after study design to estimate the association between flooding and overall and cause-specific ED visits after adjusting for the baseline period, seasonal trends, and individual-level characteristics. We estimated rate ratios stratified by CDC/ATSDR SVI quartiles (overall and 4 themes separately) and tested for the presence of effect modification. Positive effect modification was found such

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2022.102986.

that total ED visits from flooded census tracts with moderate, high, and very high levels of social vulnerability were less reduced compared to tracts with the least vulnerability during flooding and the month following the flood event. The CDC/ATSDR SVI socioeconomic status theme, household composition and disability theme, and housing and transportation type theme explained this result. We found predominantly negative effect modification with higher ED visits among tracts with the least vulnerability for ED visits related to insect bites, dehydration, and intestinal infectious diseases.

Keywords

CDC/ATSDR Social vulnerability index; Flood and health; Hurricane Harvey; Earth observation; Emergency department visit; Effect modification

1. Introduction

Identifying factors modifying adverse health impacts associated with flood events is important because the frequency and intensity of extreme precipitation events, including precipitation from tropical cyclones, have been increasing over time [1–3]. Over the past two decades, the number of storm-related disasters and the five-year average economic losses caused by extreme weather events have increased [4]. Flooding and tropical cyclones can negatively affect physical and mental health, and the health outcomes may be short-term or long-lasting. Outcomes may include injuries, intestinal infectious diseases, pregnancy complications [5], upper respiratory allergic symptoms [6], and posttraumatic stress disorder [7,8].

The association between health outcomes and flooding has been summarized in several literature reviews [9–12]. Effect modification, i.e. exposure to flooding has a different effect on health outcomes among different population subgroups, has been characterized in some instances. For example, previous studies generally suggest the health impacts among populations exposed to flooding vary by age, with increases in those over 65 years of age [13–20]. Variation by gender or sex has also been noted in previous studies, with increased rates of heat-related injury in women and increased rates of water-borne infection in men following flooding, but no differences in fatalities [15,21,22]. Previous studies examining socioeconomic status (SES) or educational attainment show mixed results, with some suggesting associations between flooding and adverse health impacts decrease and other studies showing increased impacts with increasing SES or educational attainment [13,23] and a well-controlled study saw no effect [24]. Previous studies provide evidence for variation in flooding impacts by race or ethnicity, with some studies detecting increased impacts in persons identifying as Hispanic, Native American or non-Hispanic Black [7,13,25], while other studies found no significant differences across race or ethnicity categories [15,19]. Collins et al. [13] found increased impacts with English language proficiency in a Hispanic population after a 2006 flooding event in Texas [13], and food and emergency requests were increased following Hurricane Florence [26].

In addition to effect modification by individual-level sociodemographic factors, area-level social factors may modify the effect of flooding on health outcomes. Area-level social vulnerability metrics, including population measures of SES within a census tract, for example, can be coupled with a measure of exposure to floodwaters to understand how social vulnerability increases or decreases health effects associated with exposure. Several vulnerability indices designed for the United States exist. The Centers for Disease Control and Prevention (CDC)/Agency for Toxic Substances and Disease Registry (ATSDR) Social Vulnerability Index (SVI), previously known as the "CDC SVI" and currently "CDC/ ATSDR SVI," is a freely available measure that has been widely utilized [27]. The CDC/ ATSDR SVI was created by the Geospatial Research, Analysis, and Services Program (GRASP) to aid public health officials and emergency response planners in assisting populations with unique social vulnerabilities before, during, and after natural or human-caused disasters and infectious disease outbreaks. This index combines four themes, each of which influences a community's ability to withstand and recover from disaster events: socioeconomic status (theme 1); household composition and disability (theme 2); minority status and language (theme 3); and housing type and transportation (theme 4).

Applications of the CDC/ATSDR SVI are broad. The CDC/ATSDR SVI has been shown to be associated with health outcomes, such as heat-related illness and mortality, cardiovascular disease mortality, and postoperative health outcomes and mortality [28–31]. It has also been used to create hazard-specific vulnerability indices to address wildfire and climate extremes vulnerability [32,33]. Previous analyses using the overall CDC/ATSDR SVI did not find associations with tornado related or Hurricane Sandy related mortality [34]; however, the age-based vulnerability theme (theme 2) of the CDC/ATSDR SVI was associated with mortality caused by Hurricane Katrina [27]. Also, following Hurricane Harvey, individuals affected by flooding were predominantly from tracts with high CDC/ ATSDR SVI rankings [35], and communities where more residents sought medical care were spatially clustered, experienced more flooding, and were from census tracts with higher CDC/ATSDR SVI socioeconomic status theme vulnerability and lower household composition theme vulnerability [36].

Hurricane Harvey was a Category 4 hurricane that made landfall in Texas on August 26, 2017 [37]. After landfall, Houston experienced 25 inches of rainfall in the next 48 h [37]. The majority of the National Weather Service (NWS) river forecast locations in the southeast part of Texas reported flooding [38]. Approximately 40,000 people affected by flooding were evacuated to shelters in Texas and Louisiana [37]. The hurricane destroyed 16,930 houses and 300,000 to 500,000 vehicles, damaged 290,063 homes, and caused 68 deaths [38]. Hurricane Harvey damages were estimated to be $125 billion dollars, making it the second costliest tropical cyclone in the United States [38]. Posttraumatic stress disorder [7,8] and upper respiratory allergic symptoms [6] were elevated among the population exposed to floods caused by the hurricane. Our previous work showed emergency department (ED) visits related to carbon monoxide (CO) poisoning, dehydration, hypothermia, insect bites, intestinal infectious diseases, and pregnancy complications increased following Hurricane Harvey among flooded census tracts compared to non-flooded census tracts [5]. The present study builds from this prior work by examining the influence of area-level social vulnerability on health outcomes associated with flooding. In a study area defined as census tracts in southeast Texas impacted by the floods of Hurricane Harvey in 2017, we analyze how CDC/ATSDR SVI modifies the association between remotely observed flooding and overall ED visits as well as four types of cause-specific ED visits that have been shown to be associated with flooding: dehydration, insect bites, intestinal infectious diseases, and pregnancy complications.

2. Materials and methods

Three types of datasets were used for this study: 1) flood data comprises a remote sensing based inundation map and observed stream gauge data, 2) overall and thematic census tract-level vulnerability data from the CDC/ATSDR SVI, and 3) total and cause-specific daily ED visit records with individual-level demographic data, for residents in the study area. The study area comprised all census tracts in Texas that were within the boundary of the Dartmouth Flood Observatory inundation map (N = 2862) (Fig. 1).

