Impact of weather and season on stored water contamination and infant diarrhea in climate-vulnerable, urban Mozambique

Short title: Season, Stored Water, and Diarrhea in Beira, Mozambique

Authors

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Abstract

Background: Diarrhea remains one of the leading causes of morbidity and mortality for children under the age of five, despite reductions in its overall global burden in recent decades. However, climate change, and its associated meteorological conditions - heavy rainfall, temperature, flooding - has the potential to impede or reverse progress that has been made toward alleviating the burden of diarrheal diseases. This is especially true in low-income, climate-vulnerable communities that are currently bearing many impacts of climate change. Better characterization of the impact of weather and season on drinking water quality and child health will allow us to capture the anticipated health burden associated with climate change.

Methods: We characterized the associations of weather and season on infant diarrhea and household stored water quality in the city of Beira, Mozambique. We collected data from mother-child dyads in the third trimester of pregnancy and when the infant was 3-, 6-, 9-, and 12-months old. Using modified Poisson regression mixed effects models, we evaluated associations between weather (i.e. season, heavy rainfall events, ambient temperature, and flooding) and (1) household stored water quality and (2) infant diarrhea.

Results: Rainy season (aPR: 1.49; 95% CI: [1.34, 1.67]) was associated with a higher prevalence of stored water contamination, and higher temperatures were associated with a higher prevalence of stored water contamination during the dry season only (aPR: 1.14; 95% CI: [1.03, 1.27]). Source water contamination was associated with a higher prevalence of stored water contamination during both rainy (aPR: 1.32; 95% CI: [1.11, 1.56]) and dry seasons (aPR: 1.56; 95% CI: [1.22, 2.00]). Rainy season (aPR: 1.18; 95% CI: [1.01, 1.38]) was associated with a higher prevalence of infant diarrhea, as was higher temperatures, though only during the dry season, (aPR: 1.19; 95% CI: [1.05, 1.35]).

Conclusions: This study highlights the importance of addressing household water contamination for reducing the burden of diarrheal disease as well as the importance of understanding the seasonal and weather-dependent variation in both water contamination and infant diarrhea.

Introduction

Diarrheal diseases are the second leading cause of death and the third-leading cause of disability-adjusted life-years (DALYs) among children under the age of five worldwide,[1,2] and this burden of disease from diarrhea is expected to increase due to climate change.[3,4] Climate change has both direct impacts on health (e.g., injuries during a flood or heat stress) as well as indirect impacts via changing social and environmental determinants of health, such as declines in air quality, safe and available drinking water, damages to infrastructure, and food security.[3,5] Rapid population growth and urbanization have led to an increase in informal settlements in low and middle income countries (LMICs)[3,6,7] which often have limited infrastructure (e.g., piped water, storm drainage, paved roads) and are therefore particularly vulnerable to extreme or variable weather conditions as well as disease.[8,9] Global improvements in water, sanitation, and hygiene (WASH) service have played an important role in reducing the global burden of diarrheal diseases.[10,11] However, climate change has the potential to reverse decades of public health progress, by interfering with the benefits accrued through investments in WASH infrastructure and service provision.[12–14]

Diarrhea risk increases with weather conditions closely associated with climate change, including heavy rainfall events, increasing temperatures, drought and flooding.[15–18] Diarrheal diseases exhibit seasonal patterns, usually peaking in warmer, rainier times of the year.[15–17,19,20] These seasonal changes in diarrhea are driven by many factors including differences in taxa-specific enteric pathogen transmission patterns (i.e., bacterial vs. viral transmission),[21–23] changes in drinking water access and quality,[12,13,24] and changes in human behaviors.[15,25] While the seasonal variation in diarrheal disease is well established, the drivers of these variations are less clear.

Seasonal and weather-dependent changes in drinking water sources and household water storage practices may play an important role in driving seasonal changes in disease risk.[13–15] Heavy rainfall events can result in flooding, water service outages, and water infrastructure damage, increasing the risk of drinking water contamination.[17,25,26] High temperatures and drought often lead to water shortages and water intermittency that force people to rely on longer periods of unsafe water storage.[27] Intermittent water supplies, or water supplies with regular service outages, are estimated to be responsible for approximately 17.2 million infections, causing 4.5 million cases of diarrhea and 1,560 deaths each year.[28] An estimated 300 million people globally currently rely on intermittent water supplies, and this number is expected to increase with climate change.[29] With the increasing global reliance on intermittent water supplies, household water storage acts as a key contributor to waterborne transmission of enteric pathogens.[30–32]

Even in settings with good source water quality, water storage represents a key point of exposure to enteric pathogens because there is a high risk of recontamination of water at the household level.[30,32–35] Recontamination can occur due to lack of cleaning of the storage vessel and contact with contaminated hands, vessels for transferring water, or other contaminated objects.[30,31,36] Weather conditions may contribute to changes in household stored water due to changes in environmental contamination, source water quality, and changes in human behavior.[37,38] While previous research has focused primarily on the relationship between weather conditions and contamination in water sources at the point of collection,[24,39–44] fewer have assessed how these same weather conditions or seasonality impact stored water quality,[37,38] or associations with diarrheal diseases, particularly in an urban setting.

