ABSTRACT

NIVEN, CAITLIN GRACE. Climate Threats to Water, Sanitation and Hygiene (WASH)
and Global Environmental Health. (Under the direction of Dr. Ayse Ercumen).

This dissertation investigates the intersections of weather extremes, water insecurity, sanitation interventions, and health outcomes, with a focus on the impacts of extreme weather events and water intermittency on fecal contamination and child health in rural Bangladesh and peri-urban Malawi as well as caregiver stress in the latter. Using a combination of longitudinal field data, randomized controlled trials, and cross-sectional studies, this research explores how climate-related stressors influence water, sanitation, and hygiene (WASH) interventions and microbial safety of drinking water in low-resource settings.

Chapter 1 evaluates the influence of extreme rainfall and temperature on the fecal contamination across eight key environmental pathways in rural Bangladeshi households. Data from a 3.5-year period (n=26,659 samples) were spatiotemporally matched with daily weather data to assess *E. coli* contamination in hand rinses from children under five and their mothers, stored food, stored drinking water, tubewell water, captured flies, pond water, and courtyard soil. The results demonstrate that extreme rainfall and temperature significantly impact *E. coli* levels, with extreme rainfall associated with increased contamination in food, stored water, and ponds, and a reduction in soil contamination. Temperature extremes also increased *E. coli* in stored water and food. These findings highlight the need for targeted water and food safety measures during weather extremes, particularly focusing on proper water storage and treatment to reduce contamination and the risk of enteric infections.

Chapter 2 investigates how extreme weather events, specifically rainfall and temperature, modify the effectiveness of a sanitation intervention aimed at reducing fecal contamination in rural Bangladesh. The same data from the WASH Benefits trial were analyzed, linking *E. coli* measurements from the sanitation and control arms of the intervention (n=23,238 samples) with weather data. The results reveal that the sanitation intervention, which included double-pit latrines and behavior change promotion, was more effective in reducing contamination during periods of higher rainfall and temperature. Specifically, the intervention resulted in larger reductions in *E. coli* on hands, food, ponds, and flies during wet and warmer conditions. These

findings suggest that sanitation interventions can mitigate the effects of extreme weather on environmental fecal contamination, emphasizing the importance of incorporating weather variability into future WASH intervention designs.

Chapter 3 explores the relationship between intermittent water supply, microbial contamination, child health, and caregiver stress in a peri-urban setting in Blantyre, Malawi. This was a cross-sectional study involving 232 households that examined how water intermittency affected child health outcomes, water quality, and caregiver stress. Our results show that an intermittent water supply was associated with increased prevalence of diarrhea, respiratory infections, and elevated caregiver stress. Children in households with intermittent water access had a significantly higher risk of acute respiratory infections (ARI), and caregivers reported heightened stress, potentially due to concerns over water availability and child health. These findings underscore the need for interventions that address the challenges of water intermittency, including safe water storage, alternative water sources, and support for caregivers.

Taken altogether, these chapters highlight the compounded risks of extreme weather and water insecurity in low-resource settings. While sanitation interventions can mitigate some of the negative impacts of weather extremes on fecal contamination, water intermittency remains a significant challenge for both public health and caregiver well-being. This research emphasizes the importance of integrating climate resilience into WASH programs and developing strategies to improve water storage and sanitation practices in response to weather extremes. Future efforts should focus on reducing waterborne disease transmission through adaptive WASH interventions, and long-term studies should investigate the health consequences of antimicrobial resistance associated with environmental contamination in these settings.

Climate Threats to Water, Sanitation and Hygiene (WASH) and Global Environmental Health.

by
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DEDICATION

To my grandmother, Catharine Niven -- the first female winemaker in San Luis Obispo County in 1973. A pioneer who was unafraid to be a strong woman in a male dominated field.

BIOGRAPHY

Caitlin Niven is a doctoral candidate in the College of Natural Resources at North Carolina State University in the Department of Forestry and Environmental Resources. She will graduate with a PhD in Forestry and Environmental Resources, with a concentration in Environmental Epidemiology and a minor in Environmental Engineering and Statistics. She received a graduate certificate in Environmental Assessment, was awarded a North Carolina State University Global One Health Academy fellowship in 2023 and was inducted into the Xi Sigma Pi international honors society in 2022. Caitlin received her Bachelor of Arts degree in Public Health studies with a concentration in Biology from Elon University. She is passionate about water quality, universal access to water, sanitation, and hygiene, and global environmental health. Her academic focus has been on emerging challenges and microbiological threats to global health particularly in the field of water, sanitation, and hygiene (WASH) as it pertains to waterborne contaminants, pathogens and the spread of infectious disease. Caitlin's research has evaluated the impacts of climate related events on *E. coli* contamination in various environmental reservoirs and how extreme weather events modify the efficacy of an on-site sanitation intervention on *E. coli* contamination and her current research allowed her to engage in field work in Malawi on a National Science Foundation funded research project evaluating the impact of an intermittent water supply on drinking water quality, child health outcomes, and caregiver emotional stress. After completing her degree, she hopes to pursue a career in the global one health and WASH sectors, to continue disrupting pathogen transmission!