2.1. Spatiotemporal flood exposure classification

An inundation map created using satellite imagery (i.e., NASA MODIS, ASI Cosmo SkyMed, Radarsat 2 and ESA Sentinel 1) between August 28 and September 4,2017 was obtained from the Dartmouth Flood Observatory [39], The 2862 census tracts with CDC/ ATSDR SVI values within the study area as defined by the extent of the inundation map were categorized as flooded or non-flooded based on the inundation data (Fig. 1). United States Geological Survey (USGS) stream gauge data along with the National Weather Service (NWS) flood stages were used to determine the persistence of floods in the study region [40]. Using these data, the flood period was defined as August 26 to September 13, 2017, the period during which one or more of the 597 USGS stream gauges in the study area indicated stage (water level) greater than the NWS flood stage (Supplementary Figure 1) [40]. In addition to the flood period, two post-flood periods were considered: 1) Post-flood period 1 extends one month after the retraction of floods (September 14 to October 13, 2017) to capture health outcomes that occurred during the recovery and clean-up phase and 2) Post-flood period 2 extends from the end of post-flood period 1 until the end of the year (October 14 to December 30, 2017) to capture more delayed health outcomes.

2.2. CDC/ATSDR Social Vulnerability Index and themes

The CDC/ATSDR SVI is determined by ranking each census tract on 15 equally weighted census variables, such as poverty status, race/ethnicity, and household vehicle access, and grouping the variables into four themes: socioeconomic status, household composition and disability, minority status and language, and housing type and transportation. The CDC/ ATSDR SVI rankings are percentile ranks ranging from 0 to 1, and each tract receives a separate ranking for each of the four themes as well as an overall ranking. We obtained overall and theme-specific CDC/ATSDR SVI rankings from the 2016 CDC/ATSDR SVI database for all census tracts in Texas and reranked for census tracts in the study region, using the procedure outlined in CDC documentation [41]. Based on the reranked indices, the census tracts were categorized into quartiles: least vulnerability (0–0.25), moderate vulnerability (0.2501–0.5), high vulnerability (0.5001–0.75), and very high vulnerability (0.7501–1).

2.3. Emergency department visits

Inpatient and outpatient ED visit data from patients who resided within the study area were obtained from the Texas Department of State Health Services for the last two quarters (July–December) of 2016 and 2018 and the last three quarters (April-December) of 2017 [42]. After removing 0.07% of the records that were incomplete or belonged to census tracts that did not have a CDC/ATSDR SVI ranking, the final dataset contained 9,043,518 ED visits with patients' reported sex, age, race, and ethnicity, geocoded census tracts based on the patient addresses, and primary and secondary International Classification of Diseases (ICD) 10 diagnostic codes of the patients' visit data. The patient's geocoded census tract ID was used to link the ED visit data to the CDC/ATSDR SVI quardle (overall and themes) and flooding status.

Total ED visits were evaluated, as well as ED visits related to insect bites, dehydration, intestinal infectious diseases, and pregnancy complications, categorized using the relevant ICD-10 codes in the primary and secondary diagnosis fields [5]. These four cause-specific ED visit types were selected because in our previous analysis, they were associated with flood exposure during and following Hurricane Harvey [5], Though CO poisoning, drowning, and hypothermia were also shown to be associated with flood exposure during the flood period, they were not suitable for evaluation of effect modification due to the few cases identified.

Patient sex was reported as male or female, and patient age was reported in years. We collapsed reported patient race into White, Black, and Other due to lower numbers in each of these reported categories: Asian, Pacific Islander, American Indian, Eskimo, and Aleut. Patient ethnicity was reported as non-Hispanic or Hispanic.

2.4. Analysis

A controlled before-after study design (e.g., see Lopez Bernal et al., 2018) was implemented, where ED visits that occurred before the flood (July to December 2016 and January 1 to August 19, 2017) and after the post-flood periods (July to December 2018) were used to define the baseline rates of ED visits within each census tract. This epidemiological approach adjusts for time-invariant and time variant confounders and has been used previously to characterize disaster-related health outcomes [25,43–45]. A modified Poisson regression model, a commonly applied approach with count or binary outcome data, was used to estimate rate ratios of overall ED visits where:

$$log_e[Y_i] \sim \beta_0 + \beta_1 \; Period_k + \beta_2 \; flood_i + \beta_3 \; Period_k \times \; flood_i + \beta_4 \; SVI_i + \beta_5 \; SVI_i \times \; Period \; \times \; flood_i + \ldots + \beta_j V_j + log_e(Population_i)$$

Such that Y is the expected counts of daily ED visits in census tract i and is related to independent variables characterizing period of time $((\beta_1), \mathrm{k} = \mathrm{control}$, flood period, post-flood 1, and post-flood 2), the flood status of census tract i during the flood period (β_2), the SVI quartile (overall or theme specific) of census tract i, and individual-level sex, age, race, and ethnicity as reported in the ED visit records (β_j). We also add variables for year, month, and day of week of the ED visit to control for temporal trends. Population in census tract i

was used as the offset in the model for the overall ED visits. For cause-specific ED visits, we modeled similarly, but use the binary outcome from individual records and census tract as a group id, and total ED visits per day in census tract i as the offset. The p-value of the coefficient of the 3-way interaction term (β_5) was used to test for effect modification by the CDC/ATSDR SVI on the association (rate ratio) between flooding and ED visits. Significant effect modification (p-value < 0.05) implies that the rate ratio in moderate/high/very-high quartile was statistically different (greater/lower) compared to the least vulnerable quartile (reference). Rate ratios for the association between flooding and ED visits within each quartile of overall CDC/ATSDR SVI and the four CDC/ATSDR SVI themes were separately estimated using stratified models. Rate ratios were calculated by exponentiating the coefficient for the 2-way interaction term (β_3) estimated from the respective quartile specific model.

We ran models testing for effect modification by individual-level characteristics reported on ED visit records (Supplementary Table 9). We also ran models without individual-level characteristics to determine if effect modification by CDC/ATSDR SVI changed (Supplementary Table 10). To evaluate the potential effect of additional unaccounted for spatial autocorrelation, a hierarchical generalized linear model was used to fit a Poisson Simultaneous Autoregressive (SAR) model with random effects for census tracts and spatial weights defined using queen neighborhood. The model was fitted using the hglm package in R [46]. As the covariance matrix estimation was computationally intensive, we collapsed the model to weekly ED visit summaries instead of daily individual level data. The model was adjusted for monthly trends, proportion of male, average age of the patient, race, and ethnicity. Results are presented in Supplementary Table 11.

