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Journal

Environmental Health Perspectives, 132(4)

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Publication Date

2024-04-01

DOI

10.1289/EHP13807

Peer reviewed

A Section 508–conformant HTML version of this article
is available at https://doi.org/10.1289/EHP13807.

Influence of Temperature and Precipitation on the Effectiveness of Water, Sanitation, and Handwashing Interventions against Childhood Diarrheal Disease in Rural Bangladesh: A Reanalysis of the WASH Benefits Bangladesh Trial

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Background: Diarrheal disease is a leading cause of childhood morbidity and mortality globally. Household water, sanitation, and handwashing (WASH) interventions can reduce exposure to diarrhea-causing pathogens, but meteorological factors may impact their effectiveness. Information about effect heterogeneity under different weather conditions is critical to refining these targeted interventions.

Objectives: We aimed to determine whether temperature and precipitation modified the effect of low-cost, point-of-use WASH interventions on child diarrhea.

Methods: We analyzed data from a trial in rural Bangladesh that compared child diarrhea prevalence between clusters ($N = 720$) that were randomized to different WASH interventions between 2012 and 2016 (NCT01590095). We matched temperature and precipitation measurements to diarrhea outcomes ($N = 12{,}440$ measurements, 6,921 children) by geographic coordinates and date. We estimated prevalence ratios (PRs) using generative additive models and targeted maximum likelihood estimation to assess the effectiveness of each WASH intervention under different weather conditions.

Results: Generally, WASH interventions most effectively prevented diarrhea during monsoon season, particularly following weeks with heavy rain or high temperatures. The PR for diarrhea in the WASH interventions group compared with the control group was 0.49 (95% CI: 0.35, 0.68) after 1 d of heavy rainfall, with a less-protective effect [PR = 0.87 (95% CI: 0.60, 1.25)] when there were no days with heavy rainfall. Similarly, the PR for diarrhea in the WASH intervention group compared with the control group was 0.60 (95% CI: 0.48, 0.75) following above-median temperatures vs. 0.91 (95% CI: 0.61, 1.35) following below-median temperatures. The influence of precipitation and temperature varied by intervention type; for precipitation, the largest differences in effectiveness were for the sanitation and combined WASH interventions.

Discussion: WASH intervention effectiveness was strongly influenced by precipitation and temperature, and nearly all protective effects were observed during the rainy season. Future implementation of these interventions should consider local environmental conditions to maximize effectiveness, including targeted efforts to maintain latrines and promote community adoption ahead of monsoon seasons. https://doi.org/10.1289/EHP13807

Introduction

In 2019, diarrheal disease caused >500,000 deaths in children <5 years of age.[1] Children that suffer from repeated diarrheal episodes are at high risk of malnutrition, stunted growth, and impaired cognitive development.[2] The World Health Organization estimates that more than half of diarrhea deaths are directly attributable to inadequate water safety, sanitation, and handwashing (WASH). Low-cost, household-level WASH interventions may prevent the spread diarrhea-causing pathogens, leading to improvements in child growth and development.[2] However, randomized controlled trials of WASH interventions in rural Kenya and Bangladesh found surprisingly modest effects on diarrhea; in Bangladesh, there was a 39% reduction in diarrhea prevalence among children who received a combined water, sanitation, and hygiene intervention, and in Kenya there was no reduction.[3,4]

Diarrheal disease is associated with temperature[5–9] and precipitation[6–10] across many different settings, and there are multiple pathways through which environmental conditions might influence the relationship between WASH interventions and diarrhea. Each type of WASH intervention prevents different subsets of enteric pathogen transmission pathways, and each may be distinctly influenced by weather.[11] Improved latrines may prevent fecal matter from overflowing into the environment during heavy rainfall, preventing the contamination of household surfaces, living areas, and nearby food and water sources.[12,13] High temperatures can increase pathogen growth and survival in food sources and water supplies,[6,14–16] but lidded containers and chlorination treatments may help reduce pathogen concentrations in household water.[17,18] Flooding could increase children's exposures to pathogens in the environment,[19,20] but handwashing interventions may reduce pathogen ingestion during hand–mouth contact.[21]

Yet, few studies have examined how meteorological and environmental factors modify the effect of WASH interventions on

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Supplemental Material is available online (https://doi.org/10.1289/EHP13807).

The authors declare they have nothing to disclose.

Conclusions and opinions are those of the individual authors and do not necessarily reflect the policies or views of EHP Publishing or the National Institute of Environmental Health Sciences.

Received 12 August 2023; Revised 8 March 2024; Accepted 13 March 2024; Published 11 April 2024.

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diarrhea. There is some evidence that the relationships between diarrhea prevalence and unimproved water sources and sanitation systems change under different levels of precipitation and runoff[10,22] but that water treatment could mitigate increases in diarrhea following heavy rainfall in some conditions.[23] In Bangladesh, one study found that tubewells were most effective in non–flood-controlled areas.[24] Another study found that reductions in diarrhea from sanitation interventions occurred exclusively during the rainy season in Bangladesh.[25] However, most prior studies used observational designs, and estimates of WASH intervention effectiveness were likely to be confounded by household wealth given that wealthier households have greater access to WASH in nonrandomized settings.[26–28]

Our objective was to assess whether temperature and precipitation modified the effect of water, sanitation, and handwashing interventions on child diarrhea prevalence in a randomized trial in rural Bangladesh. We merged individual-level outcome data with granular weather measurements from remote sensors to model how environmental conditions influence intervention effectiveness.

Methods

Here, we describe the trial design, data processing, and statistical analyses that were conducted under the study. These methods reflect prespecified steps that we published in a preanalysis plan for this study on Open Science Framework (https://osf.io/yt67k/files/osfstorage/624788a7a0fedd00bf94d18b). We describe deviations from this preanalysis plan below, and a list of changes is available in "Supplement 1: Deviations from the pre-analysis plan," in the Supplemental Material.

