Heavy Rainfall Events and Diarrheal Diseases: The Role of Urban–Rural Geography

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Abstract. Diarrheal diseases remain a significant contributor to the global burden of disease. Climate change may increase their incidence by altering the epidemiology of waterborne pathogens through changes in rainfall patterns. To assess potential impacts of future changes in rainfall patterns, we analyzed 33,927 cases of diarrhea across all Ministry of Health clinical facilities in Esmeraldas Province, Ecuador, for a 24-month period from 2013 to 2014, using mixed-effects Poisson regression. We assessed the association between the incidence of diarrheal diseases and heavy rainfall events (HREs) and antecedent rainfall conditions. In rural areas, we found no significant associations between HREs and incidence. In urban areas, dry antecedent conditions were associated with higher incidence than wet conditions. In addition, HREs with dry antecedent conditions were associated with elevated incidence by up to 1.35 (incidence rate ratio, 95% CI: 1.14–1.60) times compared with similar conditions without HREs. These patterns may be driven by accumulation of fecal contamination during dry periods, followed by a flushing effect during HREs. This phenomenon is more important in dense urban environments with more impervious surfaces. These findings suggest that projected increases in rainfall variability and HREs may increase diarrhea burden in urban regions, which are rapidly expanding globally.

INTRODUCTION

Diarrheal diseases remain a significant cause of mortality and morbidity, causing more than 81.0 million disability-adjusted life years (DALYs) in 2017. Importantly, children younger than 5 years bear a disproportionate amount of this burden (48.3 million DALYs (59.6%) and more than 533,000 deaths).^{1,2} In addition to causing acute diarrhea, enteric pathogens have been linked to long-term health outcomes such as child growth failure.^{3–6} The incidence of diarrheal diseases is expected to increase with climate change.^{7,8} Considering the large burden of disease associated with diarrhea, it is critical to understand the role of climatic drivers in the epidemiology of diarrheal diseases, and social factors that may affect this burden.⁹

Rainfall and temperature are major environmental factors linked to the incidence of diarrheal diseases.^{10,11} Increases in temperatures have been associated with increases in the incidence of all-cause and bacterial diarrhea. The relationship between temperature and diarrhea has received more attention than the relationship between rainfall and diarrhea,^{10,12} in part because the latter is more complex.^{12,13} Low rainfall and drought conditions can lead to water scarcity, lower water quality, and increased risk for diarrheal diseases.¹³ For example, studies in Bangladesh¹⁴ and the Pacific Islands¹⁵ have documented associations between low rainfall and diarrheal diseases. On the other hand, high rainfall and flooding may flush enteric pathogens into waterways used for drinking water, leading to greater exposure and in turn higher risk of diarrhea, as seen in North America,^{16,17} Bangladesh,^{18,19} and Mozambique.²⁰ Previous studies have demonstrated the risk for diarrhea at both ends of rainfall extremes, and the reported measures of association vary widely. In a previous study in Esmeraldas Province, we found that the relationship between heavy rainfall events (HREs) and diarrhea incidence was modified by both antecedent rainfall conditions and the type of

household water treatment.²¹ In addition, several other studies have found an association between rainfall following a dry period and elevated rates of diarrhea.¹⁰ The Intergovernmental Panel on Climate Change estimates an increase in the frequency of extreme weather events such as drought and HREs due to changes in the water cycle from climate change.²² Therefore, it is critical to disentangle the role of rainfall in the epidemiology of diarrheal diseases such that appropriate policies and interventions can be designed to mitigate risk of diarrheal disease morbidity and mortality under current and future climate conditions.

Given that both rainfall extremes may be associated with increased risk for diarrheal diseases, it is important to consider the factors that contribute to a community's vulnerability and coping capacity. Access to safe drinking water and sanitation is core to a community's ability to reduce the burden of diarrheal diseases, as these factors directly affect the transmission of enteric pathogens.^{23,24} There are large gaps across the urban–rural gradient in access to safe drinking water and sanitation as well as other risk factors for diarrheal diseases such as education.^{25,26} It is therefore important to consider how meteorological factors such as rainfall might differentially affect urban compared with rural areas.

Previous studies have analyzed the association of heavy or low rainfall with diarrheal diseases within specific contexts¹⁰ or contextualized the relationship of HREs within wet or dry seasonal periods,²¹ but we are not familiar with studies that have specifically examined the influence of HREs within urban versus rural contexts. In this study, we have analyzed 33,927 cases of diarrheal diseases in Esmeraldas Province, Ecuador, over a 2-year period to assess how the relationship between HREs and diarrhea is modified by antecedent rainfall conditions in urban versus rural contexts.