Our study was approved by the Virginia Polytechnic Institute and State University's Institutional Review Board (IRB Protocol # 18–914) and the Texas Department of State Health Services' Institutional Review Board (IRB Protocol # 19–024).

3. Results

Fig. 1 illustrates flood exposure and levels of CDC/ATSDR SVI for census tracts in the study area. Out of 9,043,518 ED visits in the dataset, 55% belonged to residents from non-flooded census tracts and 45% from flooded census tracts. The demographic distribution of the ED visits is provided in Supplementary Table 1. Males accounted for 43% and females 57% of the total ED visits. With regards to ethnicity and race, 38% of the patients were Hispanic, and 60%, 19%, and 21% were White, Black, and of other races, respectively. The distribution of patients within age categories was the following: 23% aged less than 18 years, 38% aged between 18 and 45 years, 21% aged between 46 and 64 years, and 18% aged greater than 64 years.

Effect modification by individual-level characteristics reported on the ED visit records (age, race, sex, and ethnicity) was first examined, and full results are presented in Supplementary Table 9, since these characteristics are also represented in the CDC/ATSDR SVI at the census-tract level. Briefly, patients >64 years of age, ethnicity recorded as Hispanic, or race recorded as non-White had heightened rates of ED visits in the flood or post-flood periods.

Effect modification by individual-level characteristics for cause-specific ED visits was more varied. Patients >64 years of age had elevated ED visits for dehydration but reduced visits for intestinal infectious disease during the flood period. Patients with ethnicity recorded as Hispanic had increased visits for insect bites but reduced visits for dehydration, intestinal infectious diseases, and pregnancy complications. Patients recorded as non-White and non-Black (i.e., other reported race) had increased visits for pregnancy complications but reduced visits for dehydration during the second post-flood period. The detailed results presented in Sections 3.1 to 3.5 below are for models that adjust for individual-level characteristics and test for additional effect modification by census tract CDC/ATSDR SVI quartile.

3.1. Overall emergency department visits

ED visits that occurred before the flood (July to December 2016 and January 1 to August 19, 2017) and after the post-flood periods (July to December 2018) define the baseline rates of ED visits within each census tract. During these baseline time periods, ED visits increased with increasing levels of overall CDC/ATSDR SVI by an average of 1.38 times (95% CI: 1.32–1.43) for census tracts with moderate vulnerability (25th to 50th percentile ranks), 1.69 times (95% CI: 1.62–1.76) for tracts with high vulnerability (50th to 75th percentile ranks), and 2.03 times (95% CI: 1.94–2.11) for tracts with very high vulnerability (75th to 100th percentile ranks) when compared to tracts with the least vulnerability (0–25th percentile ranks). Rate ratios (exponentiated (β_3) in Equation 1, stratified models) for each CDC/ATSDR quartile were calculated to characterize variation in flood-related ED visits across CDC/ATSDR SVI quartiles. During the flood period and initial post-flood period (1 month following active flooding), the average rate of overall ED visits decreased more in the flooded census tracts compared to non-flooded tracts across all levels of CDC/ATSDR SVI, with tracts with the least vulnerability experiencing the largest decrease (Fig. 2, Panel 1). Effect modification by CDC/ATSDR SVI was significant during the flood period and post-flood period 1 (p-value <0.05 for 3-way interaction term (β_5) Supplemental Tables 3 and 4). ED visits declined less during the flooding period among tracts with moderate vulnerability (RR = 0.91, 95% CI = 0.88–0.93) and high vulnerability (RR = 0.89; 95% CI = 0.87–0.92) compared to tracts with the least vulnerability (RR = 0.86, 95% CI = 0.83–0.88, interaction term p-values ≤ 0.02). This pattern persisted during the initial month following flooding (Fig. 2). Tracts with higher levels of vulnerability had less of a decline in ED visits: moderate vulnerability (RR = 0.98, 95% CI = 0.97–1.00), high vulnerability (RR = 0.98, 95% CI = 0.96–1.00), and very high vulnerability (RR = 0.98, 95% CI = 0.96–1.00) compared to tracts with the least vulnerability (RR = 0.94, 95% CI = 0.93–0.96, interaction term p-values ≤ 0.002). During the second post-flood period (2–3 months after the active flooding), ED visits were slightly elevated among tracts with moderate vulnerability (RR = 1.02, 95% CI = 1.00–1.04), high vulnerability (RR = 1.03, 95% CI = 1.01–1.06), and very high vulnerability (RR = 1.03, 95% CI = 1.01–1.05); however, effect modification by CDC/ATSDR SVI was non-significant (Fig. 2).

When analyzing CDC/ATSDR SVI themes, the household composition and disability theme and the housing type and transportation theme explain the effect modification described above during the flood period (Fig. 2). Effect modification by the minority status and language theme showed opposite directionality, with decreased ED visits among tracts with high and very high vulnerability compared to tracts with the least vulnerability (interaction term p-values ≤ 0.008). Effect modification during the first post-flood period was driven by the socioeconomic status theme (interaction term p-values ≤ 0.002) and the housing type and transportation theme (interaction term p-values ≤ 0.024). Though effect modification was not observed by overall CDC/ATSDR SVI for the second post-flood period, effect modification by the household composition and disability theme and the minority status and language theme was observed. With respect to the minority status and language theme, the ED visits were slightly increased among tracts with high (RR = 1.01, 95% CI = 0.99–1.03) and very high (RR = 1.05, 95% CI = 1.03–1.06) vulnerability compared to tracts with the least vulnerability (RR = 1.00, 95% CI = 0.98–1.01, interaction term p-values ≤ 0.041).

Removal of individual-level sociodemographic variables minimally affected CDC/ATSDR SVI effect modification results (Supplemental Table 10). A hierarchical spatial autoregressive model adjusting for spatial autocorrelation between census tracts reduced baseline (control period) effects of CDC/ATSDR SVI on total ED visits; however relative effects during the flood and post-flood periods within flooded tracts were unchanged (Supplemental Table 11).