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BACKGROUND

Climate change is increasingly recognized as a critical driver of health outcomes worldwide, particularly in low- and middle-income countries (LMICs), where environmental vulnerability is closely intertwined with infrastructural and resource limitations. Among the many health challenges amplified by climate-related pressures are enteric and waterborne diseases, which remain leading contributors to global child morbidity and mortality. These illnesses are transmitted through various, diverse environmental transmission pathways—including food, hands, water, and soil—that may be sensitive to fluctuations in weather as well as broader environmental changes.

Despite growing evidence linking climatic factors like rainfall and temperature to increases in diarrheal disease, the mechanisms driving these associations are not fully understood. Environmental conditions may alter both the distribution and behavior of fecal pathogens across multiple transmission routes, yet much of the existing research has a narrow focus on drinking water. Expanding our understanding of how climate variables influence a wider array of exposure pathways is essential for developing comprehensive, sustainable disease prevention strategies. Across all three studies in this dissertation, we measure *Escherichia coli* (*E. coli*) contamination as a fecal indicator to assess environmental pathogen presence, providing a measurable proxy for evaluating enteric pathogen exposure and microbial risks in water, food, and household environments.

In vulnerable contexts, water, sanitation, and hygiene (WASH) interventions remain a pivotal aspect of improving public health. However, their efficacy may be modified by climate variability. Extreme weather events, such as flooding or prolonged heat, can both amplify pathogen transmission and challenge the functionality of sanitation infrastructure. While WASH interventions may buffer against increased disease risk during such periods, few studies have explored how environmental conditions shape their impacts on microbial contamination within the domestic environment. The first two chapters of this dissertation examine these dynamics by leveraging high-resolution weather and environmental data from the WASH-Benefits randomized controlled trial conducted in rural Bangladesh. These analyses assess both how rainfall and temperature influence *E. coli* contamination across multiple exposure pathways and whether these factors modify the effectiveness of sanitation interventions in reducing fecal contamination.

Beyond acute weather events, longer-term water system stressors also pose significant public health challenges. Intermittent water supply, which is an increasingly common phenomenon in climate-vulnerable regions, can undermine water quality, limit hygiene, and generate substantial psychosocial burdens. Households dependent on irregular water access may experience elevated risks for microbial contamination of their water supply, adverse child health outcomes such as respiratory and enteric infections, and heightened stress and anxiety due to the uncertainties associated with water availability. The third chapter of this dissertation focuses on these intersecting outcomes in peri-urban Malawi, where *E. coli* contamination was used to evaluate microbial water quality. By examining microbiological, health, and psychosocial impacts together, this research contributes to a more holistic understanding of how climate-related water challenges affect household well-being.

Together, these studies in this dissertation aim to generate actionable evidence on the complex and climate-sensitive pathways of pathogen transmission and exposure, WASH intervention performance, and household vulnerability—ultimately with the hope of informing more resilient strategies to protect global health in an era of uncertain environmental change.

CHAPTER 1

Associations between weather extremes and fecal contamination along pathogen transmission pathways in rural Bangladeshi households

Introduction

Increased temperature and rainfall are associated with child diarrhoea but the mechanisms behind these associations are not well investigated.[1,2] Diarrhoea-causing pathogens are transmitted via the faecal–oral route through environmental compartments (eg, water, soil), food, fomites, and vectors (eg, flies), which can be influenced by weather.[3] Rainfall can increase pathogen loading into waterbodies, soil and crops while higher temperatures can support viability, reproduction and incubation.[4] Increased faecal contamination in drinking water sources has been observed following higher rainfall and temperature.[5] Higher temperatures are also associated with increased contamination of food stored at home,[6] while there is mixed evidence on the association between temperature and contamination on raw produce.[7] Data on weather effects on other faecal–oral transmission pathways are scarce. A single study found lower *Escherichia coli* counts on children's hands following increased temperature but not rainfall in Kenya.[8] Understanding how weather fluctuations affect different faecal–oral pathways is critical to identify dominant drivers of enteric pathogen transmission in the face of climate change, predict climate influences on child enteric infections and their sequelae, and design and implement climate-resilient interventions.