Study Data

The WASH Benefits Bangladesh trial (NCT01590095) delivered low-cost, household-level WASH interventions and estimated their effects on diarrheal disease.[4,29] The trial enrolled pregnant women in their second or third trimester between 31 May 2012 and 7 July 2013 in the Gazipur, Kishoreganj, Mymensingh, and Tangail districts of rural Bangladesh. The study enrolled up to eight households per village cluster (mean = 6.75 households per cluster; range: 3–8). Village clusters were block-randomized to one of the following arms: *a*) chlorinated drinking water (W); *b*) upgraded sanitation (S); *c*) promotion of handwashing with soap (H); *d*) nutrition education with lipid-based supplement (Nutrition); *e*) combined water, sanitation, and handwashing (WASH); *f*) combined water, sanitation, handwashing, and nutrition (WASH + Nutrition); or *g*) control. In total, 720 village clusters were included in the trial; 90 clusters were randomized to each intervention arm and 180 clusters were randomized to a double-sized control arm. Here, we excluded the Nutrition arm from the present analysis because the effectiveness of nutrition alone is unlikely to depend on environmental factors. For similar reasons, we merged the WASH and WASH + Nutrition groups to a single "combined WASH" group.

The water intervention included a lidded storage container and regular supply of sodium dichloroisocyanurate tablets. The sanitation intervention included the installation of a double-pit pour–flush latrine compared with the more common single-pit pour–flush latrine. Fecal matter can be diverted to a secondary chamber for compost in the double-pit latrine, whereas waste needs to be manually removed from the single-pit latrine. The handwashing intervention included the installation of handwashing stations in households with index children near the latrine and in the kitchen, as well as a regular supply of detergent sachets to make soapy water. All interventions were delivered by community promoters who provided instruction for proper use.

There were 4,747 children born to the enrolled mothers ("index children"). In the study region, children lived within compounds shared by their extended family consisting of their own household (the "index household") and an average of 1.5 other households (range: 0–10). The water and handwashing interventions were only implemented in the index household, whereas the sanitation intervention was provided to all households in the compound. Additional enrollment criteria and intervention details have been reported elsewhere.[4]

Outcome Data

During the trial, the evaluation team visited each participating household twice. Household visits occurred ~ 1 and 2 y after intervention delivery. The first round of evaluation took place between 9 September 2013 and 21 September 2014, and the second round between 23 December 2014 and 31 October 2015. The order of household visits was set based on the ages of children in each study cluster (follow-ups intended to collect data when children were 12 and 24 months of age) and on field logistics.

During these visits, trained field staff interviewed caregivers to record reported diarrhea for index children and children living in the same compound who were <3 years of age at enrollment. A diarrhea case was defined as having at least three loose stools in 24-h or at least one bloody stool within the past 7 d.[4] The trial also measured caregiver-reported bruising within the prior 7 d, which we used as a negative control outcome.[30,31]

At enrollment, field staff recorded household geocoordinates using a Global Positioning System locating device, allowing us to map outcomes to a specific point in space and time. We leveraged these data to assess the underlying meteorological conditions of reported outcomes.

Environmental Data

We assessed various measures of precipitation and temperature as possible effect modifiers, as described below and prespecified in our published preanalysis plan. We matched precipitation and temperature values from spatiotemporal remote sensing data to each trial measurement by household coordinates and the date of outcome assessment.

Precipitation. We obtained precipitation data from the Multi-Source Weighted-Ensemble Precipitation dataset from GloH2O [daily temporal resolution, $0.1°$ ($\sim 10.1 \times 11.1$ km at study site) spatial resolution], which merges numerous gauge, satellite, and reanalysis precipitation data sources and corrects for bias.[32] We calculated the total weekly precipitation, and created binary indicators of whether these sums exceeded the median weekly total precipitation across the study period. We also investigated periods where weekly total precipitation was zero, although this analysis was not prespecified. To measure heavy rain, we created binary indicators for at least 1 d in the week in which total precipitation was above the 80th percentile of all daily totals; we also conducted a sensitivity analysis to estimate effect estimates under a 90th percentile heavy rain threshold. We chose to use precipitation thresholds based on the percentile of all daily totals rather than season-specific totals to maximize the generalizability of our results.

We defined the rainy season as the continuous period during which the 5-d rolling average of daily precipitation was >10 mm and constructed variables to indicate if diarrhea measurements were taken during the rainy season. In Bangladesh, precipitation is heavily concentrated during the rainy season, and the first instance of continuous rainfall typically marks the start of the season; using rolling averages of rainfall allowed us to identify when this period started. Based on observed precipitation values in the study region, we selected a threshold of 10 mm to capture the beginning of the period of consistent rainfall during the monsoon months.

We had prespecified the inclusion of a variable that described heavy rainfall that followed dry vs. wet season. However, we were not able to conduct this analysis because high levels of rainfall almost never followed a dry period in this study region.

Temperature. We obtained daily near-surface air temperature data from the Famine Early Warning Systems Network Land Data Assimilation System (FLDAS) Central Asia dataset [daily temporal resolution, 0.01° ($\sim 1.0 \times 1.1$ km at study site) spatial resolution] from the National Aeronautics and Space Administration (NASA).[33] We used the FLDAS dataset over the prespecified NASA Terra Moderate Resolution Imaging Spectroradiometer (MODIS) product owing to extensive missing values for our study period in MODIS.

We computed the minimum, maximum, and average temperatures. We also constructed binary indicators for whether the minimum, maximum, and average temperatures exceeded the median value across the study period. We had previously prespecified additional 1-, 30-, and 90-d lag periods for temperature measurements, but we omitted these from the present analysis to maintain consistency with the precipitation measurements.