MATERIALS AND METHODS

Health outcome data. Ecuador is subdivided into provinces which are further subdivided into cantons and then parishes. We used health records from all public hospitals and clinics in Esmeraldas Province reported by the Ecuadorian

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Ministry of Health from January 8, 2013 to December 31, 2014. The records comprised all data from this time period across Esmeraldas Province, collected from the seven cantons and 63 parishes of the province. Cases were categorized by the International Classification of Diseases-10 system.²⁷ Cases with a primary, secondary, or tertiary ICD-10 code of A09.X, designating “gastroenteritis of infectious origin,” were considered as cases of diarrhea. In instances where A09X was only applied to the secondary or tertiary diagnosis, the primary diagnosis was verified by expert review to be related to diarrhea (e.g., amebiasis). We categorized cases as younger or older than 5 years, and the race of the patient as “black,” “white/other,” “mixed race,” or “indigenous”.

The parishes of Esmeraldas Province were categorized as urban or rural by the Ecuadorian census bureau (Instituto Nacional de Estadística y Censos) for 2012.²⁸ Cases of diarrhea were aggregated for each parish by age, gender, and race categories to generate time series of case data spanning the observational period and further classified by urban–rural status.

Rainfall data. Gridded estimates of total daily rainfall were obtained for the study period across Esmeraldas Province at a spatial resolution of $0.25 \times 0.25^\circ$ from the Tropical Rainfall Measuring Mission 3B42 real time satellite data.²⁹ These estimates were spatially aggregated for each parish using shapefiles of administrative boundaries,²⁸ to generate rainfall time series for each parish at the daily resolution.

An HRE was defined as any day with rainfall exceeding the 90th percentile of daily rainfall across the study period for a given parish. Rolling sums were calculated across a window of the previous 8 weeks for the time series to characterize antecedent rainfall conditions. Sums of rainfall over the previous 8 weeks were considered “wet” antecedent conditions if they exceeded the 67th percentile, “dry” if below the 33rd percentile, and “medium” otherwise. In this manner, a binomial variable of the HRE and an ordinal multinomial variable of antecedent conditions were created across the entire time series for each parish.

Statistical analyses. We fit mixed-effects Poisson log-linear models to daily counts of cases of diarrheal diseases to assess the relationship between HREs, antecedent rainfall conditions, and incidence of diarrheal diseases. Separate models were run by urban and rural stratification. Gender, age, and racial categorization were used as covariates to control for potential confounding. In addition, rolling sums were calculated for the number of cases observed over the previous 7 days. These sums were used as a covariate to control for potential temporal confounding. The model also included random intercepts by parish to control for residual spatial confounding. In addition, time was included as a linear covariate to control for any potential mean temporal trends in the data. Heavy rainfall events and antecedent conditions were included as fixed effects to assess their relationship with diarrheal diseases, as well as an interaction term between HREs and antecedent conditions to assess any effect modification of the HRE–diarrhea relationship by antecedent conditions.

To consider lagged effects of rainfall on diarrhea, data on HREs and antecedent conditions were lagged from one to 14 days because we determined that up to a 14-day lag is plausible for a case to be detected at a health facility considering infection dynamics, pathogen incubation period, and

time until case detection. The aforementioned regression models were separately fit for each of the 14 different lags of rainfall data as well as with 0-lag exposure, and incidence rate ratios (IRRs) were estimated for each environmental condition considered.

RESULTS

Most of the 33,927 cases of diarrheal diseases analyzed comprised children younger than five years (20,818 [61.4%]), as expected with diarrheal diseases. The dataset was balanced with respect to sex. The patients were predominantly identified as mixed race (21,140 [62.3%]), with black patients (10,425 [30.7%]) comprising the second highest racial category, reflecting the demographic composition of Esmeraldas Province (Table 1).

Urban areas comprised 40.2% of cases, and rural areas comprised 59.8%. The urban parish of Esmeraldas (20.5%) and the rural parishes of Quinde (16.2%) contained the overall highest number of cases (Table 2, Figure 1). The urban parish of Esmeraldas is the capital of the province, and therefore, the high number of cases is related to the large population residing there.

There was a slight seasonality to the case counts of diarrheal diseases, with most (59.7%) of the cases occurring between June and November, which is the dry season in Esmeraldas. The seasonal pattern was consistent between urban and rural areas (Figure 2).