Bangladesh is the world's seventh most climate-vulnerable country,[9] experiencing climate-related saltwater intrusion, flooding, water and food insecurity, and shifts in infectious disease patterns.[10] In Bangladesh, the monsoon season and rainfall events have been associated with increased occurrence of infectious diseases, including pneumonia, diarrhoea, and enteric infections.[11,12] Higher rainfall and temperatures have also been associated with increased faecal contamination of groundwater in Bangladesh,[13] while higher *E coli* levels have been observed in soil, ponds, groundwater, stored drinking water, food, children's hands, and flies during the monsoon season.[14] However, the latter study defined seasons based on month rather than location-specific rainfall data. Climate change might influence both the timing and duration of monsoon seasons, supporting the use of data-driven weather definitions.[15] Here, we aim to assess associations between increased rainfall and temperature and *E coli* contamination in the domestic environment, using environmental samples and daily weather data from rural Bangladesh.

Methods

Study design

We used data from the WASH Benefits Bangladesh cluster-randomised controlled trial (NCT01590095), which measured the effects of water, sanitation, hygiene, and nutrition interventions on child diarrhoea and growth.[16] The trial enrolled 5551 pregnant women in rural villages in four contiguous districts (Gazipur, Mymensingh, Kishoreganj, and Tangail) in central Bangladesh and followed their birth cohort. The study design has been reported.[16]

Environmental data

The current analysis pooled data from environmental samples from the control, sanitation, and combined water, sanitation, and hygiene intervention arms of the trial, collected longitudinally in nine rounds over 3·5 years. Sampled pathways included hand rinses from children younger than 5 years and their mothers, prepared food for children younger than 5 years (primarily rice) stored at home for later consumption, stored drinking water, source water (groundwater from tubewells), ponds, courtyard soil, and captured flies. Child hand rinses and stored drinking water were collected during all rounds, mother hand rinses during eight rounds, soil and food during three rounds, and tubewell, pond, and fly samples once. Samples were collected by field staff of the International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), trained in sterile technique by study investigators.

Samples were processed at the icddr,b field laboratory with Quanti-Tray/2000 using Colilert-18 media (IDEXX Laboratories, Westbrook, USA) and incubated at 44·5°C.[17] We enumerated the most probable number (MPN) of *E coli* per 100 mL of water, per two hands, per dry gram of food and soil, and per fly. We imputed non-detects as half the lower detection limit (0·5 MPN) and values above the upper detection limit (2419·6 MPN) as 2420 MPN; detection limits per reporting unit differed by sample type due to different dilution factors and moisture content (Appendix A Table S1). Sample collection and processing details have been reported[14] (Appendix A Text S1).

Weather data

Daily rainfall and temperature was obtained from GloH2O's Multi-Source Weighted-Ensemble Precipitation dataset with a 3-h 1·0° resolution and the National Aeronautics and Space Administration's Famine and Early Warning Systems Network Land Data Assimilation System with a daily 0·01° resolution, using our study area's bands of latitude (23·7°–25·0°) and longitude (89·8°–90·9°).[18,19] Missing data were imputed using the nearest location. Daily weather data were matched to *E coli* measurements based on sample collection date and GPS coordinates of study households using nearest neighbour matching, and a Cartesian distance was calculated for each selected match.

We generated weather variables for antecedent periods of 0, 1, 2, 7, and 14 days before sample collection. For each period, we calculated the rolling average rainfall (mm) and temperature (°C). We used daily maximum values to tabulate whether heavy or extreme rainfall, extreme heat, or heatwaves occurred during that window. Heavy and extreme rainfall were defined as the 80th or higher and 90th or higher percentiles, respectively, of daily rainfall values for our study region over the 3·5-year study period.[4,12] Extreme heat was defined as the 90th or higher percentile of daily temperature values over the study period, and a heatwave as daily maximum temperature above the 95th percentile for 3 consecutive days.[20] For a sensitivity analysis, we defined elevated heat as the 80th or higher percentile of daily temperature values over the study period. We created categorical variables for rainfall (none, some, heavy, extreme) and temperature (below-median, above-median, extreme and below-median, above-median, elevated) for each antecedent period and binary variables for heatwaves for the 7-day and 14-day periods.