Lag periods. Our primary analysis used weekly measures of temperature and precipitation with a 1-wk lag (capturing the 8–14 d period prior to date of caregiver-reported illness) to account for the period of time in which weather conditions could influence enteric pathogen transmission in the environment and the short incubation period of common enteric pathogens.[34] We assumed that any changes in pathogen exposure occurred within a short period after weather events; we expected that child diarrhea episodes were primarily caused by pathogens in the household setting that were flushed or transported rapidly following weather events.

We conducted sensitivity analyses using alternative lag periods of 0 wk (1–7 d prior), 2 wk (8–21 d prior), and 3 wk (22–28 d prior). We selected these periods to consider how possible variations in the timing of pathogen transport and incubation might influence effect estimates.

Statistical Analysis

To estimate intervention effects under different weather conditions, we conducted an intention-to-treat analysis consistent with the original trial, which had high intervention adherence.[4,35] Adherence to most interventions exceeded 90% and remained high over the 2-y follow-up period. We compared diarrhea prevalence in the control group to those receiving the following interventions: *a*) water only, *b*) sanitation only, *c*) handwashing only, *d*) combined WASH (WASH or WASH + Nutrition), and *e*) any WASH intervention (water, sanitation, hygiene, combined WASH, or combined WASH + Nutrition arms).

We assessed WASH effectiveness for both continuous and categorical meteorological variables. Continuous variables included weekly total precipitation (in millimeters), minimum temperature (in degrees Celsius), maximum temperature (in degrees Celsius), and average temperature (in degrees Celsius). Categorical variables included season, heavy rain, and binary indicators for whether total precipitation, minimum temperature, maximum temperature, and average temperature were above or below the study median.

We used prevalence ratios (PRs) to estimate intervention effect, comparing prevalence in the intervention group to that in the control group. Ratios <1 would suggest that the intervention reduced prevalence compared with the control arm, and ratios >1 would suggest that the intervention increased prevalence.

For continuous meteorological variables, we modeled how diarrhea prevalence changes with weather in each study arm. To allow for potential nonlinear relationships between continuous weather measures and intervention effects, we fit generalized additive models (GAMs) to model the outcomes as a function of the intervention and an environmental variable (as a spline).[36] We specified a binomial family with logit link functions and used restricted maximum likelihood estimation to select smoothing parameters. We estimated simultaneous confidence intervals (CIs) using a parametric bootstrap of the variance–covariance matrix under a multivariate normal distribution.[37]

For categorical meteorological variables, we estimated intervention effectiveness under different weather conditions using targeted maximum likelihood estimation with ensemble machine learning.[38] Learners included the simple mean, generalized linear model (GLM), Bayesian GLM, GAM, and lasso net GLM for treatment and outcome ensemble models.[36,39,40] We estimated the PR and corresponding CIs for intervention vs. control for each weather variable stratum. We used cluster-level influence curve-based standard errors to account for dependence within village clusters.

We adjusted the models to consider the relationships between temperature and precipitation. In models where temperature was the effect modifier, we controlled for total weekly precipitation. In models where precipitation was the effect modifier, we controlled for average weekly temperature. We did a complete case analysis, resulting in the exclusion of 38 measurements that had missing temperature values. There were no missing values of diarrhea outcomes or precipitation measurements.

To check for possible misclassification of reported diarrhea, we conducted a negative control analysis using caregiver-reported bruising in the past 7 d.[30,31] We selected bruising as a negative outcome under the assumption that it is not plausibly impacted by WASH interventions.

Analyses were conducted in R (version 4.1.3; R Development Core Team). Replication materials are publicly available on Open Science Framework (https://osf.io/yt67k/).

The original trial was registered at ClinicalTrials.gov (number NCT01590095). The study protocol was approved by the ethical review committee at the International Centre for Diarrhoeal Disease Research, Bangladesh (PR-11063), the Committee for the Protection of Human Subjects at the University of California, Berkeley (2011-09-3652), and the institutional review board at Stanford University (25863). Participants provided written informed consent before enrollment in the trial.

Results

Our analysis included 12,440 total diarrhea measurements for 6,921 children between 0.5 and 5.5 years of age (mean $\pm$ standard deviation $= 2.0 \pm 1.2$) during the period between 3 February 2013 and 31 October 2015 (Figure 1). We report additional participant characteristics and the distribution of environmental factors by group in Table 1.

Precipitation

During the study, the total weekly precipitation ranged from 0 to 295 mm, with a median of 13 mm. Precipitation was highly concentrated during the rainy season, which fell between 29 April and 9 October in 2013, 27 May and 27 September in 2014, and 1 April and 26 September in 2015. In the control arm, we observed increases in diarrhea prevalence during the rainy seasons, particularly in 2014. In households that received any WASH intervention, diarrhea prevalence remained relatively constant over time (Figure 1A; Excel Table S1). We saw that increases in diarrhea coincided with periods that experienced the most rainfall, with annual precipitation being highly concentrated in the rainy season (Figure 1B; Excel Table S1).

First, we examined effect modification of precipitation for across any WASH intervention vs. control. We found that diarrhea

