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Time-series Analysis of Combined Sewer Overflows and Gastrointestinal Illness in
Atlanta, 2002 to 2013

By

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Time-series Analysis of Combined Sewer Overflows and Gastrointestinal Illness in Atlanta, 2002 to 2013

By

Alyssa Miller

B.S., University of Michigan, 2017

Thesis Committee Chair: Stefanie Ebelt, ScD & Karen Levy, PhD

An abstract of
A thesis submitted to the Faculty of the
Rollins School of Public Health of Emory University
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Abstract

Time-series Analysis of Combined Sewer Overflows and Gastrointestinal Illness in
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Background: Combined sewer overflows (CSOs) discharge untreated sewage into surface water, often following periods of heavy precipitation, elevating concentrations of potentially pathogenic microorganisms. Given the projected increase in frequency and severity of precipitation in the southeastern United States, it is important to understand the health impacts of CSOs to inform adaptation practices. For the period 2002-2013, this study estimated associations of CSO events and emergency department (ED) visits for gastrointestinal (GI) illness among Atlanta residents, and investigated neighborhood-level poverty as a potential effect modifier.

Methods: Associations were estimated using Poisson generalized linear models, controlling for time trends. CSO events were categorized as high, medium, or low based on overflow volume and summarized by week to assess the effect of any CSO event in the week prior to the ED visits. We also considered the effect of CSO events at a two- and three-week lag. Models controlling for precipitation were compared to unadjusted models to evaluate confounding by precipitation. Effect modification by ZIP Code Tabulation Area (ZCTA)-level (neighborhood) poverty was evaluated with the inclusion of an interaction term.

Results: In the city-wide analysis, occurrence of a high volume CSO event in the previous week was associated with daily ED visits for GI illness, independent of the effects of precipitation. We identified a significant interaction by ZCTA-level poverty, observing stronger CSO-GI illness associations in areas with low poverty (percent of residents living in poverty below the median) compared to areas with high poverty. Among areas with low poverty, we observed associations at both one-week and longer lags, following high volume as well as lower volume CSO events; comparatively, among areas with high poverty, we observed associations only at a one-week lag, following high volume events.

Conclusions: Our findings suggest CSO events in Atlanta contribute to the burden of acute GI illness for city residents, and the magnitude of this risk may be higher among populations living in areas with low poverty. Given the consistent, positive associations following high volume events, avoiding exposure to surface water in the weeks following these events may reduce risk of GI illness. Moreover, when considering the projected impact of climate change in the region, future infrastructure projects should aim to reduce volume of CSO discharges.

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Background

Climate change is projected to induce increased frequency and severity of precipitation in the southeastern United States under both low and high emissions scenarios (1). The region has already experienced greater number of days with extreme precipitation events and a 16% increase in five-year maximum daily precipitation (1). These changes in precipitation patterns may pose a direct risk to health. Prior epidemiologic research has linked heavy precipitation to a variety of outcomes, including gastrointestinal (GI) illness (2, 3). In Wisconsin, any rainfall was associated with an 11% increase in pediatric emergency department (ED) visits for acute GI illness (4), and in Massachusetts, flooding events were associated with an 8% increase in GI infections (5).

One exposure pathway that may contribute to the increased incidence of GI illness following precipitation is via the municipal water system, specifically for those municipalities with combined sewer systems (CSS). Rather than providing separate piping systems for rainwater runoff, domestic sewage and industrial wastewater, a combined sewer system collects all waters into a single common pipe. Wastewater treatment plants (WWTPs) have strict flow limitations; therefore, during very high flows, such as following a heavy precipitation event, a portion must be diverted away from the WWTP and discharged directly to a nearby receiving water (6). This discharge, prior to treatment, is termed a combined sewer overflow (CSO) event. CSO events can potentiate the impact of precipitation; in fact, a recent study estimated that following heavy rain, occurrence of a CSO event following heavy precipitation led to 10 times more sewage contamination than a heavy rain event alone (7). Therefore, areas with CSS are especially vulnerable to the effects of climate change because the projected increased intensity of rainfall is expected to lead to larger volume CSOs, and consequently, greater volume of pollutants discharged to surface bodies (7, 8).

Prior environmental studies have established decreased water quality following CSO events (9, 10). The occurrence of CSOs has been linked to increased levels of pathogens in receiving waterbodies, often surpassing guidelines set by the Environmental Protection Agency (EPA) (11). Pathogenic microorganisms found in CSO effluent include bacteria, viruses and protozoa such as *E. coli*, *Cryptosporidium*, *Salmonella*, *Giardia* and norovirus (11). Overall, these types of microorganisms account for a significant portion of enteric illness in the U.S. (11). Furthermore, recent studies have shown that bacteria in CSOs are often resistant to antibiotics, with the yearly discharge of antibiotic-resistant *E. coli* from CSO events 3.7-log larger compared to WWTP effluent (12). Routes of exposure to these pathogens following CSO events include ingestion (drinking water, cooking, etc.) or direct body contact (recreation) (7). Based on the prevalence of pathogenic microorganisms in waterbodies, the annual risk of contracting GI illness among recreators in areas with CSO outfalls is estimated to be as high as 68 percent in some areas, and even higher among vulnerable populations such as the homeless, according to a risk assessment performed by Donovan et al. (2008).

Although construction of CSSs is no longer permitted in the US, nearly 860 municipalities throughout the country still rely on these systems – including many in the Southeast (6). These systems can be a liability for cities – in the 1990’s Atlanta lost a lawsuit based on the failing stormwater collection and treatment systems that resulted in poor water quality. As a result, Atlanta has been required to invest over $2 billion in the city's CSS, including sewer separation projects targeted at improving area water quality and reducing CSOs. While these improvements have resulted in an 80% reduction of bacteria levels in the Chattahoochee River, the potential protective effect of a reduction in CSO events on health in the community has not been fully explored (13).

Although there are a variety studies linking occurrence of CSOs to increased concentrations of pathogenic microorganisms, there has been less focus on examining effects of CSOs on human health. Nonetheless, some studies have indicated an increased risk for GI infections related to CSO events. For example, in a case-crossover study Brokamp et al. (2017) identified a 16% increase in risk of ED visits for GI infections among children living within 500m of a CSO outfall location two days after a CSO event. In a similar study, children living in ZIP codes that used Lake Michigan as their drinking water source saw an additional 0.2 ED visits for GI illness in the three to seven days following high volume CSO events compared to no event (15). Finally, a recent study indicated towns with CSS that discharge to drinking water sources experience a 13% increase in GI infections following heavy precipitation events, while areas without CSS experience no significant increase in risk (2). Based upon these initial findings, and the projected impact of climate change in the Southeast, it is important to characterize the relationship between CSO events and GI illness in Atlanta.

In this study, we explore the association between combined sewer overflow events and ED visits for GI illness among Atlanta residents. Additionally, the study aims to identify populations at increased vulnerability to these effects by investigating the effect by area level poverty. From a public health perspective, this is important because it may enable cities to focus resources and interventions within areas that are especially vulnerable. We hypothesized that days with any CSO event in the previous 1-3 weeks would have significantly higher counts of ED visits for GI illness compared to days with no events in the specified period, and that areas with high poverty would have increased burden compared to those with those with low poverty.