3.2. Insect bite-related emergency department visits

During the control period, among the non-flooded tracts ED visits for insect bites were lower among residents in census tracts with higher levels of CDC/ATSDR SVI (moderate vulnerability: RR = 0.94, 95% CI = 0.84–1.06; high vulnerability: RR = 0.84, 95% CI = 0.73–0.96; very high vulnerability: RR = 0.85, 95% CI = 0.76–0.96) compared to residents in tracts with the least vulnerability (β_4 in equation 1). Insect bite-related ED visits during the flood period were elevated within tracts with the least vulnerability (RR = 1.50, 95% CI = 1.18–1.91), high vulnerability (RR = 1.42, 95% CI = 1.19–1.69), and very high vulnerability (RR = 1.43, 95% CI = 1.19–1.71). Negative effect modification refers to decreasing rate ratios with increasing values of the modifier. Effect modification by the CDC/ATSDR SVI was predominantly negative, with census tracts with the least vulnerability having the highest increases in insect bite-related ED visits during the flood period (Fig. 3). Also, during the second post-flood period, ED visits for insect bites were heightened in census tracts with the least vulnerability (RR = 1.25, 95% CI = 1.06–1.48) compared to tracts with moderate (RR = 0.97, 95% CI = 0.86–1.10), high (RR = 0.91, 95% CI = 0.80–1.02), and very high vulnerability (RR = 0.90, 95% CI = 0.80–1.02, interaction term p-values ≤ 0.012).

With respect to the CDC/ATSDR SVI themes, the housing type and transportation theme explained the overall CDC/ATSDR SVI effect modification patterns described above for the flood period. Similar effect modification with lowered ED visits among tracts with moderate vulnerability compared to tracts with the least vulnerability was observed for the socioeconomic status theme during the first post-flood period. Effect modification was observed among all themes of the CDC/ATSDR SVI for the second post-flood period, and most predominantly in the socioeconomic status theme where higher levels of vulnerability (moderate, high, and very high) had a lower rate for insect bite-related ED visits compared to tracts with the least vulnerability (interaction term p-values ≤ 0.027) (Fig. 3).

3.3. Dehydration-related emergency department visits

During the control period, among the non-flooded tracts ED visits for dehydration showed a similar pattern to insect bites; visits were lower among residents in census tracts with higher levels of CDC/ATSDR SVI (moderate vulnerability: RR = 0.75, 95% CI = 0.68–0.83; high vulnerability: RR = 0.57, 95% CI = 0.50–0.64; very high vulnerability: RR = 0.57, 95% CI = 0.51–0.63) compared to tracts with the least vulnerability. During the flood period, ED visits related to dehydration were increased in flooded census tracts compared to non-flooded census tracts among areas with the least vulnerability (RR = 1.23; 95% CI = 1.09–1.38) and very high vulnerability (RR = 1.22; 95% CI = 1.08–1.38). During the first post-flood period, visits from residents in tracts with the least vulnerability remained elevated. During the second post-flood period, flooded census tracts with the least, moderate, and high vulnerability showed decreased dehydration-related ED visits compared to non-flooded census tracts (Fig. 4). Effect modification was observed only during the first post-flood period where ED visits were increased among census tracts with the least vulnerability (RR = 1.13, 95% CI = 1.04–1.22) compared to tracts with moderate (RR = 0.99, 95% CI = 0.91–1.07), high (RR = 0.97, 95% CI = 0.89–1.05), and very high vulnerability (RR = 0.96, 95% CI = 0.88–1.04, interaction term p-values ≤ 0.02) (Supplementary table 4).

Though effect modification by overall CDC/ATSDR SVI was not observed during the flood period, modification was observed by the minority status and language theme, with increased ED visits among tracts with very high vulnerability (RR = 1.30, 95% CI = 1.15–1.46) compared to tracts with the least vulnerability (RR = 1.07; 95% CI = 0.96–1.20, interaction term p-value = 0.026) (Fig. 4). The effect modification pattern observed during the first post-flood period was explained primarily by the CDC/ATSDR SVI socioeconomic status theme (Fig. 4).

3.4. Intestinal infectious disease-related emergency department visits

Similarly, over the control period, among the non-flooded tracts ED visits for intestinal infectious diseases were lower among residents in tracts with higher levels of CDC/ATSDR SVI (moderate vulnerability: RR = 0.84, 95% CI = 0.75–0.94; high vulnerability: RR = 0.67, 95% CI = 0.58–0.77; very high vulnerability: RR = 0.74, 95% CI = 0.65–0.83) compared to tracts with the least vulnerability. During the flood period, ED visits related to intestinal infectious diseases was elevated among tracts with the least (RR = 1.62, 95% CI = 1.26–2.08), high (RR = 1.48, 95% CI = 1.22–1.81), and very high (RR = 1.29, 95% CI = 1.06–1.58) vulnerability. No effect modification by CDC/ATSDR SVI was observed during the flood period and the second post-flood period (Fig. 5). During the first post-flood period, ED visits for intestinal infectious diseases were increased among tracts with the least vulnerability (RR = 1.20; 95% CI = 0.99–1.45) compared to tracts with moderate vulnerability (RR = 0.84; 95% CI = 0.71–0.99, interaction term p-value = 0.004).

Analyzing the CDC/ATSDR SVI themes, during the flood period, effect modification by the housing type and transportation theme suggests an increase in intestinal infectious disease-related ED visits among census tracts with the least vulnerability (RR = 1.78; 95% CI = 1.40–2.27) compared to tracts with high vulnerability (RR = 1.29; 95% CI = 1.04–1.58) and very high vulnerability (RR = 1.31; 95% CI = 1.09–1.58; interaction term p-values ≤

0.033). A similar effect modification pattern was observed during the first post-flood period for the household composition and disability theme, which suggests lower ED visits related to intestinal infectious diseases in tracts with high vulnerability (RR = 0.94, 95% CI = 0.81–1.10) compared to tracts with the least vulnerability (RR = 1.23, 95% CI = 1.01–1.50; interaction term p-value = 0.04).

3.5. Pregnancy complication-related emergency department visits

Over the control period, ED visits among the non-flooded tracts for pregnancy complications were lower among residents in tracts with higher vulnerability levels (moderate vulnerability: RR = 0.85, 95% CI = 0.76–0.96; high vulnerability: RR = 0.71, 95% CI = 0.63–0.81; very high vulnerability: RR = 0.74, 95% CI = 0.66–0.83) compared to tracts with the least vulnerability. Increased ED visits related to pregnancy complications in flooded census tracts compared to non-flooded tracts were observed in all four quartiles of CDC/ ATSDR SVI during the flood period and only among tracts with very high vulnerability during the first post-flood period (Fig. 6). Effect modification by overall CDC/ATSDR SVI or theme-specific CDC/ATSDR SVI was not observed during the flood or the post-flood periods (Fig. 6).