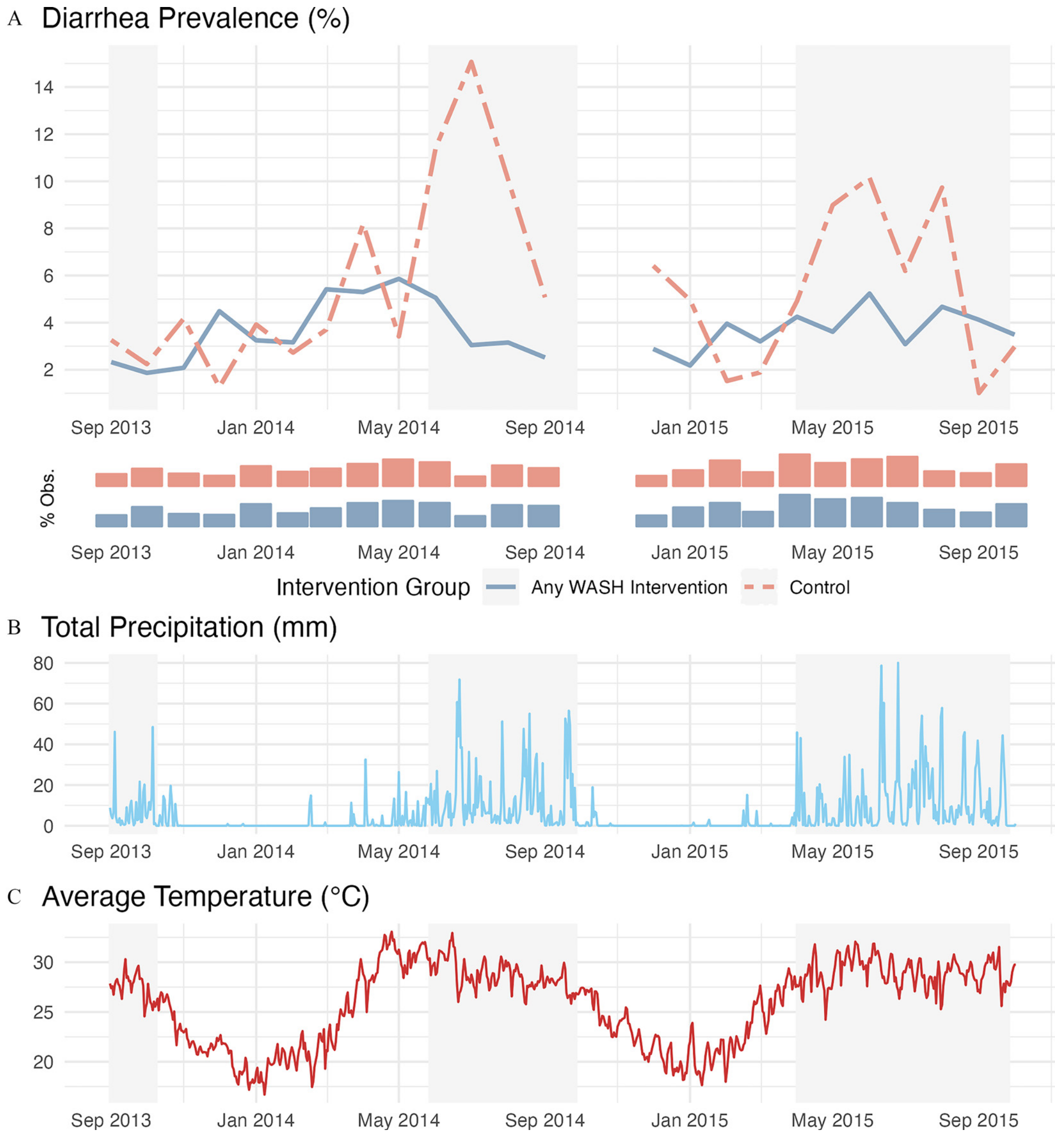

Figure 1. Diarrhea prevalence, total precipitation, and average temperature (in degrees Celsius) over time among children in the Water, Sanitation, and Handwashing (WASH) Benefits Bangladesh trial. (A) Prevalence of caregiver-reported diarrhea over time, by intervention group. Rainy season is shaded in gray. Rug plots show the percentage of diarrhea measurements made in each group per month during the trial. Plot is left-truncated at September 2013, such that the figure omits two measurements taken in March 2013 that are included in subsequent analyses. Numerical data and sample sizes are included in Excel Table S1. (B) Daily total precipitation over time, averaged across the study area. Numerical data are included in Excel Table S2. (C) Daily average temperature over time, averaged across the study area. Numerical data are included in Excel Table S3. Note: obs, observations.

prevalence in the control group increased with higher weekly total precipitation, whereas diarrhea prevalence among those who received any WASH intervention slightly decreased (Figure 2; Excel Table S4). In measurements with above-median weekly total rainfall, we estimated a PR of 0.56 (95% CI: 0.44, 0.72) for any WASH intervention compared with 0.85 (95% CI: 0.43, 1.69) in measurements with below-median total rainfall (Figure 3; Table S1). Following periods with zero total rainfall, the PR was 0.94 (95% CI: 0.39, 2.26). The PR for the pooled WASH intervention was 0.50 (95% CI: 0.40, 0.62) during the rainy season compared with 1.06 (95% CI: 0.75, 1.52) during the dry season (Figure 3; Table S1). The PR associated with any WASH intervention was lower following weeks when there was at least 1 d of heavy rainfall (PR = 0.49; 95% CI: 0.35, 0.68) compared with when there were no days with heavy rainfall (PR = 0.87; 95% CI: 0.60, 1.25) (Figure 3; Table S1).

Next, we assessed effect modification by precipitation for each intervention type (Figure 3; Table S1). During the rainy season, the sanitation, handwashing, and combined WASH interventions reduced diarrhea prevalence by 54%–61%, whereas the water intervention reduced it by 30% (Figure 3; Table S1). For all intervention arms, there was no decrease in diarrhea prevalence in the dry season. Intervention-specific trends were similar for total precipitation and heavy rainfall, with stronger effect modification for heavy rain than for total weekly precipitation. However, for the handwashing intervention, there was no evidence of effect modification by total weekly precipitation or heavy rainfall.

Temperature

During the study, the weekly average temperature ranged from 18 to 32°C (median = 27°C), the minimum temperature ranged from 17 to 31°C (median = 25°C), and the maximum temperature ranged from 18 to 34°C (median = 28°C). Temperatures reached their peak in May, immediately preceding or at the start of the annual rainy season (Figure 1C; Excel Table S3). Overall, most

Table 1. Population characteristics and meteorological conditions by intervention group in the Water, Sanitation, and Handwashing (WASH) Benefits Bangladesh trial ($N = 4{,}254$ households).