Methods

Daily CSO event data for the City of Atlanta for the period January 1, 2002 through December 31, 2013 were obtained from the City of Atlanta Department of Watershed Management Quarterly Consent Decree Status Reports, available via the Consent Decree Document Repository (16). These reports, published as PDFs, were converted to Excel tables using Docparser optical character recognition software (https://docparser.com). Each report tabulated data on CSO events at each outfall location (n=7 locations) within the quarter, including date and volume of each discharge and various associated water quality indicators. These data were used to calculate daily and weekly summaries of CSO effluent across the locations. Daily precipitation data for the study period were obtained from the weather station at Atlanta Hartsfield Jackson Airport. Daily precipitation data were used to calculate weeklong cumulative sums of precipitation.

Data on ED visits to Metro Atlanta area hospitals were obtained for the 2002-2013 period. Specifically, patient-level electronic billing records data on ED visits were acquired directly from individual hospitals (for the period 2002-2004) and from the Georgia Hospital Association (for the period 2005-2013). Data were restricted to patients living in ZIP codes covering land within the boundaries of the City of Atlanta. We assessed daily counts of ED visits for GI outcomes, defined by primary and secondary International Classification of Disease, Version 9 (ICD-9) codes 001-009d. Use of the ED data was in accordance with agreements with the hospitals and the Georgia Hospital Association, and this study was approved prior to its conduct by the Emory University Institutional Review Board.

Neighborhood-level SES was obtained via the American Community Survey (ACS) 5-year (2007-2011) summary file (17). Estimates of ZCTA-level percent of population living below the federal poverty line were used as a proxy for neighborhood-level SES to examine SES as an effect modifier. The continuous poverty variable was dichotomized to high and low poverty based on an a priori cut point above and below the median.

All analyses were performed using SAS statistical software (SAS Institute, Inc., Cary, NC). We examined univariate statistics for CSO events, precipitation, and the daily count of ED visits for GI infections, as well as correlations between these variables using Pearson and Point-Biserial correlation statistics. Daily and weekly time series plots of ED visits for GI illness, total volume of CSO discharges and precipitation were evaluated across the study period.

Multivariable analyses were conducted using Poisson generalized linear models allowing for overdispersion. Primary models assess the city-wide effect of CSO events on daily ED visits for GI illness. The basic form of the model is given by:

$$Log(ED_t) = \alpha + \beta_i \mathrm{CSO}_{ti} + \gamma_i precip_{ti} + \gamma_4 weekend_{ti} + \gamma_5 season_{ti} + \gamma_7 holiday_{ti} + \gamma_j hosp_{ti} + ns(t, degrees\ of\ freedom = 4)\ , \qquad \text{Equation 1}$$

where ED_t refers to the count of the ED visits for GI infections on day *t*. The dichotomous variable CSO_{ti} represents the occurrence of any CSO event in the one week prior (lag 0-6 day summary), two weeks prior (lag 7-12 day summary), or three weeks prior (lag 13-20 day summary). We considered the occurrence of a CSO event over a period of 21 days because incubation time and symptomatic periods for GI illnesses has been shown to last up to three weeks (18). We considered models that included the weekly sum of precipitation ($precip_{ti}$), at the same lag as the CSO event terms, and compared these to models that did not include precipitation as a covariate to identify potential confounding by precipitation. All models included indicator variables to control for weekends, season (Winter, Spring, Summer and Autumn), federal holidays, and periods of hospital participation. Long term time trends were additionally controlled with cubic splines with seasonal knots (Winter, Spring, Summer and Autumn). We estimated rate ratios (RR) for the effect of any CSO event in the given week, compared to no event, by exponentiating the beta coefficient (β) from these models.

Second, to evaluate the effect of CSOs on ED visits for GI illness with varying exposure definitions based on volume of CSO event and comparison groups, we modeled

$$Log(ED_t) = \alpha + \beta_{1i} low_{it} + \beta_{2i} med_{it} + \beta_{3i} high_{it} + \gamma_i precip_{ti} + \gamma_4 weekend_{ti} + \gamma_5 season_{ti} + \gamma_7 holiday_{ti} + \gamma_j hosp_{ti} + ns(t, degrees\ of\ freedom = 4)\ , \quad \text{Equation 2}$$

where all variables are as specified in model 1. Dummy variables were created indicating low volume CSO events (i.e., events <25th percentile of volume), medium volume events (i.e. events 25th-75th percentile of volume) and high-volume events (i.e. events ≥75th percentile). Each of these variables was summed across the week prior, 2 weeks and 3 weeks to create an indicator for any CSO event of a given level in the specified week as in the primary model. We assessed the effect of high-volume events in the week prior, 2 weeks prior and 3 weeks prior compared to weeks with no high-volume event, as well as compared to weeks with medium volume events and weeks with low volume events. Additionally, we estimated the individual effect of high-volume events, medium volume events and low volume events compared to no event.

To identify potential effect modification by area level poverty, these analyses were repeated by including a product term of CSO event * poverty. To assess significance of the interaction, the likelihood ratio test statistic for the product term was assessed at an alpha of 0.1. For models with multiple product terms, evidence of significant interaction was evaluated using likelihood ratio chunk tests for multiple predictors.

Finally, we carried out a sensitivity analysis for various cut points to assess the importance of the volume of the CSO event. We assessed the effect of any event ≥ 67th percentile of volume and ≥ 85th percentile of volume in the one week prior, 2 weeks prior or 3 weeks prior compared to no event in that time frame. The effect estimates were compared to the primary results (high volume event defined as ≥ 75th percentile) to identify potential cut points indicating especially increased risk for GI infections.

Results

Data on CSO events in the City of Atlanta were available for all but five quarters (459 days) across the 4,366 day study period (2002-2013); these periods were coded as missing in the analysis. During the 12-year study period the City of Atlanta reported 725 CSO events across seven outfall locations, with an average of 1.16 events per week (**Table 1**, **Figure 1**). The average total effluent per event was 55,522 kgals. These events were spread disproportionately throughout the year, with the highest average number of events occurring in the summer (1.84 events/week) followed by the winter (1.26 events/week), spring (1.20 events/week) and fall (0.98 events/week). Conversely, the average volume of effluent per event was highest in the fall, followed by the spring, winter and summer. High volume events (total discharge ≥ 75th percentile of volume) had an average volume of effluent of 174,458 kgals compared to medium volume events (total discharge between 25th and 75th percentile of volume) with average discharge of 22,954 kgals and low volume events (total discharge < 25th percentile of volume) with average discharge of 1,901 kgals. **Figure 2** shows the total daily volume of CSO effluent per day across the study period, highlighting events above various high-volume event cut-points utilized in the main epidemiologic analysis and sensitivity analyses.