The purpose of this study was to quantify how weather and season impact stored water and infant diarrhea. We used data from a large cohort study of informal, urban settlements in Beira, Mozambique that aimed to assess the impact of upgrades to a piped water network on children's health.[45] Mozambique is one of the most climate-vulnerable countries in the world,[46] and Beira, which is located on the eastern coast of Mozambique, is highly vulnerable to extreme weather events. This study is generalizable to similar low-income, urban settings facing the impacts of climate change and will be valuable for identifying strategies to build climate resilience within communities that rely on intermittent water systems.

Methods

In this study we quantified associations between weather on household stored water contamination (Research Question (RQ) 1) and weather on infant diarrhea (RQ2). We utilized cross-panel data from the PAASIM study ("Pesquisa sobre o Acesso à Água e a Saúde Infantil em Moçambique" - Research on Access to Water and Child Health in Mozambique), a cluster-matched study on the impact of a large-scale urban piped water supply improvement on infant enteric pathogen infection, gut microbiome development, and other health outcomes in Beira, Mozambique.[45]

Study setting

Mozambique is located on the southeastern coast of Africa and much of its population is concentrated on its expansive coastline.[47,48] Mozambique has two distinct seasons: the dry season, marked by cooler temperatures and lower precipitation, and the rainy season, marked by warmer temperatures and higher precipitation.[47] Average annual temperatures have been rising in Mozambique and are projected to increase by 1.0-2.8°C by 2060.[47] The intensity of heavy rainfall events during the rainy season is also increasing and expected to continue to rise.[47] The country's coastline is particularly susceptible to Indian Ocean-influenced monsoon rains, flooding, and sea level rise, as well as extreme weather events like tropical storms and cyclones.[47,48] Beira City is particularly vulnerable due to rising sea levels and coastal erosion, which put large parts of the city at risk of flooding and infrastructure vulnerability.[46,49,50] Recent investments in water infrastructure in the study area have increased access to piped water supplies in the informal neighborhoods of Beira,[51] but water intermittency in the system contribute to ongoing challenges with waterborne disease transmission.

The PAASIM study team enrolled mothers in their third trimester of pregnancy and followed mother-child dyads across four follow-up visits when the child was 3-, 6-, 9-, and 12-months old. Study neighborhoods, including both intervention and control neighborhoods, were identified and matched based on population density and socioeconomic status (SES).[52]

Full details of participant recruitment, eligibility, and enrollment as well as neighborhood selection and matching can be found elsewhere.[45] Here we report on observational results unrelated to intervention status of households.

Data collection and study participants

Mothers were recruited and enrolled in the study between February 19th, 2021 and October 7th, 2022, and all data for this analysis were collected between February 2021 and October 2023. We analyzed data from mother-child dyads that fully completed all visits through 12-months of age. Data were available from 642 individual mother-child dyads across five visits from pregnancy through 12-months of age, for a total of 3,210 observations. After removing observations with missing data, there were 2,800 pre-and post-birth household visits (pregnancy, 3-, 6-, 9-, and 12- month visits) that had a stored water sample available for RQ1 analyses and 2,226 post-birth household visits (3-, 6-, 9-, and 12- month visits) had diarrhea data available for RQ2 analyses (Figure S1).

Household data was collected using structured household surveys with primary caregivers. Surveys contained questions and structured observations related to household demographics, infant health, water, sanitation, and hygiene practices, household conditions, and flood exposures. Household surveys were conducted in Portuguese and data were entered electronically into password-protected tablets via the Open Data Kit (ODK) platform.

Source and stored water

Water quality data came from household stored water and source water 100-mL grab samples collected at all household visits. Staff at the Laboratório de Higiene de Águas e Alimentos (Water and Food Hygiene Laboratory) in Beira analyzed water samples for *E. coli* contamination via standard methods using Colilert-18 reagent and the IDEXX Quanti-Tray/2000 MPN method (IDEXX Laboratories, Westbrook, ME, USA).[53] We used the IDEXX data to create dichotomous variables for both source and stored water quality, comparing those with *E. coli* contamination to those without. We also adjusted models for the type and location of people's water sources, comparing households with a piped water supply in their household or yard to those that do not have a piped water source on premises (either a non-piped water source or a piped water source not in their household or yard).