4. Discussion

Determining measures that will minimize adverse health outcomes during and following disasters is a key component of local, state, and federal disaster planning and preparedness. Interventions could target modifiable area-level factors that are associated with flood-related adverse health outcomes, but first we must understand if, when, and what area-level factors are associated with adverse health outcomes during and following flood events. Our study examined effect modification of flood-related ED visits by the CDC/ATSDR SVI, an area-level (census tract) social vulnerability metric, during and following Hurricane Harvey. While ED visits were decreased among flooded census tracts during the active flood period and 1 month following, our results indicate less decrease in visits among census tracts with moderate, high, and very high vulnerability (Fig. 2), consistent with a positive association between the CDC/ATSDR SVI and flood-related ED visits. When stratified by the four CDC/ATSDR SVI themes, positive effect modification by the housing type and transportation theme and the household composition and disability theme explained the overall pattern. This finding may indicate that members of communities impacted by floods and who either did not have protective housing or efficient transportation or who resided in households with children, older adults, a member who is disabled, or single parents utilized EDs more overall as a source of healthcare during the flooding and the month following the flooding. If this finding is repeated in future studies of flooding events, it could suggest interventions such as increasing transportation access, housing quality, or care provision support prior to, during, and after flooding events could reduce flood-related adverse health outcomes.

We observed minimal positive effect modification of the CDC/ATSDR SVI on the association between flood exposure and four flood-related cause-specific ED visits. Negative effect modification was observed for the association between flooding and ED visits related to insect bites, dehydration, and intestinal infectious diseases, and no effect modification was observed for ED visits related to pregnancy complications. Visits were elevated for insect bites, dehydration, and intestinal infectious diseases during and following the flooding in flooded tracts, yet persons from the least vulnerable census tracts were more likely to visit an ED when compared to persons from high CDC/ATSDR SVI tracts. For example, two to three months after the retraction of the floods, ED visits related to insect bites were significantly higher among the tracts with the least vulnerability compared to other CDC/ATSDR SVI levels, primarily driven by the socioeconomic status theme and the housing type and transportation theme. This result might reflect differences in where care was sought for insect bites, as urgent care facilities may have been more frequented in higher quartile CDC/ATSDR SVI census tracts due to cost and/or transportation considerations [47]. An increase in ED visits for dehydration was significantly greater in tracts with very high vulnerability compared to tracts with the least vulnerability for the minority status and language theme during the flood period, suggesting rapid access to clean water and culturally specific interventions could be useful in reducing dehydration-related health burdens.

Other studies have found minimal effect modification of disaster related outcomes by area-level social vulnerability metrics. A study that compared and validated the top five United States disaster-related indices showed that though the CDC/ATSDR SVI performs well in explaining property losses and damages caused by disaster, the CDC/ATSDR SVI was not strongly associated with disaster-related fatalities compared to the Resilience Capacity Index and Community Disaster Resilience Index [48]. In accordance with the above study, the spatial correlation between the CDC/ATSDR SVI and disaster-related mortality among census tracts along the Northeast coast of the United States showed no clear evidence of association, and the CDC/ATSDR SVI did not have any significant effect modification of the association between tornado occurrences and mortality [34]. Alternatively [49], found county-level social vulnerability was associated with flood-related deaths and injuries.

Regarding individual-level characteristics, a previous study has shown that dehydration following flooding is higher in people older than 65 years of age [19], and we also found an increased rate of ED visits for dehydration related to flood exposure (RR = 1.15, 95% CI = 1.01–1.30) among patients older than 65 compared to patients between 18 and 64 (Supplementary table 9). Though the household composition and disability theme incorporates the proportion of population under 18 and 65 years of age and older, we did not find significant effect modification using this area-level measure of age vulnerability.

4.1. Limitations and future work

Though inundation data were available at a finer scale (spatial resolution 200 m), the unit of analysis for our study was census tracts, meaning that different proportions of flooding throughout a tract were considered as one category of flood exposure (flooded or non-flooded). We used binary flood exposure to avoid small sample sizes and power issues during the effect modification analyses. Also, flood inundation data were generated using multiple images taken over the study area at different times, so in regions where the data were acquired days after the peak flooding, there could be underestimation of inundation extent. Future studies with more spatially resolved (address-level) health and flood inundation data could evaluate the effect of this potential exposure misclassification limitation, which if present, would have the effect of biasing results towards the null in the present analysis. Future studies with larger sample sizes, particularly for relatively rare cause-specific ED visits associated with flooding such as CO poisoning, will help to further characterize modifying factors for flood-related health outcomes. ED visits likely miss health outcomes associated with flooding, such as acute gastrointestinal infections and non-crisis mental health conditions; therefore, future research should assess other health outcome data sources for characterizing modifiers of flood-related health effects. In testing for effect modification by CDC/ATSDR SVI quartiles, we focused on the statistically significant difference in rate ratios among census tracts with moderate, high, and very high vulnerability using tracts with the least vulnerability as the reference. Future research with larger study areas could further characterize effect modification by using a greater number of quantiles or model CDC/ATSDR SVI as a continuous predictor. Further clarification of the indirect pathways between flooding and some health outcomes, such as pregnancy outcomes, via mental stress and lack of access to health care, is an important area of future study. Finally, the static nature of the CDC/ATSDR SVI could be enhanced through inclusion of dynamic information to examine trends in vulnerability over time, such as has been completed in Germany [50].

5. Conclusion

Using ED visit data and earth observation products, our study highlights how adverse health outcomes during and following exposure to flooding is modified by the social vulnerability of populations as measured using the CDC/ATSDR SVI. We observed increased rates for overall ED visits among tracts with very high social vulnerability compared to tracts with the least social vulnerability, particularly for the household composition and disability theme and housing type and transportation theme of the CDC/ATSDR SVI. Eventually, if replicated in future studies, these results could be used to target interventions in high vulnerability tracts to improve access to resources such as transportation, quality housing, and care provision support as measures to reduce negative health outcomes associated with flooding events.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

The authors appreciate Dr. Thomas Pingel, Department of Geography, Virginia Polytechnic Institute and State University for his support in providing computational resources for running our models. This study was supported by the National Aeronautics and Space Administration (NASA) Applied Sciences Program Grant #80NSSC18K1594.