Because CSO events are most often triggered by heavy precipitation, we explored the distribution of CSO events following various categories of weeklong precipitation (**Tables 1 & 2**; **Figure 3**). There was a clear trend showing that as precipitation in the preceding week increased, the number and volume of CSO events also increased. A total of 15.51 percent (476 days) of days with no CSO event occurred after a week with no precipitation compared to 1.54 percent (11 days) of days with CSO events.

Comparatively, 60.64 percent (107 days) of days with high volume events fell after weeks where the sum of precipitation was ≥ 75th percentile, followed by 31.01 percent (111 days) of days with medium volume events, 24.02 percent (43 days) of days with low volume events and 22.04 percent (676 days) of days with no CSO event. A time-series of weekly sum of precipitation alongside weeks with various levels of CSO events is shown in **Figure 4**.

There were 22,079 ED visits for GI infections among patients visiting metropolitan Atlanta hospitals whose billing ZIP code encompassed City of Atlanta property; this equated to an average of 5.05 visits per day (**Table 3**). The average number of visits per day was highest in the winter (6.07 visits/day), followed by the spring (5.59 visits/day), fall (4.60 visits/day) and summer (4.00 visits/day). Across categories of the preceding week-long sum of precipitation, the average number of ED visits for GI infection was fairly consistent, with the highest mean following weeks without precipitation (5.36 visits per day) and the lowest following weeks with <50th percentile of precipitation (4.85 visits per day). From the daily time-series plot of ED visits for GI infection, normalized to the total number of ED visits reported, we can see that cases tend to peak in the winter months and number of visits increases across the study period (**Figure 5**).

Across Atlanta ZCTAs, summarized from 2007-2011, the minimum percent of residents living in poverty was 2.20 percent and the maximum was 35.60 percent. The median percent of residents living in poverty was 14.7 percent; this value was used to categorize ZCTAs into high poverty areas (ZCTAs with poverty >14.7%) and low poverty areas (ZCTAs with poverty ≤14.7%) (**Figure 1**). Areas with high poverty contributed an average of 3.07 ED visits for GI infection per day, whereas areas with low poverty contributed an average of 1.98 visits per day (**Table 3**).

Table 4 and **Figure 6** present associations between ED visits for GI infections and CSO events 1-3 weeks prior for models with and without sum of weekly precipitation in the given week. There was no association between a CSO event of any volume in the prior week and ED visits for GI infections when compared to weeks with no events. Regardless of the inclusion of precipitation in the model, occurrence of a high volume CSO event in the prior week was associated with an increase in ED visits for GI infections when compared to no event (adjusted for precipitation, RR = 1.09; 95% CI: 1.03, 1.14), medium volume events (adjusted for precipitation, RR = 1.07; 95%CI: 1.01, 1.14) or low volume events (adjusted for precipitation, RR = 1.11; 95% CI: 1.04, 1.19). Occurrence of a medium volume event or a low volume event in the prior week was not associated with an increase in ED visits for GI infections in our city-wide analyses. Across all CSO exposure definitions, there was no association with GI infections for events 2 weeks prior or 3 weeks prior to the visit. In general, adjusting for precipitation led to stronger estimates of the association; however, the parameter estimate related to weekly precipitation was significant only in models of the prior week where CSO events are stratified by volume.

Results of a sensitivity analysis in which exposure volume categories were varied are shown in **Table 4** and **Figure 6**. When CSO events were categorized by volume tertiles, the association between events ≥ 67th percentile and ED visits for GI infections was weakened compared to high volume events defined as upper quartile however, when adjusting for precipitation, there was still a significant association between ED visits for

GI infections and occurrence of an event ≥ 67th percentile in the prior week compared to no event (RR = 1.05; 95% CI: 1.00, 1.11). Following the pattern from the primary analyses, there were no significant associations for lower tertile events in the prior week or CSO events of any size occurring outside of the one-week time frame. When CSO events were categorized as low for volumes <15th percentile, medium for volumes 15th to 85th percentile, and high for volumes ≥85th percentile, we found no association between CSO events and ED visits for GI infections with the exception of events ≥85th percentile in the past week compared to no event when adjusted for precipitation (RR = 1.06; 95% CI: 1.01, 1.03). Interestingly, the stricter cut-off for high volume events (85th percentile) also showed an attenuated risk when compared to high volume events in the primary analysis (upper quartile events).

Table 5 and **Figure 7** present associations between ED visits for GI infections and occurrence of a CSO event (compared to no event and adjusted for precipitation) allowing for effect modification by ZCTA-level poverty. At an alpha of 0.1, there was evidence of significant interaction by poverty in five out of the six models. In general, the effect of CSO events on ED visits was higher in areas with low poverty. Among low poverty areas, there was a 12 percent increase in the number of ED visits for GI infections when there was a high volume CSO in the prior week (RR = 1.12; 95% CI: 1.05, 1.20). Among high poverty areas, the CSO effect was lower than that in low poverty areas, but still significant (RR = 1.06; 95% CI: 1.00, 1.13). Medium volume and low volume events in the prior week had no significant effect on ED visits for GI infections among high or low poverty areas. Among low poverty areas, ED visits for GI infections were associated with the occurrence of any CSO event (RR = 1.08; 95% CI:

1.02, 1.14), a high volume event (RR = 1.12, 95% CI: 1.05, 1.20) and a medium volume event (RR = 1.06; 95% CI = 1.00, 1.12) two weeks prior. There was no association between CSO events two weeks prior and GI infections among areas with high poverty. Finally, there was an association between ED visits for GI infections and any CSO event three weeks ago (RR = 1.07, 95% CI: 1.01, 1.14) as well as medium volume events three weeks ago (RR = 1.07, 95% CI = 1.01, 1.13) among low poverty areas; we found no such associations among high poverty areas.

Discussion

The current findings provide evidence of increased risk from high volume CSO events for ED visits for GI infections, independent of precipitation. For the population as a whole, we observed a 9 percent (95% CI: 3-14%) increase in ED visits following a week with at least one high volume event, but no increase for events in the prior 2- or 3-week periods. Contrary to our initial hypothesis, among areas with low poverty, the risk of ED visits for GI infection when a CSO event occurred in the prior week was exacerbated; for these neighborhoods, we observed a 12 percent increase in ED visits (95% CI: 5-20%). Among areas with high poverty, however, the pattern of risk following CSO events was similar to the study population as a whole. Furthermore, among areas with low poverty, we observed increased risk for GI infections two and three weeks after a CSO event. Our findings indicated these areas are also more sensitive to volume of effluent; in addition to high volume events, we observed significant positive associations following medium volume events among low poverty areas.

Several biological and environmental pathways may contribute to the observed findings. Because higher volume CSO events discharge a greater magnitude of untreated sewage, they may increase the concentration of pathogens in surface water past an acceptable threshold (7, 8). Medium and low volume discharges, on the other hand, may not release enough sewage to consistently reach this threshold. This could contribute to why we observe a population-wide effect following high, but not low or medium volume events.