Weather and season data

We used data from the National Oceanic and Atmospheric Administration's (NOAA) Global Surface Summary of the Day (GSOD) land surface station at the Beira International Airport, located approximately seven kilometers from our study neighborhoods,[54] using the "gsodr" package in R (Sparks, 2017).[55] This dataset contained daily total precipitation (mm) and average ambient temperature (ºC) readings for the study period that we matched to our study data.

We created a dichotomous season variable for the study period using monthly summaries of precipitation and temperature to identify seasonal demarcations for this setting.[47] We defined the dry season months as May through November, which had cooler temperatures and lower precipitation compared to the rest of the study period, and the rainy season months as December through April, which had warmer temperatures and higher precipitation. We created a dichotomous "heavy rainfall event" (HRE) variable from the precipitation data that specified whether a heavy rainfall event occurred in the week preceding a household visit (0–7-day summary). We classified a heavy rainfall event as a day of precipitation above the 90th percentile (5.55 mm) for the entire study period. We created a dichotomous variable for flooding using responses to the household survey question: "during the last month, at any time was your home or yard full of water due to heavy rains?". We included temperature in our analyses on a continuous scale.

Statistical analyses

We found that season was highly correlated with the specific weather conditions of interest – heavy rainfall events, temperature, and flooding. Therefore, to avoid multicollinearity issues in models, we assessed these relationships in two parts - we first assessed the direct relationship between season and the outcome of interest (stored water quality for RQ1 and diarrhea for RQ2), then the relationship between specific weather variables of interest, stratified by season, to assess season as an effect modifier (Table 1). The individual weather variables, heavy rainfall events, temperature, and flooding, were not highly correlated with each other so they were included in models together.

Table 1. *Summary of research questions and models.*

Research question	Model	Exposure	Outcome	Covariates
RQ1. How does seasonality & weather impact stored water quality?	**RQ1a.** Direct effect of season	Season	Stored water quality	Water source on premises, source water quality, SES, primary caregiver education
	RQ1b. Effect of weather, stratified by season	HRE, temperature, flooding		
RQ2. How does seasonality & weather impact infant diarrhea?	**RQ2a.** Direct effect of season	Season	Diarrhea	Stored water quality, water source on premises, source water quality, SES, primary caregiver education
	RQ2b. Effect of weather, stratified by season	HRE, temperature, flooding		

RQ=research question; HRE=heavy rainfall event; SES=socioeconomic status.

Diarrhea in this study was defined as caregiver-reported one-week period prevalence of any diarrhea for the child. Covariates included in each model were chosen based on *a priori* hypothesized relationships. On top of adjusting for source and stored water characteristics, depending on the model, we adjusted for household socioeconomic status (SES) and primary caregiver's education level in both aims. We used the Mozambique Simple Poverty Scorecard[56] to calculate the SES of each household at each visit, which gives a total score ranging from 0 (most likely below a poverty line) to 100 (least likely below a poverty line). We dichotomized the SES score, where scores under 66 were considered to have a higher poverty level based on the Mozambique Simple Poverty Scorecard which specifies that, across Mozambique, a score of 66 has around a 50% change of being under the 200% poverty cutoff.[57] We created a dichotomous variable to adjust for primary caregiver's education level at baseline, comparing those who received at least secondary education to those who received below secondary education. This analysis was conducted independent of the intervention, and we therefore did not include intervention status as a covariate in models. A sensitivity analysis confirmed that the inclusion of intervention status as a covariate did not substantially impact any modeling results.

For all models, we used Poisson regression with robust variances[58] to calculate the prevalence ratio estimates for the relationships of interest. We used mixed effects models, including a random effect for households to account for repeat sampling at each household. We used data from all visits, including the pre-birth visit and the 3-, 6-, 9-, and 12- month visits. All analyses were conducted using R statistical software (RStudio v. 4.3.1).[59]

Ethics statement

The PAASIM study was approved by the Mozambique National Bio-Ethics Committee for Health (Ref: 105/CNBS/20) as well as Emory University's Institutional Review Board (IRB#: CR001-IRB00098584, Atlanta, GA). We also obtained credential letters and permissions from Beira municipality and relevant municipal district administrations. Parents or guardians of children under 18 years old provided a signature to indicate consent. In the case of illiteracy of the subject, study staff verbally summarized the material with the subject, and the participants were required to mark the document with a thumbprint indicating their consent.

Results

Characteristics of the study population

Demographic characteristics are summarized in Table 2. Almost all households had access to piped water as their main source of drinking water, although only 221 (34.5%) had piped water in their yard or household, whereas the remaining people with access to piped water (412; 64.2%) accessed it through their neighbor or a public tap.