The results of our multivariate Poisson log-linear models are shown in Figure 3. In addition, the complete set of IRRs and their associated CIs, for all environmental conditions considered across all lags and urban/rural conditions, can be found in the Supplemental Data. In urban areas, across all lags tested, wet conditions with or without an HRE were associated with significantly lower case counts of diarrheal disease than dry antecedent conditions without HREs, and the strength of the inverse association tended to be weaker and more uncertain with HREs compared with without. The opposite was observed when considering dry conditions. For 14 of 15 lags tested, an IRR of > 1 was found when comparing dry conditions with HREs with dry conditions without HREs. These associations were found to be statistically significant for lags of 11 (IRR = 1.20, 95% CI: 1.02–1.42) and 14 days (IRR = 1.35, 95% CI: 1.14–1.60).

TABLE 1

Distribution of cases of diarrhea by demographic characteristics, Esmeraldas Province, Ecuador, January 8, 2013–December 31, 2014

Characteristic	Number of cases of diarrhea (n [%])
Total	33,927 (100.0)
Age (years)	
< 5	20,818 (61.4)
≥ 5	13,109 (38.6)
Sex	
Male	16,927 (49.9)
Female	17,000 (50.1)
Race	
Black	10,425 (30.7)
Indigenous	1,726 (5.1)
Mixed race	21,140 (62.3)
White/other	636 (1.9)

TABLE 2

Cases of diarrhea and temporal sparsity of data by canton administrative unit and urban/rural status, Esmeraldas Province, Ecuador, January 8, 2013–December 31, 2014

Urban/rural status	Canton (administrative unit)	Number of cases of diarrhea (<i>n</i> [% of total])	Number of parishes (<i>n</i>)	Number of days with 0 cases (<i>n</i> [%])
Urban	—	13,638 (40.2)	—	—
	Atacames	482 (1.4)	1	443 (61.3)
	Eloy Alfaro	822 (2.4)	1	371 (51.3)
	Esmeraldas	6,964 (20.5)	1	162 (22.4)
	Muisne	286 (0.8)	1	570 (78.8)
	Quininde	2,833 (8.4)	1	114 (15.8)
	Rioverde	1,138 (3.4)	1	270 (37.3)
	San Lorenzo	1,113 (3.3)	1	365 (50.5)
Rural	—	20,289 (59.8)	—	—
	Atacames	1,574 (4.6)	4	271 (37.5)
	Eloy Alfaro	3,981 (11.7)	14	46 (6.4)
	Esmeraldas	3,034 (8.9)	8	172 (23.8)
	Muisne	2,612 (7.7)	8	135 (18.7)
	Quininde	5,484 (16.2)	5	72 (10.0)
	Rioverde	1,957 (5.8)	5	195 (27.0)
	San Lorenzo	1,647 (4.9)	12	224 (31.0)

In rural areas, on the other hand, we found no statistically significant associations between HREs and incidence of diarrhea disease under any lag or either antecedent rainfall condition considered. The measures of association were very close to 1.0, with a range of 0.07 (0.97–1.04) under all conditions considered. Wet antecedent conditions with no HRE trended toward being slightly protective, and associations across the lags for HREs with dry antecedent conditions had consistently wider CIs, suggesting a similar trend as in the urban areas, although not strong enough for HREs to significantly affect diarrhea incidence as it did in urban areas.

DISCUSSION

In this study, we found that HREs and antecedent rainfall conditions had differential impacts on diarrhea incidence across urban compared with rural parishes of Esmeraldas

Province, Ecuador. In urban areas, dry conditions were associated with increased risk of diarrhea, and this effect was exacerbated under the influence of an HRE, particularly when it occurred 11 and 14 days before. By contrast, in rural areas, neither antecedent rainfall conditions nor HREs impacted diarrhea counts.

This is suggestive of a mechanism influenced by population density and/or the built environment. The impact of environmental conditions such as rainfall may be less in rural areas relative to urban areas because of a geographically sparse population distribution and more porous surfaces. A sparser population allows for fewer transmission events of enteric pathogens than the rates in denser urban areas. This could cause a lower marginal difference in rates of diarrhea at the community level because of distal environmental factors such as rainfall. In addition, urban areas contain more impervious surface areas allowing for

Spatial Distribution of Diarrhea Cases, Esmeraldas Province, Ecuador, 2013-14

FIGURE 1. Spatial distribution of cases of diarrheal diseases by parish in Esmeraldas Province, Ecuador, across the study period (January 8, 2013–December 15, 2014). This figure appears in color at www.ajtmh.org.