A variety of pathogenic microorganisms that cause enteric disease are found in untreated sewage (7, 11). These pathogens have a diverse set of incubation and symptomatic periods. For example, symptoms of cryptosporidiosis typically begin two to 10 days following exposure and can last up to four weeks (18). Comparatively, norovirus symptoms begin within two days of exposure and tend to subside within three days (19). This variation in time of first onset of symptoms and symptom duration could contribute to the variable timing in visits to the ED (from 1 to 3 weeks after CSO events).

Interestingly, our initial hypothesis, that the CSO-GI association would be stronger in high poverty areas, was not supported by this analysis. Instead, our findings suggest the association is stronger among areas with lower poverty. The potential for exposure to occur through multiple routes, including drinking water or recreation, could contribute to the excess risk in areas with low poverty. Studies have shown a positive relationship between SES and leisure time physical activity (20). In Atlanta, this may mean high SES individuals have more access to recreational opportunities on the Chattahoochee River, for example. Therefore, these individuals could have greater exposure via recreational pathways in contrast with low SES individuals, who may predominantly be exposed through the municipal drinking water system.

Although our findings indicate a stronger association between CSO events and GI infections for areas with low poverty, it is important to note that a disproportionate number of ED visits for GI infections come from areas with a high percentage of residents living in poverty (n = 13,408 vs. n = 8,631). Thus, even though the estimated effect in areas with high poverty is smaller than among areas with low poverty, a greater share of individuals visiting the ED following CSO events may be from areas with high poverty because we are estimating relative, and not absolute, risks. There are a variety of challenges related to neighborhood level socioeconomic status that may contribute to the disproportionate number of ED visits for GI infections from areas where a high percentage of individuals live in poverty. These underlying challenges include increased rates of obesity and chronic disease, that may increase severity of GI infections, availability of health insurance, and access to primary care (21).

Results from a sensitivity analysis where cut-points for CSO event volume categories were varied provided mixed results. While a relaxed cut-point for high-volume events resulted in an attenuated risk for ED visits for GI infections, a stricter cut-point also produced an attenuated effect estimate. This suggests that there is not a linear dose-response relationship between volume of discharge and risk of GI infection. One possible explanation for this finding is that for very high volume CSOs the concentration of pathogens in the discharge is diluted. Prior studies of the effect of precipitation on GI illness support this explanation: Levy et al. (2016) describes a “dilution effect”, in which heavy precipitation events initially flush out pathogens, but then dilute their concentration in a water source as the event progresses. In general, however, additional evidence from our study (i.e. greater risk for GI infections following high volume events compared to medium and low volume events) supports the notion that volume of CSO effluent is positively associated with risk.

There are a limited number of studies that have examined the role of CSO events in GI illness; nevertheless, results from previous analyses are consistent with our findings.

In Milwaukee, Redman et al. (2007) found a 50 percent increase in pediatric ED visits for diarrheal illness 3-7 days after high volume CSO events among people who lived in areas that used Lake Michigan drinking water sources. Similarly, Brokamp et al. (2017) identified a 16 percent increase in pediatric GI-related visits two days after CSO events in Cincinnati for children living within 500m of an outfall site. While these studies support our findings of a temporal association between CSO events and ED visits for GI infections, there are some key distinctions. First, neither analysis explored a lagged effect past one week; however, our study identified significant effects as far as three weeks out for low poverty areas. Second, both studies were restricted to the pediatric population, which may contribute to the higher estimated risk from their analyses. Finally, our study examined the population level effect, rather than restricting to areas deemed vulnerable *a priori*, which may also contribute to the higher observed risk in the aforementioned studies.

Further support for the observed association between CSO events and GI illness comes from a spatial analysis in Massachusetts where the authors found that presence of CSOs modified the effect of heavy rainfall events (2). Areas with CSOs discharging to drinking water sources experienced an increase in ED visits for GI infections in the eight-day period following extreme precipitation; however, in areas with CSOs discharging to recreational water bodies or without combined sewer systems there was no association (2). The authors reported similar results for the 15-day period following extreme precipitation events, providing some support for the lagged effect of CSO events observed in the current study (2).

There are a variety of strengths associated with the design of the current study. First, we were able to access detailed data describing CSO events in Atlanta. This enabled us to establish temporality between occurrence of CSO events and ED visits for GI infections. Additionally, the exposure data included measures of volume that supported an investigation into potential dose-response relationships between size of event and GI infections. Because the study period extended across 11 years, we were able to minimize bias due to long-term temporal trends within the analyses. Finally, because we were able to access ED visit data for the majority of Atlanta metropolitan hospitals, we could estimate population-level effects, in addition to stratifying by neighborhood-level SES.

The use of ED visits for GI infections as an indicator for overall GI infections is a limitation of this study. Although this practice is commonly used in epidemiological studies, only a small percentage of individuals with GI infections visit the ED, and these patients may not be representative of all cases (2). This may be of particular importance for our investigation of effect modification by neighborhood-level poverty, because SES may influence the location where an individual seeks care. Since the hospital records did not provide individual level data, ZCTA-level poverty was used as a proxy for individual indicators of SES; however, some studies have demonstrated that when an aggregated variable is expressed as a proportion and defined by internal cut-points, as in our study, we can expect the impact of the bias to be null (23). Ideally precipitation would be measured at each outfall location, but these data were not available for this analysis. Instead, the use of a single precipitation measurement at Atlanta Hartsfield Jackson Airport introduces spatial incompatibility between study population and collected rainfall data. This measurement error would tend to bias the estimated effect of rainfall on GI illness towards the null (24).

In conclusion, our findings, taken into context with those from previous studies, suggest that occurrence of high volume CSO events may increase risk for GI infections for all neighborhoods. This effect is stronger (on a relative scale) in neighborhoods with low levels of poverty compared to high levels of poverty. This suggests warning systems that notify the public following high volume CSO events and communicate the potential for exposure throughout the following 3-week period, may prevent some of the burden of GI illness in areas with CSSs. Furthermore, taking into account our findings and the projected increase in frequency and severity of extreme precipitation as a result of climate change, it will be important for future infrastructure projects to reduce volume of CSO effluent, rather than simply reducing number of events, to lower the burden of GI infection in Atlanta and elsewhere (Fourth National Climate Assessment, 2018).

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Tables

Table 1: Number of days with combined sewer overflow (CSO) events and average volume of effluent per event in Atlanta, 2002-2013. SD = standard deviation

	CSO events		Avg Volume per Event	
	No	Avg Per Week	Vol (kgals)	SD
Overall	725	1.16	55,522	116,192
Season				
Winter	176	1.26	52,561	72,754
Spring	168	1.20	61,548	105,726
Summer	258	1.84	48,286	144,227
Fall	123	0.98	66,705	113,441
Precipitation - week long sum				
≥ 95th percentile	61	---	125,850	191,481
75th - 95th percentile	200	---	75,373	95,030
50th-75th percentile	240	---	44,244	66,534
< 50th percentile	203	---	27,288	139,936
No Precipitation	11	---	70,631	116,737
CSO Volume Categories				
High Volume Events [a]	181	0.29	174,458	186,241
Medium Volume Events [b]	363	0.58	22,954	13,348
Low Volume Events [c]	181	0.29	1,901	1,866

[a] CSO event ≥ 75th percentile of volume for CSO events in Atlanta 2002-2013
[b] CSO event 25th - 75th percentile of volume for CSO events in Atlanta 2002-2013
[c] CSO event < 25th percentile of volume for CSO events in Atlanta 2002-2013

Table 2: Number and percent of combined sewer overflows (CSOs) by sum of precipitation within the week, Atlanta, 2002-2013.