Table 2. *Characteristics of study population at baseline (pregnancy visit) (N=642)*

	n (%) or Mean (SD)
Household size	4.9 (2.37)
Household socioeconomic status*	66.5 (12.1)
Household considered high poverty*	298 (46.4%)
Primary caregiver has at least secondary education	142 (22.1%)
Improved main water source⁺	641 (99.8%)
Piped water- neighbor	362 (56.4%)
Piped water- public tap/standpipe	50 (7.8%)
Piped water- yard/plot	218 (34.0%)
Piped water- household/dwelling	3 (0.5%)
Bottled water	7 (1.1%)
Tubewell or borehole	1 (0.2%)
Unprotected well (unimproved)	1 (0.2%)

**Measured using the Mozambique Simple Poverty Scorecard[57] - total scores range from 0 (most likely below a poverty line) to 100 (least likely below a poverty line); scores <66 are considered higher poverty.*
⁺JMP definition[60]

There were higher levels of precipitation, higher temperatures, and more reported flooding during the rainy season, although flooding still occurred in the dry season (Table 3). There was not a considerable difference in the water sources utilized across rainy and dry seasons, with nearly all participants using either a piped water source within their yard or household (37.6% during rainy season and 38.1% during dry season) or a piped water source from their neighbor or a public tap (62.4% during rainy season and 61.9% during dry season). The average amount of time that people spent collecting water was higher for people with water off premises (16.0 minutes during rainy season and 14.3 minutes during dry season) than those with water on premises (2.3 minutes during rainy season and 3.3 minutes during dry season). Service outages were reported during approximately 22% of visits, with a slightly higher proportion occurring in the rainy season. Participants reported that water was available, on average, 13.2 hours per day and 6.5 days per week, with no strong differences in availability across seasons. A substantially higher number of stored water samples (44.9%) were contaminated with *E. coli* compared to source water samples (11.9%), with a higher prevalence of contamination for both source and stored water during the rainy season (Table 3).

Table 3. *Summary of weather conditions and drinking water characteristics by season across all study visits (N=3,210)*

	Mean (SD) or n (%)		
	Rainy Season (N=1,429)	**Dry Season** (N=1,781)	**Overall** (N=3,210)
Weather conditions			
Mean monthly total precipitation (mm)	2.7 (10.3)	1.0 (3.9)	1.7 (7.5)
Mean daily temperature (°C)	27.4 (1.5)	23.2 (2.4)	25.1 (3.0)
Reported flooding in previous month	407 (28.5%)	305 (17.1%)	712 (22.2%)
Source water characteristics			
Uses piped water on premises (yard/household)	537 (37.6%)	678 (38.1%)	1,215 (37.9%)
Uses piped water not on premises (neighbor/public tap)	891 (62.4%)	1,101 (61.9%)	1,992 (62.1%)
Mean round trip water collection time (mins)			
Piped water on premises (yard/household)	2.34 (8.2)	3.28 (11.4)	2.86 (10.1)
Piped water not on premises (neighbor/public tap)	15.0 (19.9)	14.3 (17.8)	15.0 (18.8)
Reported service outages in previous week	364 (25.5%)	361 (20.3%)	725 (22.6%)
Mean hours per day water source is available	12.9 (5.8)	13.5 (6.0)	13.2 (6.0)
Mean days per week water source is available	6.5 (1.23)	6.6 (1.2)	6.5 (1.2)
E. coli contamination in main water source	247 (17.3%) [NA = 185]	136 (7.6%) [NA = 212]	383 (11.9%) [NA = 397]
Stored water characteristics			
E. coli contamination in household stored water	812 (56.8%)	630 (35.4%)	1,442 (44.9%)