Variable	Any WASH intervention	Control
Sample characteristics		
Children	4,965	1,956
Observations	8,974	3,466
Households	3,051	1,203
Children per household	1.63 (1.59–1.66)	1.63 (1.57–1.68)
Age at first measurement (y)	1.59 (1.55–1.62)	1.63 (1.58–1.68)
Age at second measurement (y)	2.53 (2.5–2.57)	2.52 (2.47–2.58)
Diarrhea prevalence	343 (6.9)	197 (10.1)
Missing diarrhea values	0	0
Observations by intervention group		
Water (W)	1,790	—
Sanitation (S)	1,730	—
Handwashing (H)	1,764	—
Combined WASH	3,690	—
Season		
Measured during rainy season	4,578 (51.01)	1,772 (51.13)
Temperature variables (1-wk lag)		
Mean temperature (°C)		
Mean (95% CI)	26 (25.6–26.5)	26.1 (25.4–26.8)
N (%) above overall median of weekly mean temperatures (27°C)	5,507 (61.37)	2,141 (61.77)
Minimum temperature (°C)		
Mean (95% CI)	24.7 (24.2–25.1)	24.7 (24–25.4)
N (%) above overall median of weekly minimum temperatures (25°C)	5,499 (61.28)	2,136 (61.63)
Maximum temperature (°C)		
Mean (95% CI)	27.3 (26.8–27.7)	27.3 (26.6–28)
N (%) above overall median of weekly maximum temperatures (28°C)	5,328 (59.37)	2,063 (59.52)
Missing temperature values	28	10
Precipitation variables (1-wk lag)		
Heavy rain (≥1 d ≥80th percentile)	3,942 (43.93)	1,531 (44.17)
Total precipitation (mm)		
Mean (95% CI)	41.7 (36.1–47.4)	41.5 (32.4–50.7)
N (%) above overall median of weekly total precipitation (13 mm)	5,183 (57.76)	2,009 (57.96)
Missing precipitation values	0	0

Note: Sample sizes, child demographics, diarrhea prevalence, and environmental risk factor distributions, by treatment arm. For categorical variables, the number of occurrences and ranges or percentages are reported. For continuous variables, the mean and 95% CI are reported. All environmental variables are reported for the 8- to 14-d period prior to outcome assessment (1-wk lag), with the exception of rainy season, which describes if measurement dates fell in the season. We report meteorological conditions under alternative lag periods in Table S1. CI, confidence interval.

rainfall occurred at high temperatures and weekly precipitation varied more under higher weekly average temperatures (Figure S1, Excel Table S6).

We found that as average temperature increased, diarrhea prevalence increased slightly in the intervention arms but increased rapidly in the control arm (Figure 4A; Excel Table S5). We saw similar trends when comparing above-median vs. below-median measurements and estimated PRs of 0.60 (95% CI: 0.48, 0.75) vs. 0.91 (95% CI: 0.61, 1.35) for average temperatures, 0.63 (95% CI: 0.50, 0.79) vs. 0.84 (95% CI: 0.40, 1.78) for minimum temperatures, and 0.60 (95% CI: 0.48, 0.75) vs. 0.89 (95% CI: 0.59, 1.34) for maximum temperatures (Figure 4B; Table S2).

Temperature appeared to have a larger influence on the effectiveness of the sanitation, handwashing, and combined WASH interventions compared with the water intervention (Figure 4B; Table S2). During periods in which there were above-median weekly average temperatures, we estimated between 45% and 48% lower prevalence under the sanitation, handwashing, and combined WASH interventions compared with 22% lower prevalence under the water intervention compared with control. We found no difference in effectiveness of the water, sanitation, or handwashing interventions by minimum of maximum temperatures, although the below-median temperature effects were null and the above-median effects were not. However, our estimates have low precision.

Other Analyses

We did not observe any significant differences in intervention effect estimates by temperature or precipitation on caregiver-reported bruising, a negative control outcome (Figure S2, Excel Table S7). This suggests that differential misclassification of reported diarrhea did not have a large influence on our results.

We conducted sensitivity analyses under different lag periods and alternate definitions of heavy rain. We report the distribution of environmental factors in these sensitivity analyses in Table S3. Estimates of intervention effect across different precipitation (Figure S3, Excel Table S8) and temperature (Figure S4, Excel Table S9) conditions were consistent across all lag periods we assessed. Results were similar under definitions of heavy rain that used an 80th (17.4 mm) vs. 90th (28.9 mm) percentile cutoff (Figure S5, Excel Table S10). Under the 90th percentile threshold, we observed slightly stronger but less precise effect estimates.

Discussion

WASH interventions in rural Bangladesh more effectively prevented child diarrhea under high temperatures and precipitation. We found that receipt of any WASH intervention was associated with 51% lower diarrhea prevalence following heavy rainfall and 40% after above-median temperatures compared with 34% in the original trial. Effect modification varied by intervention type; precipitation had the strongest influence on the effectiveness of the sanitation and combined WASH interventions, whereas temperature had the strongest influence on the sanitation, handwashing, and combined WASH interventions.

The annual monsoon in Bangladesh is characterized by highly concentrated, intense rainfall and warm temperatures. During this period, we observed that diarrhea prevalence increased in the control group but remained relatively constant among children that had received any WASH intervention. Our findings suggest that in this setting, interventions prevent weather-related increases in diarrhea risk during the rainy season. Generally, heavy rain could flush pathogens and fecal matter into the broader environment, contributing to the contamination of drinking water, food, household surfaces, and soil.[23,41] Other studies have found that high temperatures are strongly associated with increased all-cause and bacterial diarrhea, but decreased viral diarrhea,[5,42] and that temperature has varying impacts by pathogen on the persistence in food and drinking water and on surfaces.[43–47] It is possible that associations between diarrhea and weather were due to increased transmission of bacterial but not viral enteropathogens. Bacterial pathogens predominate during the warmer, wetter monsoon conditions[42,48] and are a common cause of diarrhea in children <2 years of age in Bangladesh.[49] A recent study from our group investigated differences in WASH effectiveness by pathogen type and found that there was lower prevalence of enteric viruses among those who received the combined WASH intervention but that there were no differences in bacteria and parasite carriage.[50] There was no evidence of seasonal effect modification by pathogen type, but that study used a smaller cohort and may not have been sufficiently powered to detect differences in intervention effectiveness.