	Week-Long Sum of Precipitation n (%)				
CSO Volume Categories	No Precip	<50th percentile	50th-75th percentile	≥ 75th percentile	Total
High Volume [a]	3 (1.69)	11 (6.18)	57 (32.02)	107 (60.64)	178
Medium Volume [b]	2 (0.56)	114 (31.84)	131 (36.59)	111 (31.01)	358
Low Volume [c]	6 (3.35)	78 (43.58)	52 (29.05)	43 (24.02)	179
No Event	476 (15.51)	1,204 (39.24)	712 (23.21)	676 (22.04)	3,068

[a] CSO event ≥ 75th percentile of volume for CSO events in Atlanta, 2002-2013

[b] CSO event 25th - 75th percentile of volume for CSO events in Atlanta, 2002-2013

[c] CSO event < 25th percentile of volume for CSO events in Atlanta, 2002-2013

Table 3: Average number of emergency department (ED) visits for gastrointestinal (GI) infections by patients living in City of Atlanta ZIP codes, 2002-2013. SD = standard deviation

	ED visits for GI Infections (*n* = 22079)	
	Mean # Per Day	SD
Overall	5.05	3.54
Season		
Winter	6.07	4.12
Spring	5.59	3.79
Summer	4.00	2.69
Fall	4.60	3.00
Precipitation - week long sum		
≥ 95th percentile	5.02	4.07
75th - 95th percentile	5.15	3.62
50th-75th percentile	5.17	3.64
< 50th percentile	4.85	3.32
No Precipitation	5.36	3.61
ZCTA Poverty %		
High [a]	3.07	2.62
Low [b]	1.98	1.67

[a] Zip Code Tabulated Area Percent Poverty ≥ 50th percentile for Atlanta, American Community Survey, 2007-2011

[b] Zip Code Tabulated Area Percent Poverty < 50th percentile for Atlanta, American Community Survey, 2007-2011

Table 4: Estimated Rate Ratios (RR) and 95% Confidence Intervals (CI) for the Effect of CSO events within a Given Week on Daily Count of ED Visits for GI Infections in Atlanta, 2002-2013

	1 week prior		2 weeks prior		3 weeks prior	
	RR	95% CI	RR	95% CI	RR	95% CI
Model with CSO as dichotomous variable						
Any Event [a] vs No Event						
Unadj for Precipitation	1.01	0.97-1.05	1.01	0.97-1.05	1.02	0.98-1.06
Adj for Precipitation [e]	1.03	0.98-1.07	1.03	0.98-1.07	1.02	0.98-1.06
Model with CSO defined by volume, 4-level variable						
High Vol Event [b] vs Other						
Unadj for Precipitation	1.05*	1.01-1.09	1.01	0.97-1.05	1.03	0.97-1.07
Adj for Precipitation	1.09*	1.03-1.14	1.03	0.98-1.08	1.03	0.98-1.09
High Vol Event vs Med Vol						
Unadj for Precipitation	1.05*	1.00-1.12	1.01	0.96-1.07	1.02	0.97-1.08
Adj for Precipitation	1.07*	1.01-1.14	1.03	0.97-1.09	1.03	0.97-1.09
High Vol Event vs Low Vol						
Unadj for Precipitation	1.08*	1.02-1.15	0.98	0.93-1.04	1.03	0.97-1.09
Adj for Precipitation	1.11*	1.04-1.19	1.00	0.94-1.07	1.03	0.97-1.10
High Vol Event vs No Event						
Unadj for Precipitation	1.05*	1.01-1.09	1.01	0.97-1.05	1.03	0.99-1.07
Adj for Precipitation	1.09*	1.03-1.14	1.03	0.98-1.08	1.03	0.98-1.09
Med Vol Event [c] vs No Event						
Unadj for Precipitation	0.99	0.95-1.03	0.99	0.96-1.03	1.00	0.96-1.04
Adj for Precipitation	0.99	0.96-1.03	1.00	0.96-1.04	1.01	0.96-1.05
Low Vol Event [d] vs No Event						
Unadj for Precipitation	0.97	0.92-1.01	1.02	0.98-1.07	1.00	0.96-1.05
Adj for Precipitation	0.98	0.93-1.02	1.03	0.98-1.08	1.00	0.96-1.05
Sensitivity Analysis						
≥ 67th percentile vs No Event						
Unadj for Precipitation	1.03	0.99-1.07	1.00	0.97-1.04	1.03	0.99-1.07
Adj for Precipitation	1.05*	1.00-1.11	1.02	0.97-1.07	1.03	0.99-1.08
≥ 85th percentile vs No Event						
Unadj for Precipitation	1.04	0.99-1.09	1.03	0.98-1.07	1.02	0.97-1.07
Adj for Precipitation	1.06*	1.01-1.13	1.06	1.00-1.12	1.02	0.97-1.08

* indicates significant CSO-GI association $(\alpha = 0.05)$

[a] CSO event of any volume

[b] CSO event ≥ 75th percentile of volume for CSO events in Atlanta, 2002-2013

[c] CSO event 25th - 75th percentile of volume for CSO events in Atlanta, 2002-2013

[d] CSO event <25th percentile of volume for CSO events in Atlanta, 2002-2013

[e] Sum of precipitation within the specified week included in model

Table 5: Estimated Rate Ratios (RR) [a] and 95% Confidence Intervals (CI) for the Effect of CSO events within a Given Week on Daily Count of ED Visits for GI Infections in Atlanta, 2002-2013, Allowing for Effect Modification by ZCTA-Level Poverty

		1 week prior		2 weeks prior		3 weeks prior	
		RR	95% CI	RR	95% CI	RR	95% CI
Any Event [c]							
High Poverty [b] (n = 13,408)		1.01	0.96-1.06	**1.00**	**0.95-1.05**	**0.99**	**0.94-1.04**
Low Poverty (n = 8,631)		1.05	0.99-1.12	**1.08***	**1.02-1.14**	**1.07***	**1.01-1.14**
Event Volume Categories							
High Volume [d]	High Poverty	**1.06***	**1.00-1.13**	**0.97**	**0.92-1.03**	**1.02**	**0.96-1.08**
	Low Poverty	**1.12***	**1.05-1.20**	**1.12***	**1.05-1.20**	**1.06**	**0.99-1.13**
Med Volume [e]	High Poverty	**0.98**	**0.94-1.03**	**0.96**	**0.92-1.01**	**0.97**	**0.92-1.01**
	Low Poverty	**1.05**	**0.99-1.11**	**1.06***	**1.00-1.12**	**1.07***	**1.01-1.13**
Low Volume [f]	High Poverty	**0.97**	**0.91-1.02**	**1.03**	**0.98-1.09**	**0.97**	**0.92-1.03**
	Low Poverty	**0.98**	**0.92-1.05**	**1.02**	**0.96-1.09**	**1.05**	**0.98-1.12**