Statistical analysis

We used generalised additive models to visualise the relationship between continuous rainfall or temperature values and *E coli* counts. We used generalised linear models with a negative binomial error distribution and robust standard errors to estimate *E coli* count ratios (ECRs) using indicator variables for (1) deciles of rainfall or temperature and (2) the weather categories described above, separately by sample type. Models for rainfall controlled for rolling average temperature during the same period, and vice versa. Models also controlled for intervention status (binary variable for intervention *vs* control) because the interventions significantly improved access to and use of hygienic latrines, handwashing materials, and drinking water treatment. Additionally, models controlled for covariates expected to influence *E coli* levels, measured either at the trial's baseline (mother's age and education, number of children younger than 18 years in household, number of individuals in compound, food security, asset-based wealth index, wall and floor materials, drinking water source, minutes to primary water source, and number of cows, goats, and chickens) or at the time of sample collection (child sex and age). Three additional variables were included for stored drinking water models (duration of storage, whether the storage container was covered and had a narrow mouth), and one additional variable was included for food models (hours since food was prepared). For stored water and food, we tabulated *E coli* levels by storage conditions to identify any protective associations with safe storage. Analyses were conducted in R (version 4.1.2, RStudio 2022.02.1+461).

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Field staff visited 1840 households in the control, sanitation, and combined water, sanitation, and hygiene arms once between July, 2013, and March, 2014, and 720 households in the control and sanitation arms eight times between June, 2014, and December, 2016, resulting in 652 study dates and 7253 study observations (unique combinations of household GPS coordinates and date). Between July, 2013, and December, 2016, we collected 6350 stored water, 2181 stored food, 5397 mother hand rinse, 7092 child hand rinse, 1669 source water, 2538 soil, 822 pond, and 610 fly samples (appendix p 1). Geometric mean *E coli* counts were 7·8 MPN/100 mL in stored drinking water, 5·0 MPN/g in food, 29·5 MPN per two mother hands, 20·5 MPN per two child hands, 0·9 MPN/100 mL in source water, 125 047 MPN/g in soil, 5397 MPN/100 mL in ponds, and 712 MPN per fly (Appendix A Table S3).

Rainfall data were available for all study observations. The mean distance between study households and rain measurements was 0·4 km (8·2 m to 0·76 km). Missing temperature data were imputed for two (0·3%) of 652 study dates. Daily rainfall ranged between 0 mm and 157·1 mm. The 80th percentile corresponded to 16·4 mm, and the 90th percentile to 28·2 mm. Daily temperature ranged between 13·1°C and 34·2°C. The 90th percentile corresponded to 30·2°C and the 95th percentile to 30·9°C. Within 14 days before sampling, 2373 (33%) of 7253 study observations experienced extreme rainfall, and 1984 (27%) experienced extreme temperature. A heatwave occurred within the past 14 days for 910 (13%) study observations (Appendix A Table S4). Highest rainfall and temperatures occurred between March and August (Appendix A Figure S1).

Controlling for temperature and confounders, increasing rainfall (analysed both as mm and deciles of rain) on the day of sampling was associated with higher *E coli* counts in food, stored water, and ponds, and lower counts in soil, with statistically significant associations in the higher deciles compared with no rainfall (Appendix A Figures S2-10). Extreme rainfall on the day of sampling was associated with 2-fold to 4-fold higher *E coli* counts in stored water (ECR=1·98 [1·36–2·88], p=0·0004), food (ECR=3·13 [1·63–5·99], p=0·0010), and ponds (ECR=3·46 [2·34–5·11], p<0·0001), and lower *E coli* counts in soil (ECR=0·36 [0·24–0·53], p<0·0001) compared with no rainfall (Figure 1, Appendix A Figure S11). Extreme rainfall the day before sampling was associated with lower *E coli* counts in tubewells (ECR=0·10 [0·02–0·62], p=0·014; Figure S11). Across sample types, associations were similar when rainfall occurred 1–7 days before sampling and attenuated when it occurred 14 days before sampling; for food samples, associations were confined to rainfall occurring 0–1 days before sampling (Figure 1, Appendix A Table S5). Rainfall appeared to be associated with higher *E coli* counts in and on flies but associations were inconsistent overall (Figure 1, Appendix A Table S5). There was no consistent association between rainfall and *E coli* on child or mother hands (Figure 1, Appendix A Table S5).