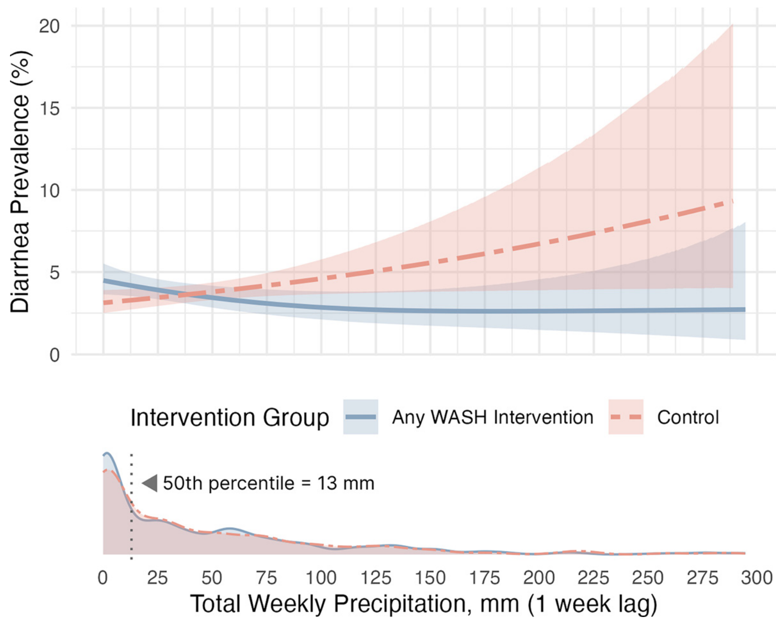

Figure 2. Diarrhea prevalence by total precipitation and intervention group in the Water, Sanitation, and Handwashing (WASH) Benefits Bangladesh trial. Predicted diarrhea prevalence and 95% confidence intervals by total precipitation in the 8- to 14-d period prior to outcome assessment, from generalized additive models that were controlled for average temperature and stratified by intervention group. Prevalence ratios for the intervention are calculated at the 10th and 90th percentile of total weekly precipitation using a nonparametric bootstrap with 1,000 resamples taken at the cluster level. The density plot shows the distribution of measurements over values of weekly total precipitation, with a dashed line marking the median. Numerical data are included in Excel Table S4.

Generally, we observed no intervention effect on diarrhea in the dry season or following periods with no rainfall. However, our continuous models predicted slightly higher diarrhea prevalence for the pooled interventions compared with the control at low values of total weekly precipitation. We do not believe that the interventions inherently increase diarrhea under these conditions, but there may be other weather conditions or behaviors that interact with precipitation to modify the effect of WASH. Future work to assess mechanisms of pathogen transmission during dry periods in Bangladesh could help bring insight to this result.

Specific sources of increased contamination following extreme weather could inform differences in how meteorological factors