[a] all estimates adjusted for precipitation, reference group no event
[b] ZTCA Percent Poverty ≥ 50th percentile for Atlanta, American Community Survey, 2007-2011
[c] CSO event of any volume
[d] CSO event ≥ 75th percentile of volume for CSO events in Atlanta, 2002-2013
[e] CSO event 25th - 75th percentile of volume for CSO events in Atlanta, 2002-2013
[f] CSO event <25th percentile of volume for CSO events in Atlanta, 2002-2013
* indicates significant CSO-GI association ($\alpha = 0.05$)
Bolded values indicate significant interaction by poverty($\alpha = 0.1$)

Figures

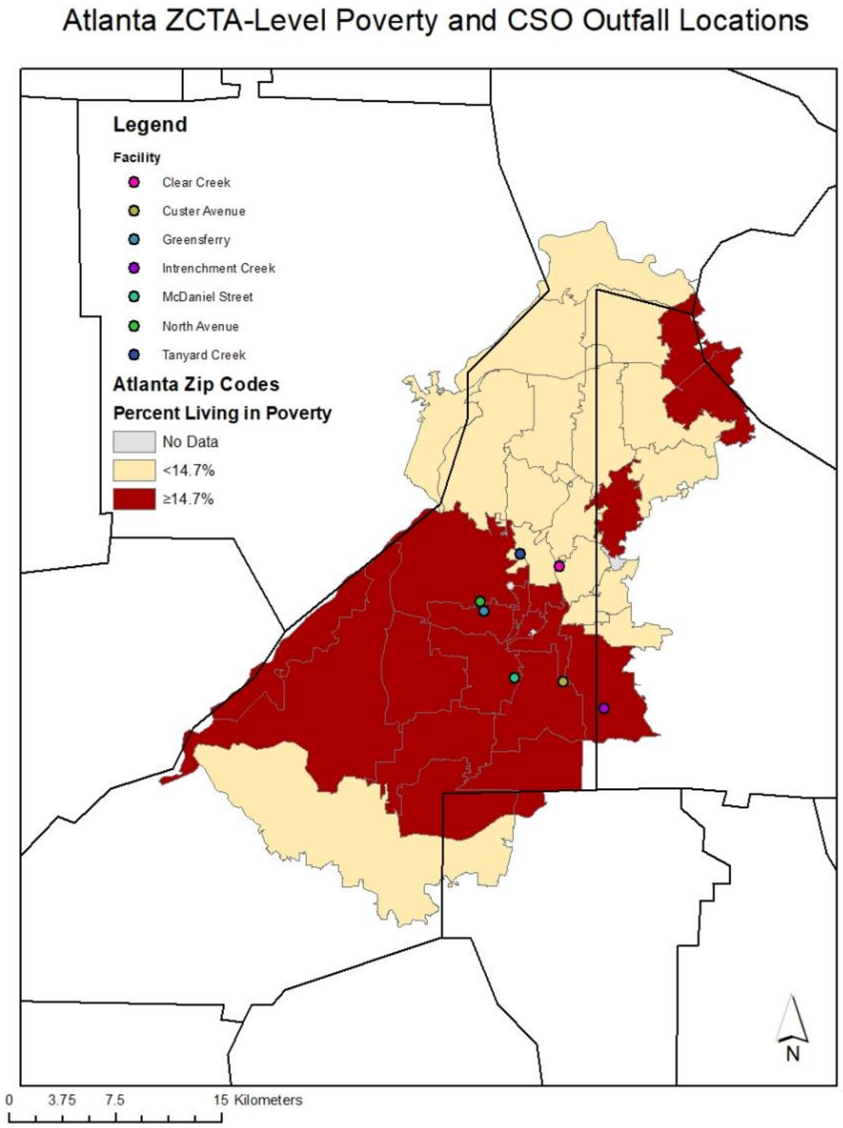


Figure 1. Distribution of poverty by ZIP code tabulation area (ZCTA) and combined sewer overflow (CSO) outfall locations in Atlanta, GA. Poverty classification determined by percent of residents living in poverty above (high poverty, red) and below (low poverty, yellow) the median for Atlanta (14.7%), 2007-2011. CSO outfall locations as documented by City of Atlanta Department of Watershed Management, 2002-2013.

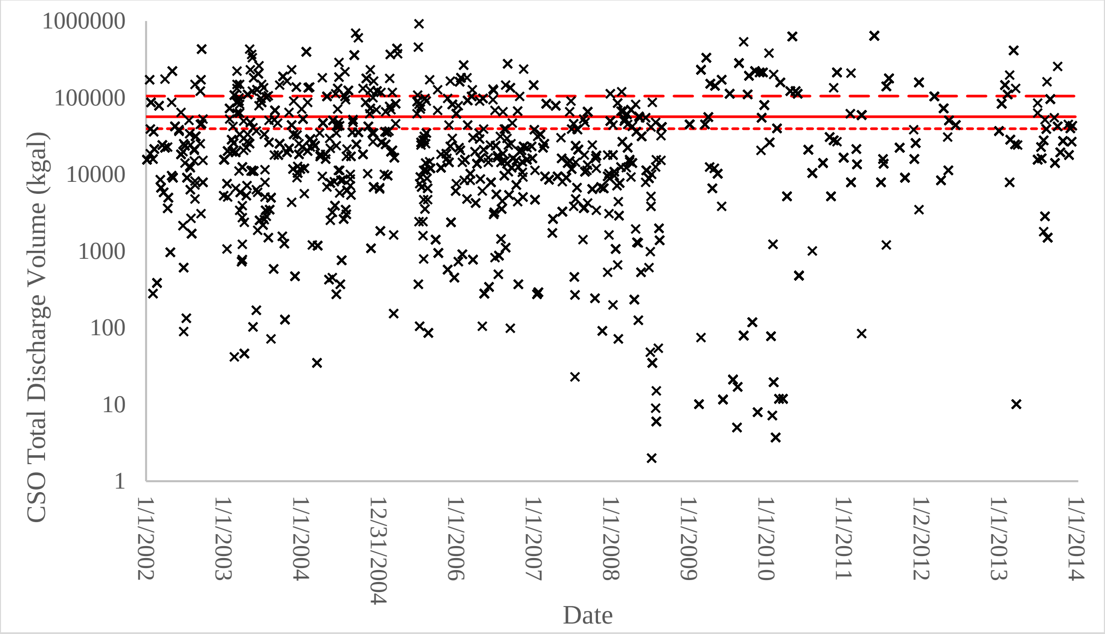


Figure 2. Time series plot of combined sewer overflow (CSO) discharges by volume (kgals), 2002-2013. Event volumes are plotted on a logarithmic scale. Red lines indicate high volume event cut-points utilized in primary (— , 75th percentile or 56,548 kgal), and secondary analyses (- - - , 67th percentile or 39,088 kgal; — — , 85th percentile or 105,704 kgal).