RQ1. Season and weather on stored water quality

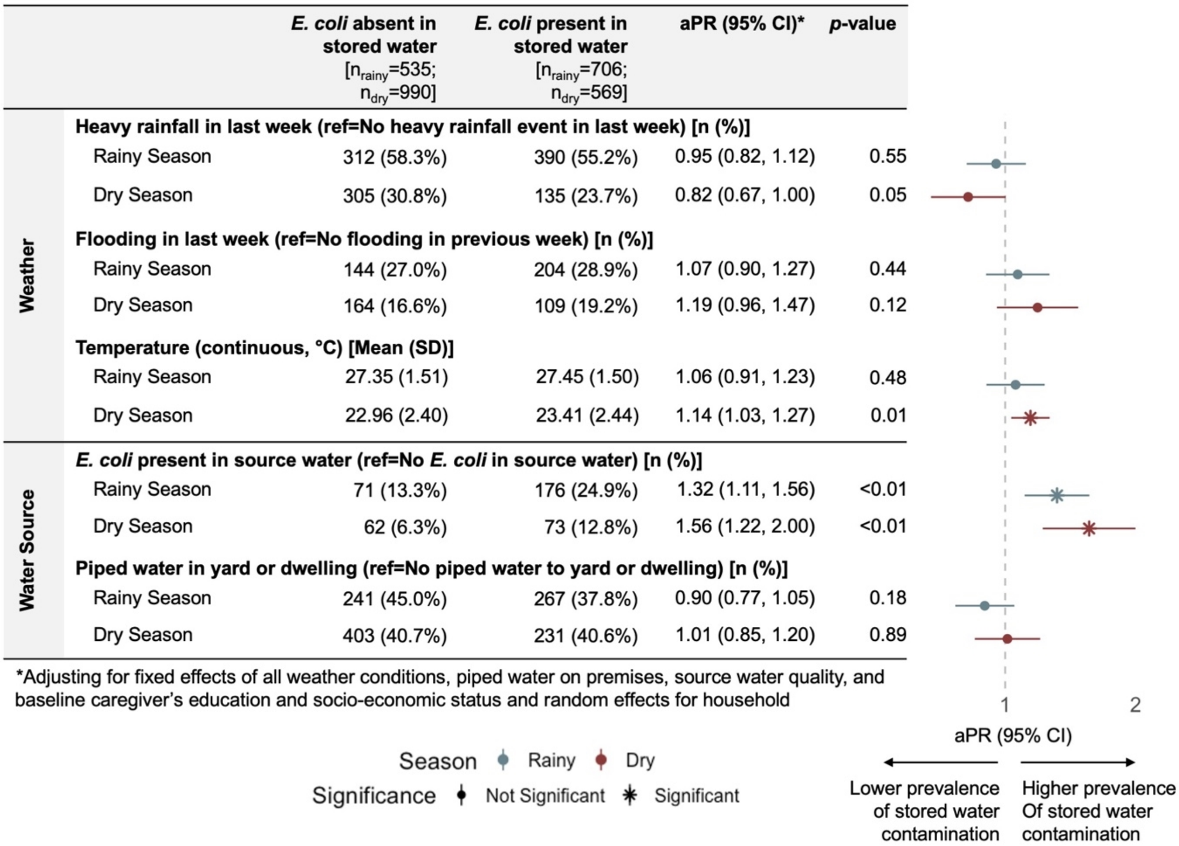
There was higher prevalence of stored water contamination during the rainy season (aPR: 1.49; 95% CI: 1.34, 1.67) compared to the dry season (Table 4). In the dry season, stored water contamination was associated with higher temperatures (aPR: 1.17; 95% CI: 1.08, 1.25) (Figure 1). *E. coli* contamination in source water was associated with stored water contamination across both rainy (aPR: 1.32; 95% CI: 1.11, 1.56) and dry (aPR: 1.56; 95% CI: 1.22, 2.00) seasons.

Table 4. *Summary of direct association of season on stored water quality (RQ1a) using modified Poisson regression with mixed effects (N=2,800)*

	E. coli absent in stored water	*E. coli* present in stored water	aPR (95% CI)* (ref=dry season)	*p*-value
Rainy Season [n=1,241]	535 (43.1%)	706 (56.9%)		
Dry Season [n=1,559]	990 (63.5%)	569 (36.5%)	1.49 (1.34, 1.67)	<0.01

*Adjusting for fixed effects for source water quality, piped water on premises, baseline socio-economic status, and baseline primary caregiver education and random effects for household

Figure 1. *Summary of effect of weather and water source on stored water quality overall and stratified by season (RQ1b) using modified Poisson regression with mixed effects (N=2,800)*