Controlling for rainfall and confounders, increasing temperature (analysed both as °C and deciles of temperature) on the day of sampling was associated with higher *E coli* counts in or on food, stored water, child hands, and flies (Appendix A Figures S2-9, S11). For food, stored water, and flies, associations progressively increased in magnitude for each decile increase in temperature, while for child hands, most deciles were associated with a uniform increase in *E coli* counts compared with the lowest decile (Appendix A Figure S11). Extreme temperature on the day of sampling was associated with higher *E coli* counts in stored drinking water (ECR=1·49 [1·05–2·12], p=0·025) and food (ECR=3·01 [1·51–6·01], p=0·0020) compared with below-median temperature. These associations were similar for all antecedent periods (0–14 days) and particularly pronounced for food (Figure 2, Appendix A Table S5). Extreme temperature was not associated with *E coli* on child or mother hands across any antecedent period but above-median temperature 0–2 days before sampling was borderline associated with increased *E coli* on child hands (Figure 2, Appendix A Table S5). We could not estimate associations between extreme temperature or heatwaves and contamination of tubewell water, ponds, and flies because only a small number of sampling days for these sample types met these temperature cutoffs. The sensitivity analysis using elevated temperature showed no associations with *E coli* for these sample types, and associations were similar to extreme temperature for stored water and food (Appendix A Figure S12). A heatwave within 7 days or 14 days before sampling was associated with lower *E coli* counts in soil (ECR=0·54 [0·38–0·78], p=0·0011 and ECR=0·50 [0·36–0·70], p<0·0001, respectively) but was not associated with *E coli* along other pathways (Appendix A Figure S13).

Among drinking water storage containers, 45% (2882/6357) had a narrow mouth and 30% (1900/6357) were covered. The median storage duration was 2 h (IQR 1–4, range 0–600); storage duration was similar on days with and without extreme rain. Mean *E coli* counts were 123 MPN when water was stored for less than 1 h, 148 MPN when stored for 1 to <8 h, and 222 MPN when stored for ≥8 h. Among samples stored for ≥8 h, the rainfall-associated increase in *E coli* counts was largest when water was stored in an uncovered wide-mouth container and smallest when stored in a covered narrow-mouth container (Appendix A Table S6).

The median food storage time was 3·5 h (IQR 2–5, range 0–29). Mean *E coli* counts were 157 MPN when food was stored for less than 4 h, 346 MPN when stored for 4 to <8 h, and 2467 MPN when stored for ≥8 h. The temperature on food sampling days was between 16·7°C and 33·3°C, within the "danger zone" for bacterial incubation in food (5–60°C) and close to the optimum growth temperature (around 35°C) for enteric bacteria.[21] Of 1910 food samples collected on days when the temperature was 20°C or higher, 84% (1606) were stored for 2 h or longer (maximum recommended duration at room temperature[21]); these samples had a mean *E coli* level of 645 MPN, compared with 46 MPN for samples stored for less than 2 h in the same conditions. Of 6 food samples collected on days when the temperature was 32°C or higher, 100% (6) were stored for 1 h or longer (maximum recommended duration at this temperature[21]); these samples had a mean *E coli* level of 1297 MPN.

Discussion

Rainfall and temperature significantly influenced *E coli* contamination along multiple faecal–oral pathways in rural Bangladeshi households. Extreme rainfall was associated with increased contamination of stored food, stored drinking water, and ponds, and reduced contamination of tubewell water and courtyard soil. Extreme temperature was associated with increased contamination of stored food and stored drinking water. Associations were more pronounced when these extremes occurred within 7 days of sampling and attenuated when they occurred 14 days before sampling. In a parallel analysis that focused on caregiver-reported diarrhoea and enteropathogen detection in child stool in the parent trial, increased rainfall was associated with higher prevalence of diarrhoea and *Cryptosporidium*, enterotoxigenic *E coli* (ETEC), Shiga toxin-producing *E coli* (STEC), *Shigella*, *Campylobacter*, *Aeromonas,* and adenovirus 40/41 detection in stool, and lower prevalence of *Giardia*, sapovirus, and norovirus detection in stool.[12] Increased temperature was associated with higher prevalence of diarrhoea and STEC, ETEC, and *Cryptosporidium* detection in stool.[12] Our findings can help interpret the environmental mechanisms behind these associations between weather and child health outcomes.