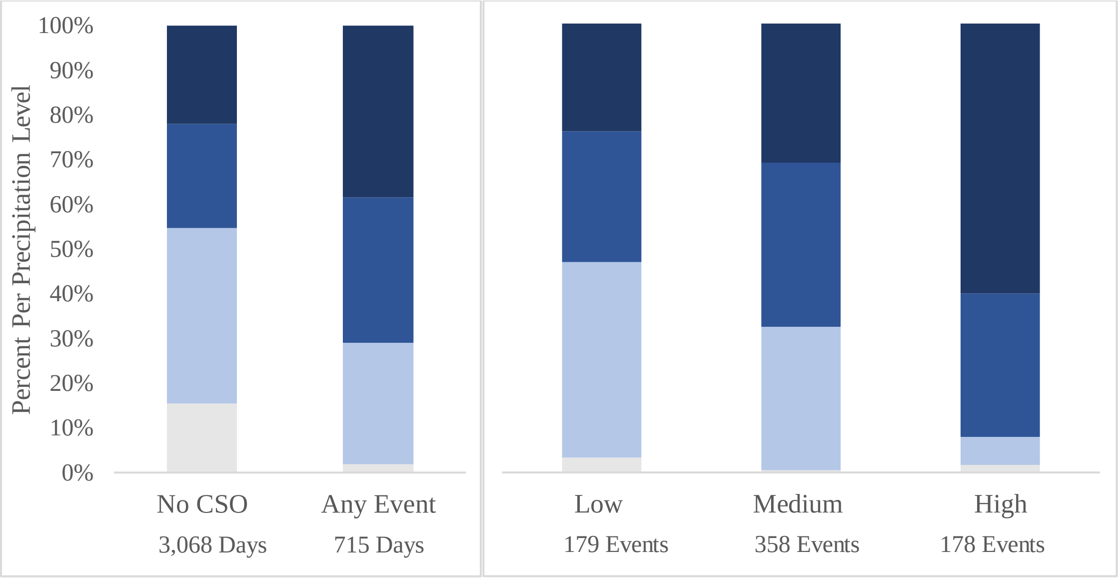


Figure 3. Percent of combined sewer overflow (CSO) events following various levels of weeklong precipitation. Events <25th percentile of volume defined as Low Volume, events 25th-75th percentile of volume defined as Medium Volume, and events ≥ 75th percentile of volume defined as High Volume. No precipitation in previous week (░), <50th percentile of precipitation (▒), 50th -75th percentile of precipitation (▓), ≥75th percentile of precipitation (█). Precipitation data collected at Hartsfield Jackson Airport, Atlanta, GA, 2002-2013.

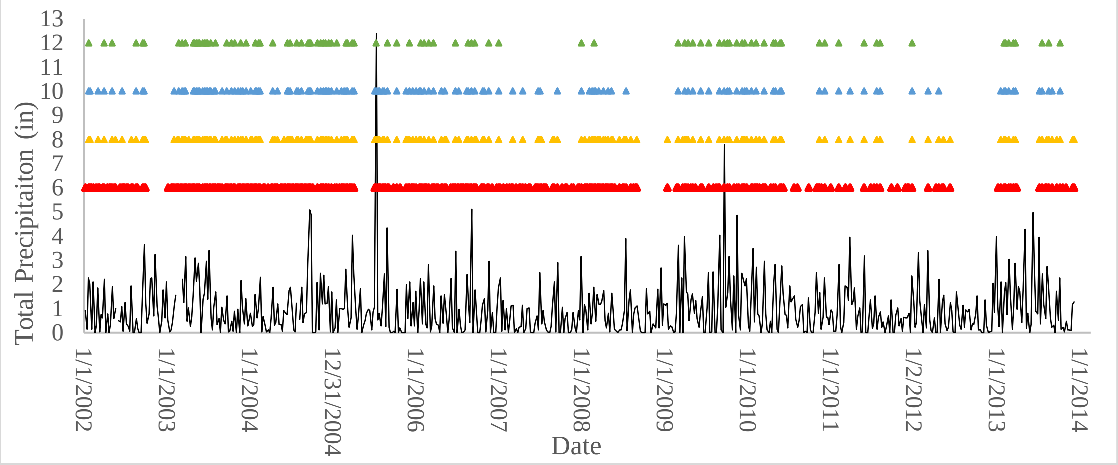
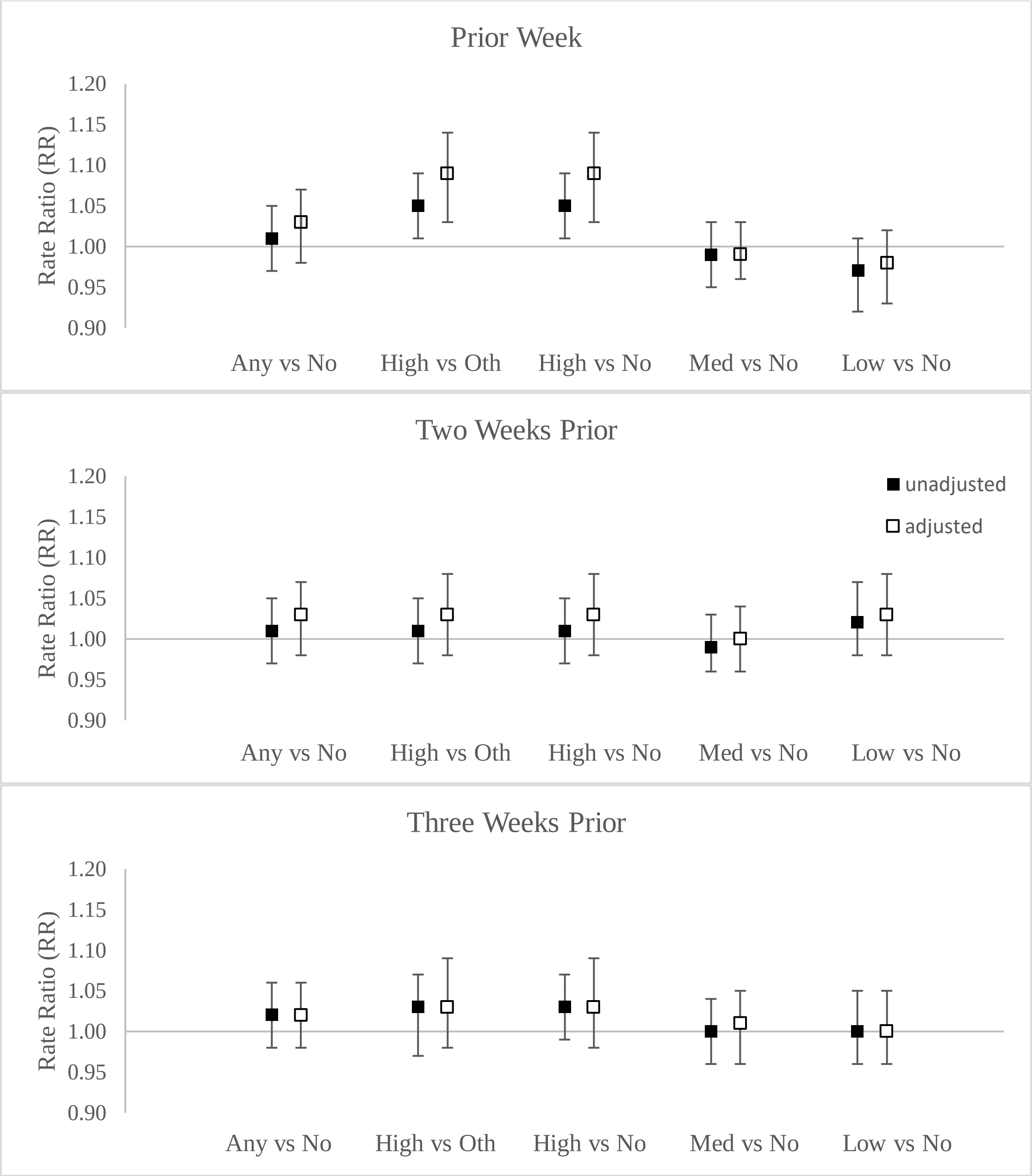