		E. coli absent in stored water [n_{rainy}=535; n_{dry}=990]	*E. coli* present in stored water [n_{rainy}=706; n_{dry}=569]	aPR (95% CI)*	*p*-value
Weather	**Heavy rainfall in last week (ref=No heavy rainfall event in last week) [n (%)]**				
	Rainy Season	312 (58.3%)	390 (55.2%)	0.95 (0.82, 1.12)	0.55
	Dry Season	305 (30.8%)	135 (23.7%)	0.82 (0.67, 1.00)	0.05
	Flooding in last week (ref=No flooding in previous week) [n (%)]				
	Rainy Season	144 (27.0%)	204 (28.9%)	1.07 (0.90, 1.27)	0.44
	Dry Season	164 (16.6%)	109 (19.2%)	1.19 (0.96, 1.47)	0.12
	Temperature (continuous, °C) [Mean (SD)]				
	Rainy Season	27.35 (1.51)	27.45 (1.50)	1.06 (0.91, 1.23)	0.48
	Dry Season	22.96 (2.40)	23.41 (2.44)	1.14 (1.03, 1.27)	0.01
Water Source	***E. coli* present in source water (ref=No *E. coli* in source water) [n (%)]**				
	Rainy Season	71 (13.3%)	176 (24.9%)	1.32 (1.11, 1.56)	<0.01
	Dry Season	62 (6.3%)	73 (12.8%)	1.56 (1.22, 2.00)	<0.01
	Piped water in yard or dwelling (ref=No piped water to yard or dwelling) [n (%)]				
	Rainy Season	241 (45.0%)	267 (37.8%)	0.90 (0.77, 1.05)	0.18
	Dry Season	403 (40.7%)	231 (40.6%)	1.01 (0.85, 1.20)	0.89

*Adjusting for fixed effects of all weather conditions, piped water on premises, source water quality, and baseline caregiver's education and socio-economic status and random effects for household

RQ2: Season and weather on infant diarrhea

Caregiver-reported diarrhea (seven-day recall) prevalence within this cohort was 33.6% in the rainy season and 28.1% in the dry season (Table 5). There was a higher prevalence of reported diarrhea during the rainy season (aPR: 1.18; 95% CI: 1.01, 1.38) than the dry season, and the association of rainy season on diarrhea was strongest among 3-month-old children (aPR: 1.41; 95% CI: 0.84, 2.38). Higher temperatures were associated with a higher prevalence of diarrhea in the dry season (aPR: 1.19; 95% CI: 1.05, 1.35) (Figure 2). We found no other associations between weather conditions or drinking water characteristics and diarrhea in adjusted analyses (Figure 2).

Table 5. *Summary of direct effect of season on infant diarrhea (RQ2a) using modified Poisson regression with mixed effects (N=2,226)*

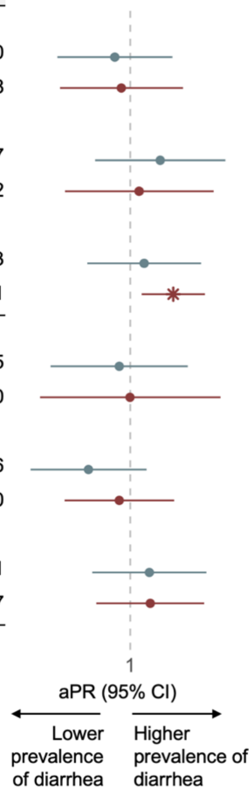
	No Diarrhea	**Diarrhea**	**aPR (95% CI)* (ref=dry season)**	***p*-value**
Overall model				
Rainy Season [n=951]	632 (66.5%)	319 (33.6%)		
Dry Season [n=1,275]	918 (72.2%)	357 (28.1%)	1.18 (1.01,1.38)	0.04
Model stratified by child age				
3 months [n=567]	502 (88.5%)	65 (11.5%)	1.41 (0.84, 2.38)	0.19
6 months [n=561]	383 (68.3%)	178 (31.7%)	0.99 (0.72, 1.34)	0.93
9 months [n=551]	333 (60.4%)	218 (39.6%)	1.00 (0.76, 1.32)	1.00
12 months [n=547]	332 (60.7%)	215 (39.4%)	1.08 (0.82, 1.43)	0.58

*Adjusting for fixed effects of source and stored water quality, piped water on premises, and baseline socio-economic status and primary caregiver education and random effects of household

Figure 2. *Summary of effect of weather and source and stored water on diarrhea stratified by season (RQ2b) using modified Poisson regression with fixed effects (N=2,226)*