In our study, samples from the outdoor environment—ponds, groundwater from tubewells, and soil—were sensitive to rainfall but influenced by it in opposite directions (higher contamination of ponds, lower contamination of groundwater and soil). It has been hypothesised that rain releases microorganisms from faecal sources into surface waters via runoff and saturation of the subsurface, and suspends and flushes them out of sediments or soil, while rainfall-associated surface recharge initially delivers contaminants that accumulated on the surface during dryer conditions into aquifers but ultimately dilutes them due to increased groundwater volume.[3,22] Our findings broadly support this conceptual model. In our study setting, faecal sources include leaking or overflowing latrine pits, open defecation (especially by young children), and animal faeces. Reduced soil contamination following heavy rain could also be due to changes in sanitation practices, such as less open defecation or indoor corralling of domestic animals on rainy days. Our findings are consistent with previous evidence of increased faecal contamination of surface waters following rainfall,[23] but differ from a recent review that found generally higher *E coli* in groundwater with increasing rainfall.[5] Soils in our study region are primarily alluvial and silt; these soil types pose an effective barrier against pathogen transport.[24] Groundwater in regions with different hydrogeological features might experience different effects from rainfall. Also, tubewells are an improved water source; groundwater from unimproved or unprotected sources might be more vulnerable to contamination from runoff during heavy rainfall. Among samples collected from the outdoor environment in our study, the only consistently observed association with temperature was reduced *E coli* in soil following heatwaves, consistent with previous evidence of bacterial die-off after prolonged heat exposure.[25]

For samples stored indoors—stored drinking water and prepared food—both extreme rainfall and temperature were associated with increased contamination. Given that rainfall did not adversely affect groundwater quality at the source, increased contamination of stored water likely stemmed from rainfall-associated bacterial intrusion and/or growth in storage containers during collection, transport, or storage. Mechanisms for this might include splashing of faecally contaminated soil or mud into storage containers while filling them at the tubewell in the rain or during storage, less thorough or frequent cleaning of storage containers to avoid going outside to the tubewell, or use of runoff-contaminated pond water to wash storage containers and utensils that will contact stored water; similar mechanisms could also explain the increased contamination of stored food following increased rainfall. In our study, drinking water was stored at home longer (maximum 600 h) than food (maximum 29 h); this might explain why associations with food contamination were confined to rainfall occurring 0–1 days before sampling, whereas associations with stored water contamination persisted for rainfall occurring up to a week before. The increase in stored water contamination associated with rainfall appeared largest when water was stored unsafely (in uncovered wide-mouth container) and smallest when stored safely (in covered narrow-mouth container). A previous study in Bangladesh found that safe storage of tubewell water in a container with a narrow mouth, tight-fitting lid, and spigot significantly improved stored water quality and reduced diarrhoea.[26] In a recent study in Kenya, rainfall-associated increases in *E coli* in stored drinking water were mitigated if households treated their water.[8] Our findings suggest that water treatment and safe storage of drinking water and food is especially important immediately following extreme rainfall. Household-level water treatment interventions often have low uptake; focusing treatment recommendations on these high-risk times might help achieve higher uptake and maximize health benefits.

Higher *E coli* counts in stored water and food associated with increased ambient temperatures may be due to increased bacterial growth during storage under warm conditions. Higher food storage temperature has been associated with increased contamination, with substantial increases when foods are stored for longer than 4 h after preparation.[6] WHO recommends that food not be stored for more than 2 h at room temperature, and not be left out for more than 1 h when ambient temperatures exceed 32°C.[21] In our study, *E coli* levels in food stored for 1 h or longer doubled at ambient temperatures of 32°C or higher versus 20°C. Additional mechanisms for temperature-associated contamination of stored drinking water and food could include less frequent reheating of food to avoid additional heat exposure or less frequent or thorough cleaning of storage containers and utensils to avoid stepping outdoors in the heat. Our findings emphasise the importance of minimising the duration of food storage during extreme ambient temperatures to reduce pathogen growth, as well as adequate reheating before consumption.