Figure 4. Time series plot of weekly sum of precipitation at Atlanta Hartsfield Jackson overlayed with the occurence of CSO events of various volumes within the week in Atlanta, GA, 2002-2013. Red triangles indicate weeks with any CSO event, yellow triangles indicate weeks with an event ≥67th percentile of volume (39,088 kgals), blue triangles indicate week with an event ≥75th percentile of volume (56,548 kgals), and green triangles indicate weeks with an event ≥85th percentile of volume (105,704 kgals).



Prior Week

Two Weeks Prior

Three Weeks Prior

Figure 5. Comparison of rate ratios (RRs) and 95% confidence intervals for the association between emergency departemt (ED) visits for gastrointestinal (GI) infections and combined sewer overflow (CSO) events of various volumes in the specified week, adjused and unadjusted for weekly sum of precipitation, Atlanta, GA, 2002-2013. Any is a CSO event of any volume. High volume events are defined as an event ≥75th percentile of volume, medium (Med) volume events are defiend as an event 25th-75th percentile of

volume, and low volume events are defined as an event <25th percentile of volume. Comparison groups are no event in the specified week (no), and no event or low/medium volume event in the specified week (oth).

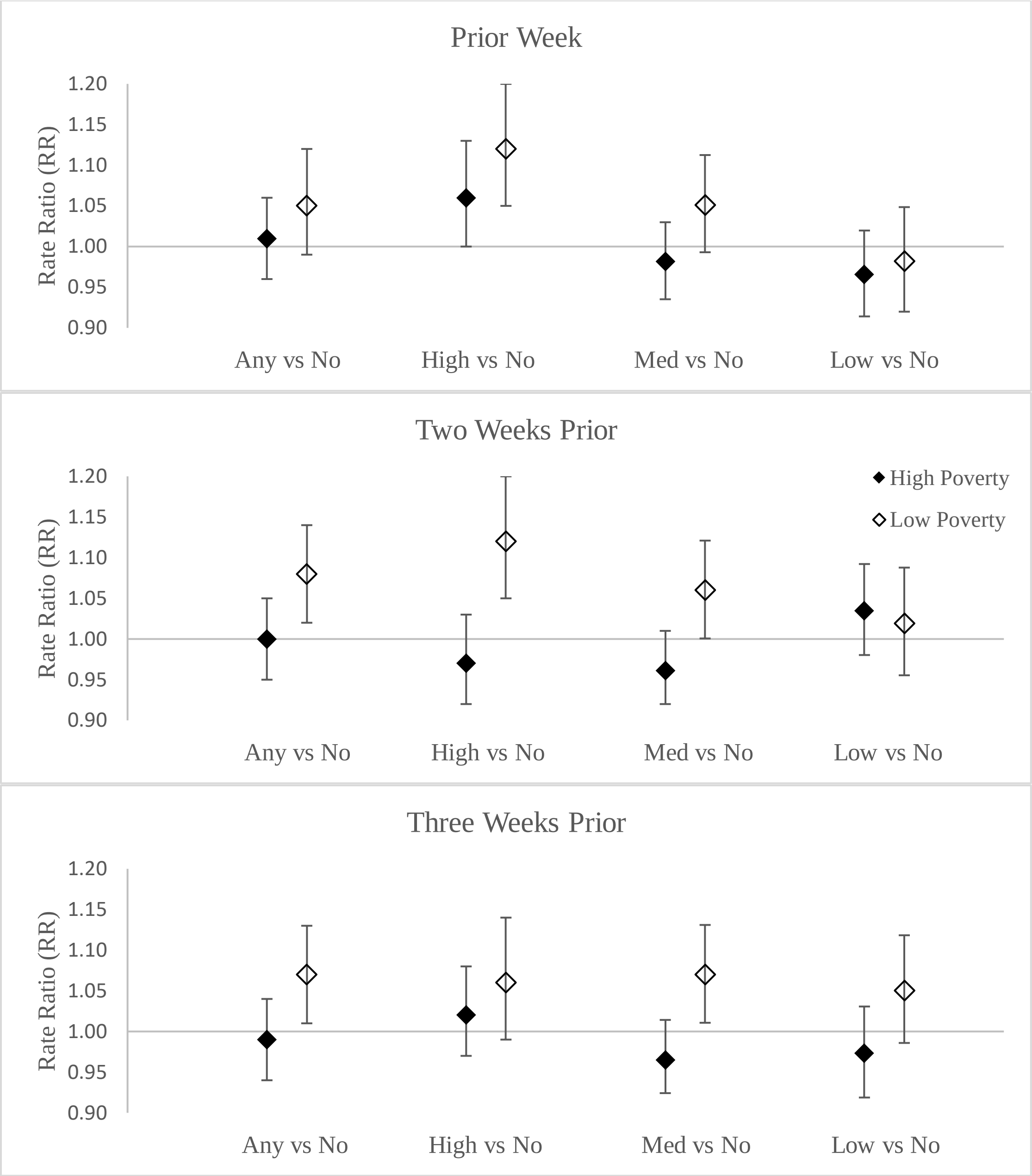


Figure 6. Comparison of rate ratios (RRs) and 95% confidence intervals for the association between ED visits for GI infections and CSO events of various volumes in the specified week allowing for effect modification by area-level poverty, Atlanta, GA, 2002-2013. All estimates adjusted for weekly sum of precipitation. Any is a CSO event of any volume. High volume events are defined as an event ≥75th percentile of volume, medium (Med) volume events are defiend as an event 25th-75th percentile of volume, and low

volume events are defined as an event <25th percentile of volume. No event in the specified week (no) is the comparison group for all models.