		No Diarrhea [n_{rainy}=632; n_{dry}=918]	Diarrhea [n_{rainy}=319; n_{dry}=357]	aPR (95% CI)	*p*-value
Weather	**Heavy rainfall in last week (ref=No heavy rainfall event in last week) [n (%)]**				
	Rainy Season	323 (51.1%)	156 (48.9%)	0.94 (0.75, 1.18)	0.60
	Dry Season	148 (23.4%)	83 (26.0%)	0.97 (0.76, 1.23)	0.78
	Flooding in last week (ref=No flooding in previous week) [n (%)]				
	Rainy Season	148 (23.4%)	83 (26.0%)	1.13 (0.87, 1.46)	0.37
	Dry Season	145 (15.8%)	55 (15.4%)	1.04 (0.77, 1.40)	0.82
	Temperature (continuous, °C) [Mean (SD)]				
	Rainy Season	27.55 (1.5)	27.61 (1.5)	1.06 (0.84, 1.33)	0.63
	Dry Season	23.06 (2.5)	23.59 (2.5)	1.19 (1.05, 1.35)	0.01
Drinking Water	***E. coli* present in source water (ref=No *E. coli* in source water) [n (%)]**				
	Rainy Season	137 (21.7%)	67 (21.0%)	0.96 (0.73, 1.26)	0.75
	Dry Season	83 (9.0%)	33 (9.2%)	1.00 (0.70, 1.43)	1.00
	Piped water in yard or dwelling (ref=No piped water to yard or dwelling) [n (%)]				
	Rainy Season	282 (44.6%)	123 (38.6%)	0.85 (0.67, 1.07)	0.16
	Dry Season	391 (42.6%)	145 (40.6%)	0.96 (0.77, 1.19)	0.70
	***E. coli* present in household stored water (ref=No *E. coli* in stored water) [n (%)]**				
	Rainy Season	367 (58.1%)	194 (60.8%)	1.08 (0.86, 1.36)	0.51
	Dry Season	329 (35.8%)	141 (39.5%)	1.08 (0.87, 1.34)	0.47

*Adjusting for fixed effects of all weather conditions, piped water on premises, source and stored water quality, and baseline caregiver's education and socio-economic status and random effects for household



Discussion

Our analysis of seasonal associations with household water quality and diarrhea among children under 1 year old revealed seasonal and weather-related associations. Rainy season was associated with stored water contamination, as was temperature, though only during the dry season. There was also a higher prevalence of child diarrhea during the rainy season, and at higher temperatures during the dry season. Future studies of water and health should consider the impact of season and weather and consider targeted intervention strategies during high-risk periods.

Weather and stored water

Water storage practices within this study population represent a high risk of exposure to enteric pathogens.[30,61] Nearly all participants in the study area store their water, likely due to the high level of water intermittency in the system which limits the availability of water throughout the day.[33] We found approximately four times the prevalence of *E. coli* contamination among stored drinking water samples compared to source samples. *E. coli* contamination in source water was associated with contamination in stored water during both rainy and dry seasons, suggesting household recontamination is a risk across various seasonal conditions. These findings illustrate the degradation of water quality from the source to the household, a trend that has been observed in many other studies, particularly in intermittent water systems.[32,61–68]

Our results align with previous research showing a higher prevalence of water storage contamination during rainy season and at higher ambient temperatures.[37,38] During rainy season, there may be more opportunities for stored water contamination due to the increased mobilization of pathogens in the environment from rainfall and flooding.[15] Higher temperatures can impact bacterial growth in water systems and lead to higher levels of drinking water consumption, impacting exposures to pathogens in the environment.[15,16,21] Here, we add to previous studies by demonstrating that the impacts of temperature may be seasonally dependent. Higher temperatures may lead to stronger risks during dry season because of the increased opportunity for concentration of fecal pathogens in the environment as well as changes in water use behaviors during dry season.[15,69] For example, people may be more likely to store their water for longer periods of time during hotter, dryer periods,[33] leading to more opportunities for contamination in stored water. Water storage represents a key point of exposure to enteric pathogens at the household level, and it is important to consider the seasonal and weather-dependent variation in contamination risk. Recent studies have shown seasonally-dependent effectiveness of WASH interventions, highlighting the need for the timing of interventions to prioritize high risk seasons and weather conditions.[12,70] Results from this analysis suggest that rainy season and periods with higher ambient temperatures may be particularly important for interventions aimed at addressing the risk associated with household water storage practices.

Weather, drinking water and infant diarrhea

We found a higher prevalence of infant diarrhea during the rainy season. In Mozambique, seasonality in weekly clinical case counts of diarrhea has been observed, with peaks occurring near the end of the rainy season and lower counts typically during the dry season months.[71] This study adds to these findings by showing that rainy season was associated with a higher prevalence of diarrhea specifically among infants under 1 year old. Specifically, we show that the effect of season on diarrhea may be modified by child age, with a stronger effect in the youngest children. The effects of diarrhea and enteric pathogen infections are particularly harmful for younger children who are at an important stage of growth and cognitive, motor, and social-emotional development.[72,73] With a diarrhea prevalence of 30.4% throughout the study period (3-, 6-, 9-, and 12-months combined), this study population faces a high burden from diarrheal disease. Seasonality may be important to consider as a risk factor when estimating the burden of diarrheal disease among infants in low-income settings.