We did not find a consistent association between rainfall or temperature and contamination of child or mother hands. In Kenya, children had less *E coli* on their hands on days with higher temperatures while there was no association with rainfall.[8] Others have hypothesised that children might have cleaner hands during higher rainfall and temperatures because they might play outside less or have more water for handwashing.[8] Children in our study were young (85% ≤3 years, 30% ≤1 year). Children in this age range have frequent hand contact with objects, indoor surfaces, and floors; unmeasured contamination from these pathways may have obscured associations with weather conditions. In Bangladesh, *E coli* on child hands was associated with subsequent child diarrhoea,[27] and hand mouthing was a dominant contributor to *E coli* ingestion by children younger than 3 years.[28] Lack of associations between weather and child hand contamination in our analysis indicates that increases in child diarrhoea following increased rainfall or temperature might not be mediated by faecal contamination of child hands. We are unaware of previous studies on associations between weather and caregiver hand contamination. *E coli* levels on caregiver hands are highly temporally variable;[29] our findings indicate that the contribution of weather to contamination of mother hands might be negligible compared with other dominant factors (eg, domestic chores or contact with domestic animals). Additionally, although caregiver hand contamination is predictive of stored water contamination,[30] our findings indicate that the higher *E coli* levels we observed in stored drinking water and food after increased rainfall or temperature are not due increased mother or child hand contamination.

This study spatiotemporally matched daily weather data to more than 26 000 *E coli* measurements. Study strengths include a large sample size to allow statistical precision, comprehensive set of sample types to evaluate associations with weather across the F-diagram, longitudinal measurements over multiple years to capture a range of weather conditions, and use of daily weather data as opposed to regional definitions of seasonality.

Our study also had limitations. The nearest available rainfall data were located up to 0·76 km from households, and temperature data were aggregated over 0·01× 0·01° pixels, potentially not reflecting exact conditions at sampling sites. Any resulting weather misclassification would be non-differential with respect to our outcomes and bias findings towards the null. *E coli* as a faecal indicator is imperfectly correlated with pathogen presence and can originate from non-faecal sources.[25] Therefore, our analysis might not capture the weather responses of pathogens, especially non-bacterial pathogens. For example, higher temperatures are associated with reduced viral infections and increased protozoan infections.[3] Future research should investigate weather effects on specific pathogens in the environment. However, phenotypic and genotypic characterisation of a subset of hand rinse and soil samples from our study indicated that *E coli* isolated from these sample types were indistinguishable from *E coli* isolated from cow, chicken, and human faeces collected in the study area, indicating that the *E coli* in the environmental samples were of faecal origin.[31] Furthermore, 22% of mother hands, 32% of child hands, 37% of stored drinking water, and 60% of soil samples harboured at least one *E coli* virulence gene, indicating disease-causing potential through these pathways.[32] *E coli* on child hands has been associated with subsequent child diarrhoea in Banglades,[27] and a meta-analysis found that *E coli* contamination of drinking water, child hands, and fomites was associated with increased diarrhoea and reduced linear growth.[33] Therefore, our findings on the associations between weather and *E coli* in different sample types in the domestic environment are likely informative of child health risks associated with these pathways under extreme weather conditions.

Bangladesh experiences a high burden of enteric infections; therefore, understanding how weather extremes influence infectious disease transmission in this setting can inform other countries with similar infection burdens. However, several factors might limit the generalisability of our study. Bangladesh has a distinct monsoon season that delivers 80% of the annual rainfall; the associations between weather and environmental contamination could be different in settings with different meteorology and hydrogeology. Our study was conducted in a rural environment with high on-premise access to improved water sources and pit latrines but commonly practiced child open defecation and unsafe management of child and animal faeces. Associations between weather and faecal–oral transmission pathways might vary in urban or densely populated areas and settings with varying water and sanitation infrastructure and waste management practices. Additionally, it is possible that the relationship between weather and *E coli* is spatially variable within our study area, but we did not explore this heterogeneity as the parent trial was conducted in contiguous areas with relatively homogenous environmental conditions.

In conclusion, our findings provide insight on the environmental mechanisms behind a body of literature indicating increased diarrhoeal illness during warmer or rainy periods. As extreme weather events become more frequent and severe, it is important to identify and target the transmission pathways most impacted by these events. Our findings indicate that drinking water and food stored in the home and surface waters are vulnerable to contamination from increased rainfall or temperature. Preventive messaging should consider targeting the immediate week, especially the first 2 days, after extreme rainfall and temperatures to emphasise protective practices (eg, water treatment, safe storage of drinking water and prepared food, adequate reheating of stored food) to reduce exposure to faecal organisms. Following extreme rainfall, avoiding bathing or swimming in surface waterbodies to prevent accidental ingestion and not using surface water for cooking and washing utensils that will contact food or stored water can also help reduce exposures.

Figure 1. Adjusted *E. coli* count ratios by sample type associated with rainfall intensity, compared to no rainfall, during different antecedent periods.