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the Centers for Disease Control and Prevention/the Agency for Toxic Substances and Disease Registry.

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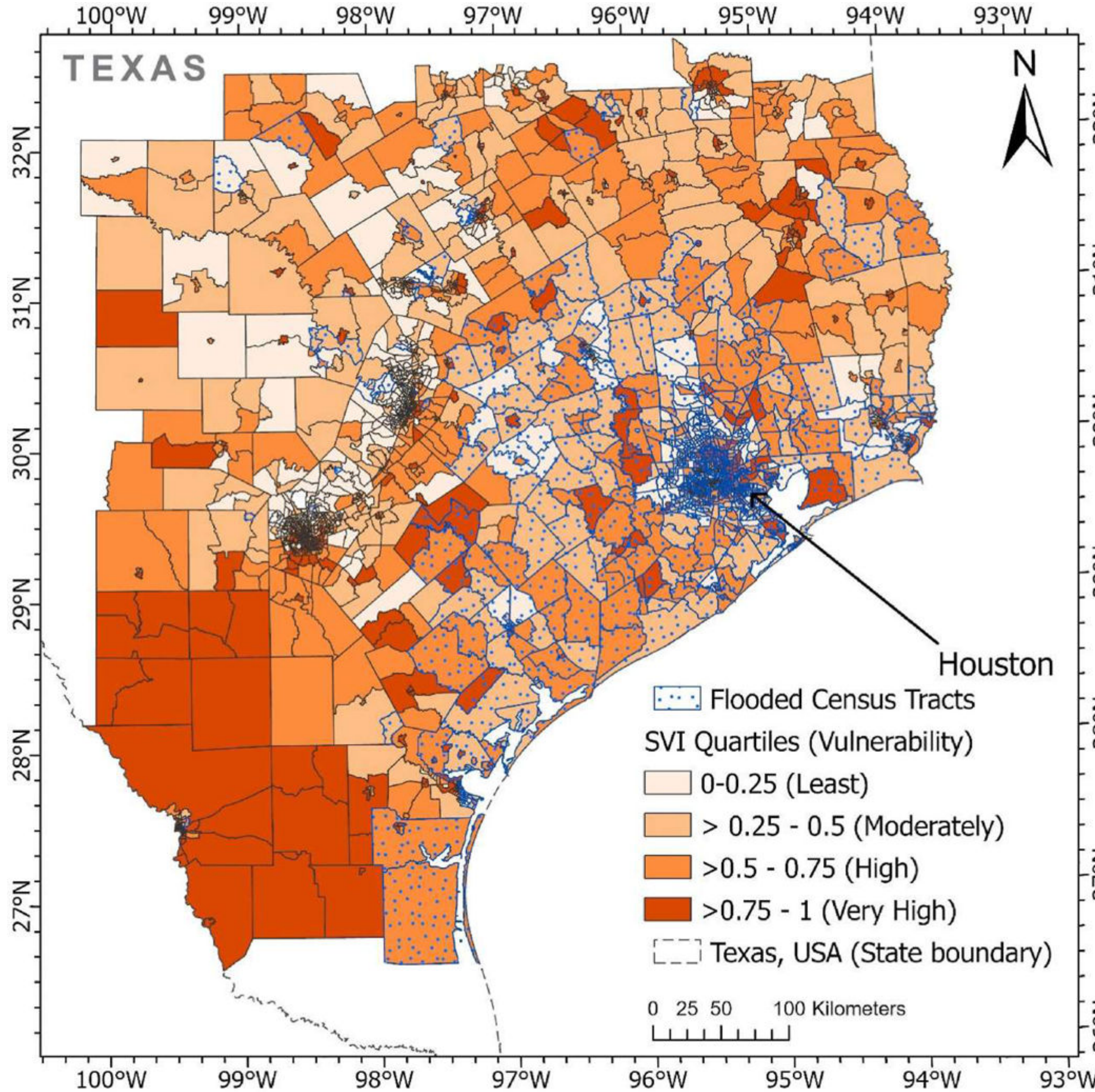

Fig. 1.

Geographic distribution of flood exposure in southeast Texas and the reranked 2016 Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry Social Vulnerability Index (CDC/ATSDR SVI) for census tracts in the study area. Flooded census tracts in the study area are displayed with blue dotted pattern. The CDC/ATSDR SVI of the census tracts is displayed in shades of orange. Geographic latitude and longitude are displayed on the outer grid of the map in decimal degrees.

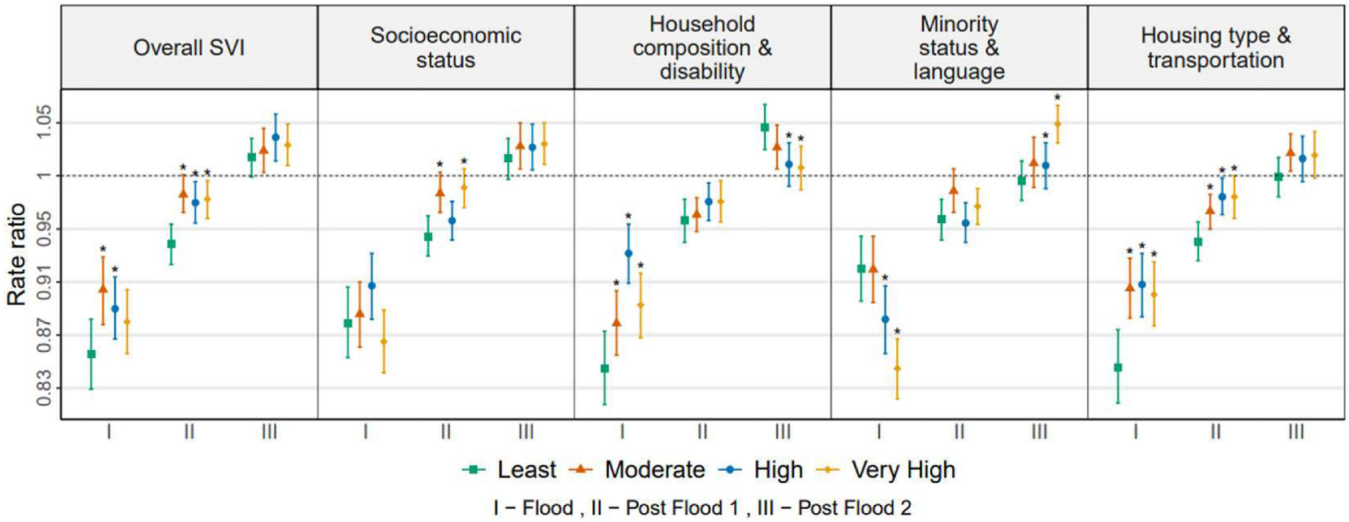

Fig. 2.