Our analyses also found a higher prevalence of diarrhea with increased temperatures, but, surprisingly, only in the dry season. The association between higher prevalence of diarrhea and higher temperatures is well established,[15,16] including in coastal regions of Mozambique.[74] Higher temperatures may increase food spoilage and increased bacterial pathogen loads in animal reservoirs.[75–78] In water systems, fecal coliform bacteria can replicate at higher temperatures with adequate nutrient levels, and larger yields of bacteria have been found in drinking water systems during warmer months.[79,80] Our analysis revealed that not only were higher temperatures associated with a higher prevalence of diarrhea, but that the higher prevalence of diarrhea at higher temperatures is stronger during the dry season. This stronger association in the dry season may be explained by pathogen factors, including differences in infection pressure or pathogen transmissibility under different environmental conditions,[81,82] individual level factors, including changes in host susceptibility, or seasonal variation in behaviors like handwashing, water storage and handling practices, food hygiene, or animal ownership,[17,38,41,83] or a combination of these mechanisms.

Limitations

Despite its careful design and implementation, this study had several limitations. First, there is potential for unmeasured confounding due to the complex relationships and interconnected environmental transmission pathways for enteric pathogens.[84,85] We assessed a wide range of potential confounders in preliminary analyses to reduce the risk of confounding as much as possible, but there is still potential for unmeasured confounding or biases in our caregiver-reported measures. Second, our assessment of disease was limited by the use of caregiver-reported diarrhea, which is an indicator subject to recall bias and one that captures only symptomatic cases of enteric infection.[84,86] Future studies could build on these analyses by assessing the effects of weather and drinking water on health outcomes using data on specific pathogen infections. Third, our indicator of drinking water quality relied on the detection of *E. coli,* which is a widely used fecal indicator bacteria, but is not a direct measure of pathogens and is subject to high variability in measurement.[87] The detection of *E. coli* in water may not be a strong indicator of non-bacterial pathogen contamination, particularly protozoan or viral pathogens, and may therefore underestimate exposure. Finally, several of our variables for weather, water access, and health outcomes relied on either a 24-hour or 1-week recall period, which can only be indicative of short-term exposure experiences. For example, it is possible that a person's main water source within the recall period was not the same as what they use at other times, which may bias results. For other variables, where possible, standard metrics were used and adjustments to regression models were made to avoid influence of bias.

Conclusions

In this dense, urban setting, short term weather variability has the potential to impact waterborne disease transmission despite the high level of access to piped water supplies. Rainy season, heavy rainfall, increased temperatures, and flooding were all associated with a higher prevalence of stored water contamination and may have downstream impacts on the prevalence of infant diarrhea. In areas with intermittent water supplies, household water storage represents a key point of exposure to enteric pathogens at the household level. This study adds to previous evidence of weather-related risks on water sources by highlighting downstream impacts of weather on household stored water quality as well as the diarrheal disease burden among infants.

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Supplemental Materials

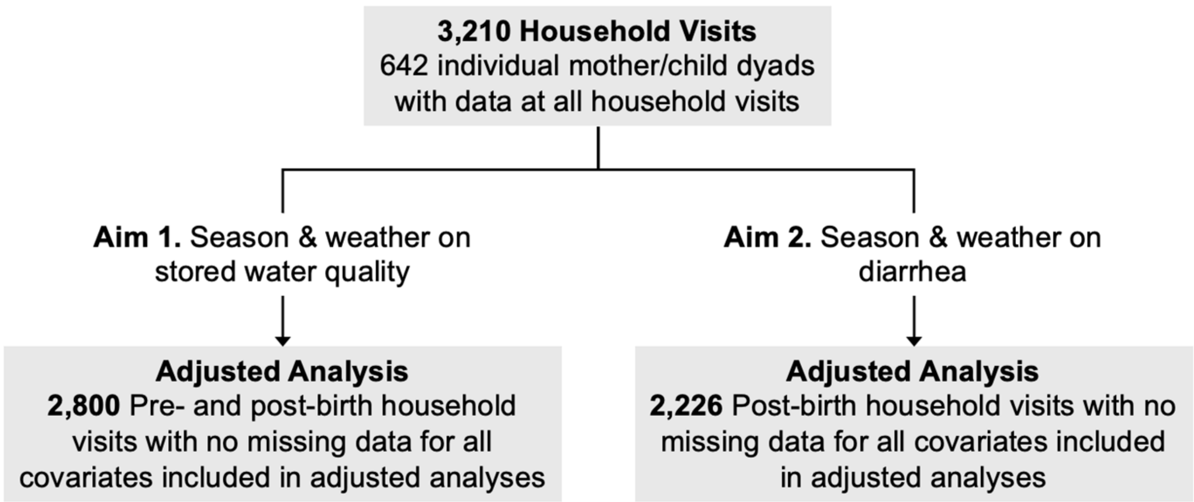

Figure S1. *Flow diagram showing sample size for each analysis*