FIGURE 2. The distribution of cases of diarrheal diseases and total rainfall in millimeters is displayed by month across the observational period of January 8, 2013–December 31, 2014. The distribution is separately displayed for urban and rural and further subdivided by canton for comparison. This figure appears in color at www.ajtmh.org.

farther transmission of contamination via runoff after rainfall. Whereas Carlton et al.²¹ observed an effect on diarrheal incidence after heavy rainfall in a rural area, the lack of a significant effect in rural areas observed in our study may be a result of different data sources on diarrhea. In Carlton et al.,²¹ diarrhea was measured from household visits which could have a higher sensitivity to mild cases of diarrhea and nuanced fluctuations in diarrheal rates, whereas our study used data from clinics and hospitals which could have a bias toward a low sensitivity to mild cases and high sensitivity to severe cases of diarrhea. In addition, there could be unmeasured factors driving the differential effects observed between urban and rural areas, beyond the built environment or population density.

The incidence of diarrhea in urban areas did not statistically significantly differ with HREs versus without HREs in wet periods. Overall diarrheal incidence were attenuated in wet periods compared with dry periods, suggesting that environmental fecal contamination in the community is regularly flushed out of the system by regular rainfall, and additional rain to such a system results in a negligible increase in relative risk. With dry antecedent conditions, HREs were associated with higher incidence of diarrhea, especially with lags of 11 and 14 days. Dry conditions could result in water scarcity and/or increased accumulation of

fecal contamination in the environment.¹³ An HRE in such conditions could result in mobilization of these accumulated contaminants, resulting in increased transmission to inhabitants of urban areas, and ultimately elevated counts of diarrheal diseases. Carlton et al.²¹ also found a delay in the effect of HREs, with effects observed at 2-week, but not 1-week, lags, suggesting that the effects of HREs might be in secondary rather than primary transmission events. This may further explain why effects are more prominent in dense urban environments, than rural environments, where lower rates of transmission may not lead to sufficient buildup of localized epidemics.

Limitations. The limitations of our study should be considered while interpreting the results. First, we only controlled for individual-level confounding from age, gender, and racial characteristics. However, the use of aggregated case counts for each parish has the advantage in examining time-varying environmental exposures that the underlying population serves as its own control across time, such that potential confounders (e.g. diet and comorbidity) that do not vary at the same temporal scale as the exposure can be controlled for by the inclusion of a temporal trend. Second, considering our case counts were from public hospitals and clinics, there is a potential for selection bias toward more severe cases of diarrhea. There could be many more cases of diarrheal diseases

FIGURE 3. Incidence rate ratios are reported for urban (right) vs. rural (left) conditions, environmental conditions, and exposure lags of 0–14 days from Poisson regression for case counts of diarrheal diseases. Rate ratios are reported for dry antecedent conditions with heavy rainfall events (HREs) (top), wet antecedent conditions with HREs (middle), and wet antecedent conditions without HREs (bottom) compared with dry antecedent conditions without HREs. This figure appears in color at www.ajtmh.org.

that are less severe for which patients did not seek treatment and therefore were not included in our study. Furthermore, there is a small risk of confounding if changes in healthcare seeking due to environmental conditions vary differentially within urban and rural areas. Considering HREs occurred throughout the year in the analysis, the relative variation in healthcare seeking behavior week to week across the year is unlikely to have a major impact on the observed effects. Third, we used a satellite product for assessing rainfall exposure, which may contain a level of error in relation to the rainfall received on the ground.³⁰ Because of limited access to rain gauge data across all study sites, the satellite product provided the best spatial coverage for our analysis. In addition, our analysis used relative measures of exposure, each calculated separately for each parish, limiting the potential for bias from errors in satellite measurements.

In our study, cases were divided approximately equally between the genders and disproportionately from ages less than 5 years, matching the established epidemiological characteristics of diarrheal diseases. Furthermore, most of the cases were from black and mestizo populations, as expected from Esmeraldas Province of Ecuador. This indicated there is minimal selection bias along age, gender, or race characteristics in our data. The overall temporal trends

in rainfall and case burden were similar across urban and rural areas, ensuring comparability of urban and rural results from statistical analyses.

CONCLUSIONS

Our results indicate diarrheal incidence was elevated by up to 1.35 times (95% CI: 1.14–1.60) with HREs following dry periods in urban areas of this region of Ecuador. This finding is of concern, given anticipated future climate changes that are expected to increase rainfall variability and the frequency of HREs in this and other regions.^{31,32} The occurrence of this phenomenon in urban, but not rural areas, is of particular concern, given the increasing global trend of urbanization in low- and middle-income countries.³³ Considering the large global burden of diarrheal mortality and morbidity, even relatively small percentage increases could have dramatic implications for child health.^{34,35} Further research is needed to elucidate the mechanisms driving the relationship between rainfall and incidence of diarrheal diseases in urban areas and to inform policy for assessing vulnerability and building coping mechanisms to ensure that climate change does not reverse the substantial progress made in recent decades in reducing the global burden of diarrhea disease.

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