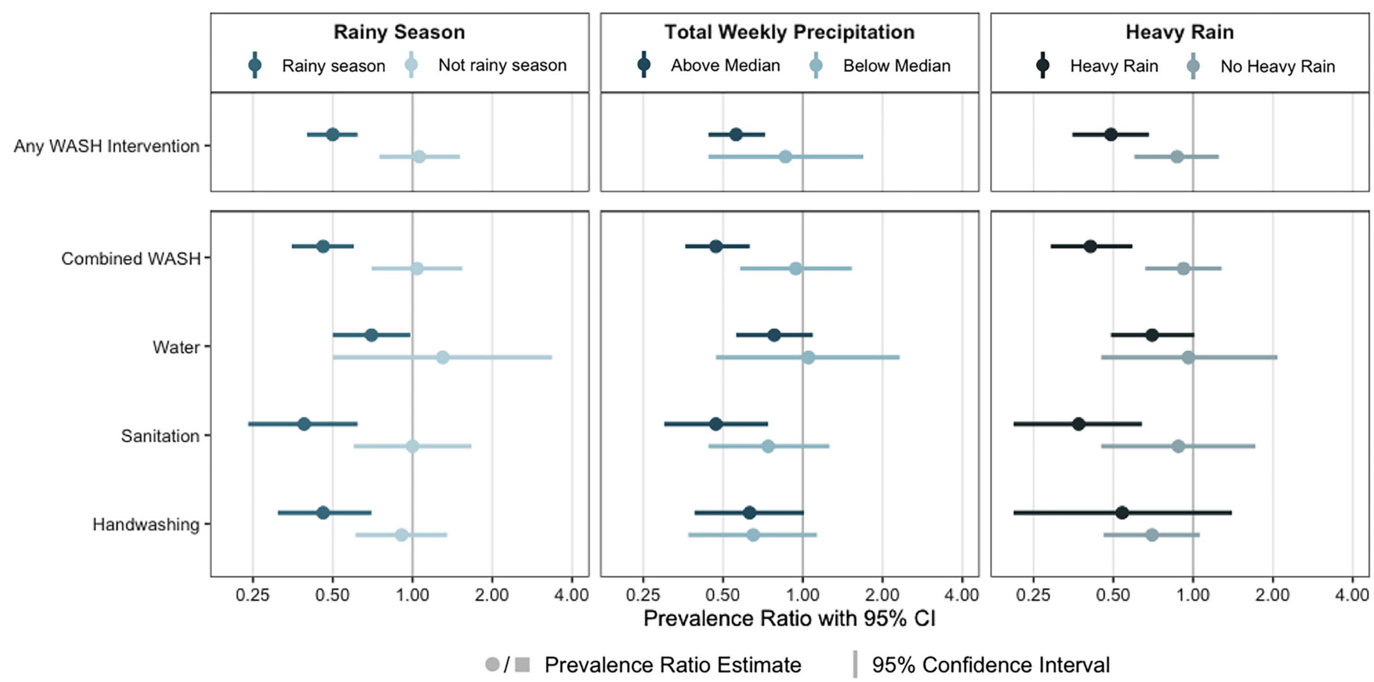

Figure 3. Differences in diarrhea prevalence under varying precipitation conditions, by intervention group in the Water, Sanitation, and Handwashing (WASH) Benefits Bangladesh trial. Prevalence ratios and 95% CIs for caregiver-reported diarrhea in the intervention vs. control groups. Heavy rain describes whether there is at least 1 d with >80th percentile daily rainfall in the 8–14 d prior to outcome assessment. Total precipitation is also measured for the 8- to 14-d period prior to outcome assessment, with a median value of 13 mm. All effect estimates controlled for average weekly temperature. We used targeted maximum likelihood estimation with ensemble models that integrated simple mean, GLM, Bayesian GLM, generalized additive model, and lasso net GLM learners. Corresponding numerical data and sample sizes are included in Table S2. Note: CI, confidence interval; GLM, generalized linear model.

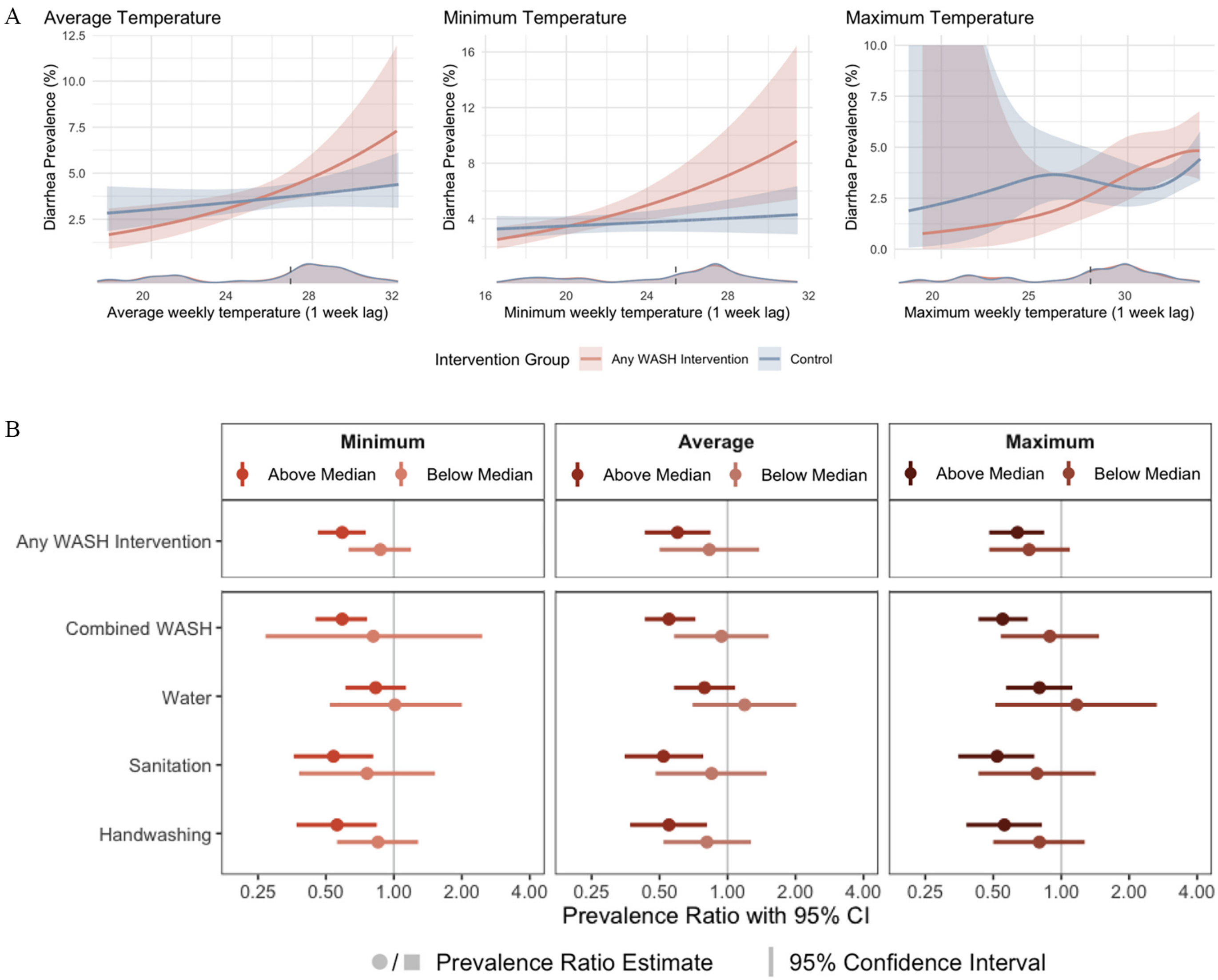

Figure 4. Differences in diarrhea prevalence under varying temperature conditions (in degrees Celsius), by intervention group in the Water, Sanitation, and Handwashing (WASH) Benefits Bangladesh trial. (A) Predicted diarrhea prevalence and 95% CIs by average, minimum, and maximum temperatures in the 8- to 14-d period prior to outcome assessment, from generalized additive models that were controlled for total weekly precipitation and stratified by intervention group. Density plots show the distribution of measurements over values of total temperature, with a dashed line marking the median. Numerical data are included in Excel Table S5. (B) Prevalence ratios and 95% CIs for caregiver-reported diarrhea in the intervention vs. control groups. The median values were 27°C for average temperature, 25°C for minimum temperature, and 28°C for maximum temperature. All effect estimates have controlled for total weekly precipitation. We used targeted maximum likelihood estimation with ensemble models that integrated simple mean, GLM, Bayesian GLM, generalized additive model, and lasso net GLM learners. Corresponding numerical data and sample sizes are included in Table S3. Note: CI, confidence interval; GLM, generalized linear model.