Overall CDC/ATSDR SVI and theme-specific CDC/ATSDR SVI quartile stratified rate ratios describing the association between flooding and total ED visits during flood, post-flood 1 and post-flood 2 periods among census tracts. 95% confidence intervals are shown. “*” over the confidence intervals (applicable only for the moderate, high, and very high quartiles) indicates the rate ratio among census tracts belonging to these CDC/ATSDR SVI quartiles was statistically different from the rate ratio among census tracts belonging to tracts with the least vulnerability, as determined by the significance (p-value <0.05) of the 3-way interaction term (β_5) in Equation 1.

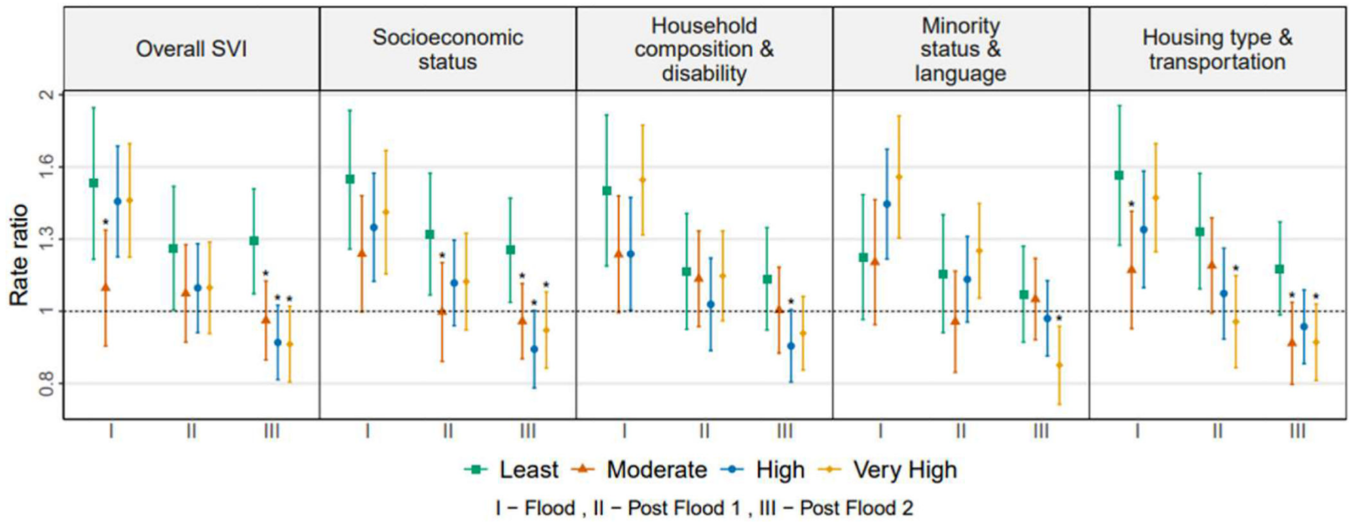

Fig. 3.

Overall CDC/ATSDR SVI and theme-specific CDC/ATSDR SVI quartile stratified rate ratios describing the association between flooding and ED visits related to insect bites during flood, post-flood 1 and post-flood 2 periods among census tracts. 95% confidence intervals are shown. "*" over the confidence intervals (applicable only for the moderate, high, and very high quartiles) indicates the rate ratio among census tracts belonging to these CDC/ATSDR SVI quartiles was statistically different from the rate ratio among census tracts belonging to tracts with the least vulnerability, as determined by the significance (p-value <0.05) of the 3-way interaction term (β_5) in Equation 1.

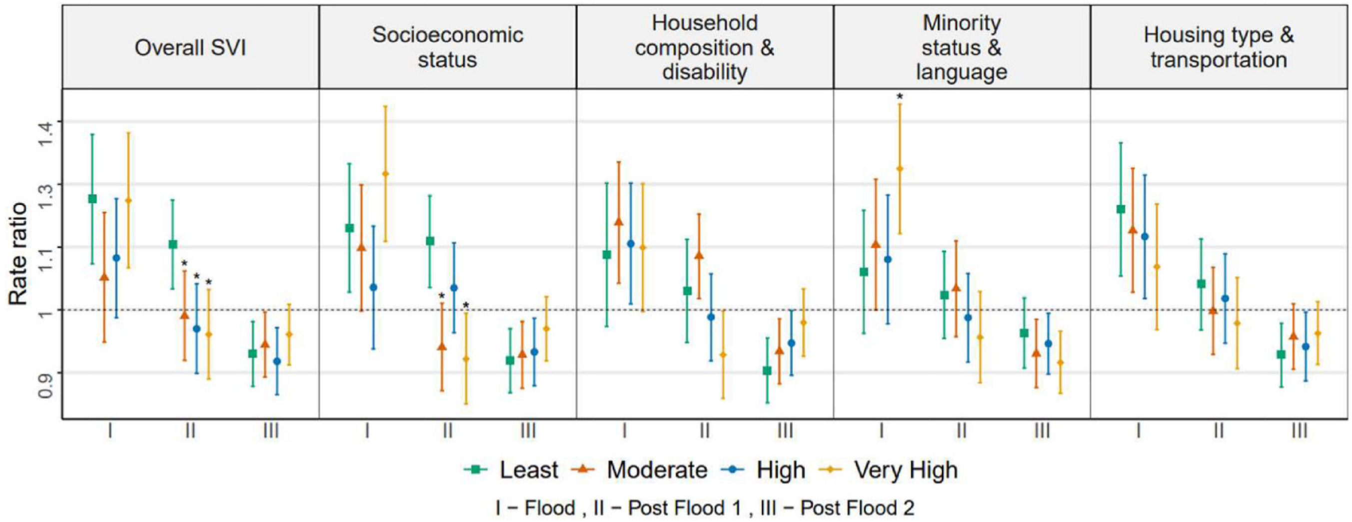

Fig. 4.