influence each intervention. Here, we found that the sanitation and handwashing interventions more effectively mitigated increases in diarrhea prevalence following precipitation and higher temperatures, and the water intervention had the smallest preventive effect on diarrhea in these conditions. Higher organic loads, high turbidity, or the presence of pathogens resistant to chlorine (such as *Cryptosporidium*) in stored water might require higher doses of chlorine to sufficiently treat water and eliminate risk of infection following heavy rainfall.[17,51,52] The adoption of handwashing practices could counteract weather-related increases in pathogen exposure to soil and surface water.[21] Improved latrines may help contain fecal matter and prevent pathogens from being flushed into the environment, although this somewhat contradicts prior studies that found increased groundwater contamination near sewage systems following heavy rain.[10,12,53,54] Compared with other regions, the presence of alluvial soil (consisting of loose silt, clay, and sand) in Bangladesh's flood plains may prevent the transport of pathogens from latrines into groundwater supplies.[55,56] A study conducted in Indore and Kolkata, India, found that wells near latrines surrounded by alluvial formations had significantly lower fecal coliform and nitrate concentrations compared with wells near latrines with fractured rocks.[57]

Our findings also have implications for the design and interpretation of studies of WASH interventions. In future studies, it would be valuable to consider how regional meteorological conditions impact baseline diarrhea risks. If heterogeneity in effects by weather is likely, studies should ensure that statistical power is sufficient to examine these influences on treatment effects. When possible, meta-analyses of WASH intervention studies should stratify by season in estimating effects; pooling results from trials conducted year-round vs. only during the rainy or dry season may produce estimates that do not account for strong seasonal effect modification. In addition, it may be valuable to consider WASH interventions that are targeted to the period of the year in which transmission is expected to be highest or when preventive behaviors might be most impactful.

Bangladesh is projected to experience rapidly increasing temperatures and precipitation under climate change, which may increase the burden of childhood diarrhea in rural communities.[58,59] Our findings suggest that WASH interventions will be particularly impactful for preventing diarrhea under more extreme weather conditions and may be resistant to damages during typical monsoon seasons. As rural, low-income communities increasingly experience the negative impacts of climate change, investment into WASH interventions may increase the resilience of vulnerable populations against diarrhea. Interventions that address multiple pathways of enteric pathogen transmission may be most effective in mitigating the impacts of climate change on diarrhea.

Our study is subject to several limitations. We measured caregiver-reported diarrhea, which is susceptible to courtesy bias; however, our negative control analysis using an alternative caregiver-reported outcome suggested that there was no evidence of misclassification. Prior studies of the WASH Benefits trial have also found similar effect sizes between caregiver-reported diarrhea and other objective measures of pathogen exposure, such as the reduction of hookworm, *Giardia*, and enteroviruses in stool.[50,60,61] In addition, higher temperature and higher precipitation mostly coincided during the study period, making it difficult to fully isolate the influence of each on WASH intervention effectiveness. We were also not able to investigate the influence of flooding owing to a lack of available data, and we could not investigate the interaction between heavy rain preceded by dry periods owing to data sparsity. Finally, we were limited by the type of weather data that is publicly available for rural Bangladesh. Weather stations, considered the gold standard for meteorological measurements, are sparse in the region; on average, households in the trial were >79 km away from the nearest weather station. Remote sensing data sources help approximate ground conditions at a higher spatiotemporal scale, but their measurements can carry high degrees of uncertainty in areas with few ground sensors. These data can introduce nondifferential misclassification of weather exposures and have been shown to attenuate estimates of the relationship between weather and diarrheal disease.[62] We acknowledge this possibility, under which our study's estimates would represent a lower bound to the influence of temperature and precipitation on WASH effectiveness.

Conclusion

In the present study, we rigorously assessed the influence of temperature and precipitation on WASH intervention effectiveness using data from a randomized trial with high adherence and high-resolution weather data. Low-cost, household-level WASH interventions more effectively reduced diarrhea prevalence following periods of higher temperatures, higher precipitation, and heavy rainfall. Effect modification varied by intervention type, and we observed the largest differences in diarrhea reductions following heavy rainfall under the sanitation intervention. In regions with similar climates, WASH interventions may increase community resilience against extreme weather under climate change by preventing environmentally mediated enteric infections.

Acknowledgments

We greatly appreciate the contributions of the study participants and field workers who delivered the interventions and led data collection. We also acknowledge the Stanford Research Computing Center for providing computational resources at the Sherlock high-performance cluster.

This study was supported by the Gates Foundation (grant OPPGD759 to the University of California, Berkeley). The original trial was implemented by ICDDR,B. Research reported in this publication was supported in part by the National Institute of Allergy And Infectious Diseases of the National Institutes of Health (NIH) under awards K01AI141616 (PI: Benjamin-Chung) and R01AI166671 (PI: Arnold), the National Heart, Lung, And Blood Institute of the NIH under award T32HL151323 (Nguyen), the National Institute of General Medical Sciences of the NIH under award T32GM144273 (Athni), and a Stanford University School of Medicine Dean's Postdoctoral Fellowship (Grembi). The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH. Jade Benjamin-Chung is a Chan Zuckerberg Biohub Investigator.

The funders of the study had no role in study design, data analysis, interpretation, writing of the manuscript, or the decision to submit the manuscript for publication.

Individual participant data and metadata for this study will be made available at the time of publication and posted at https://osf.io/yt67k/. The preanalysis plan and ancillary results are also available at the same URL. To protect participant privacy, household geocoordinates are not included in the public dataset.

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