Overall CDC/ATSDR SVI and theme-specific CDC/ATSDR SVI quartile stratified rate ratios describing the association between flooding and ED visits related to dehydration during flood, post-flood 1 and post-flood 2 periods among census tracts. 95% confidence intervals are shown. "*" over the confidence intervals (applicable only for the moderate, high, and very high quartiles) indicates the rate ratio among census tracts belonging to these CDC/ATSDR SVI quartiles was statistically different from the rate ratio among census tracts belonging to tracts with the least vulnerability, as determined by the significance (p-value <0.05) of the 3-way interaction term (β_5) in Equation 1.

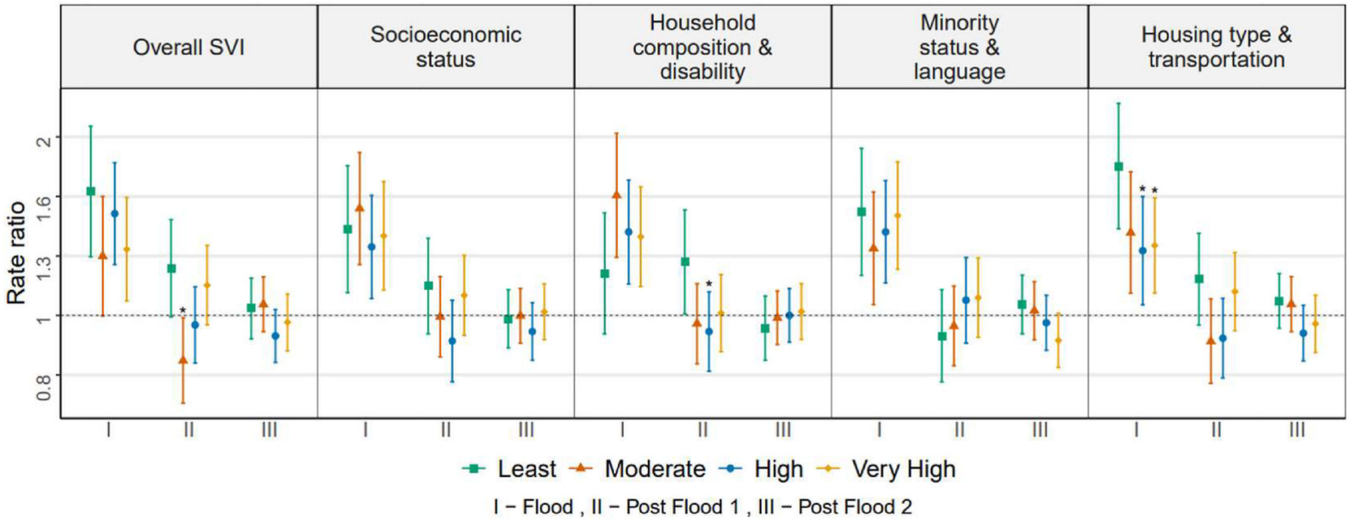

Fig. 5.

Overall CDC/ATSDR SVI and theme-specific CDC/ATSDR SVI quartile stratified rate ratios describing the association between flooding and ED visits related to intestinal infectious diseases during flood, post-flood 1 and post-flood 2 periods among census tracts. 95% confidence intervals are shown. “*” over the confidence intervals (applicable only for the moderate, high, and very high quartiles) indicates the rate ratio among census tracts belonging to these CDC/ATSDR SVI quartiles was statistically different from the rate ratio among census tracts belonging to tracts with the least vulnerability, as determined by the significance (p-value <0.05) of the 3-way interaction term (β_5) in Equation 1.

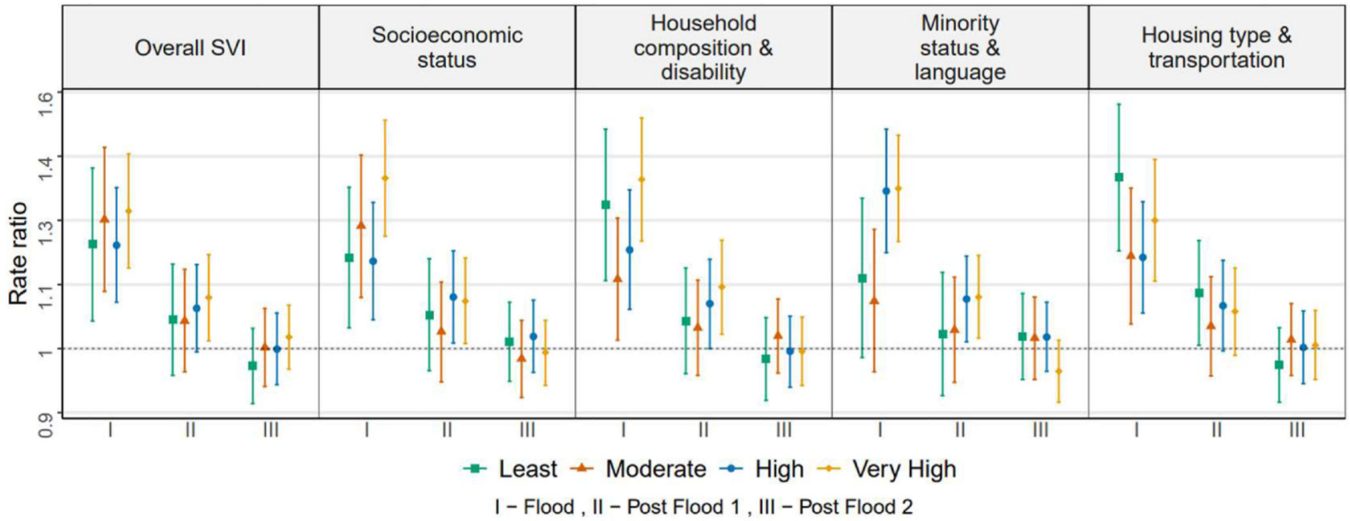

Fig. 6.

Overall CDC/ATSDR SVI and theme-specific CDC/ATSDR SVI quartile stratified rate ratios describing the association between flooding and ED visits related to pregnancy complications during flood, post-flood 1 and post-flood 2 periods among census tracts. 95% confidence intervals are shown. "*" over the confidence intervals (applicable only for the moderate, high, and very high quartiles) indicates the rate ratio among census tracts belonging to these CDC/ATSDR SVI quartiles was statistically different from the rate ratio among census tracts belonging to tracts with the least vulnerability, as determined by the significance (p-value <0.05) of the 3-way interaction term (β_5) in Equation 1.