All adjusted rainfall models controlled for the following variables: rolling mean temperature for the same antecedent period, binary intervention variable (intervention or control), sex of index child, age of index child (in days), number of children under the age of 18 in the household, number of people in the compound, mother's age (in years), mother's educational status, food security category (using HFIAS scale), minutes to water source, household having improved walls, household having improved floors, household wealth quintile based on owned assets, number of cows, goats and chickens/ducks in the compound, source water origin from a tubewell. Food models included hours since stored food was prepared and stored drinking water models included covered storage container, narrow-mouth storage container, and hours water has been stored. Rainfall intensity was defined as no rain (0 mm), some rain (<16·4 mm), heavy rain (≥16·4 and <28·2 mm), and extreme rain (≥28·2 mm).

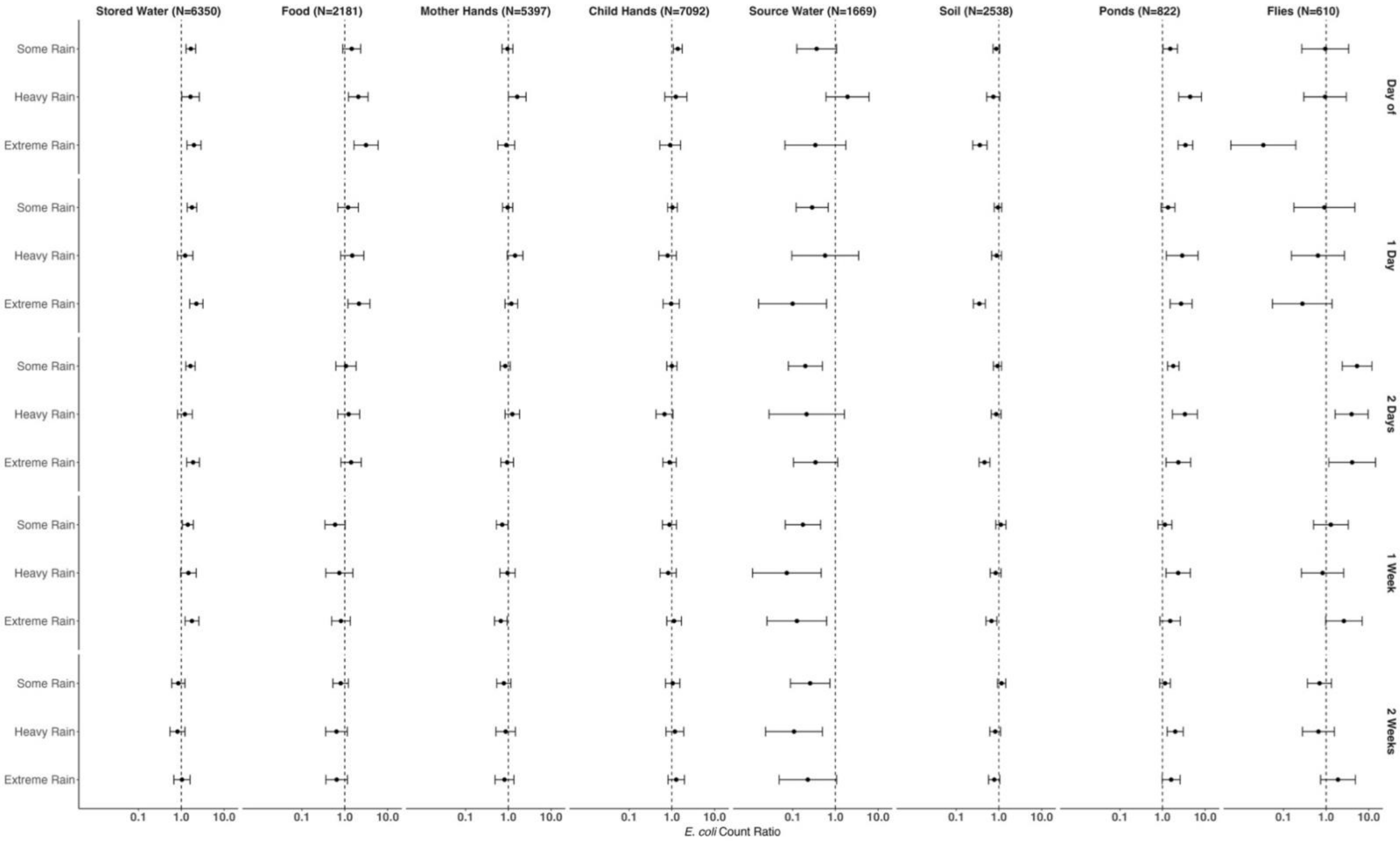
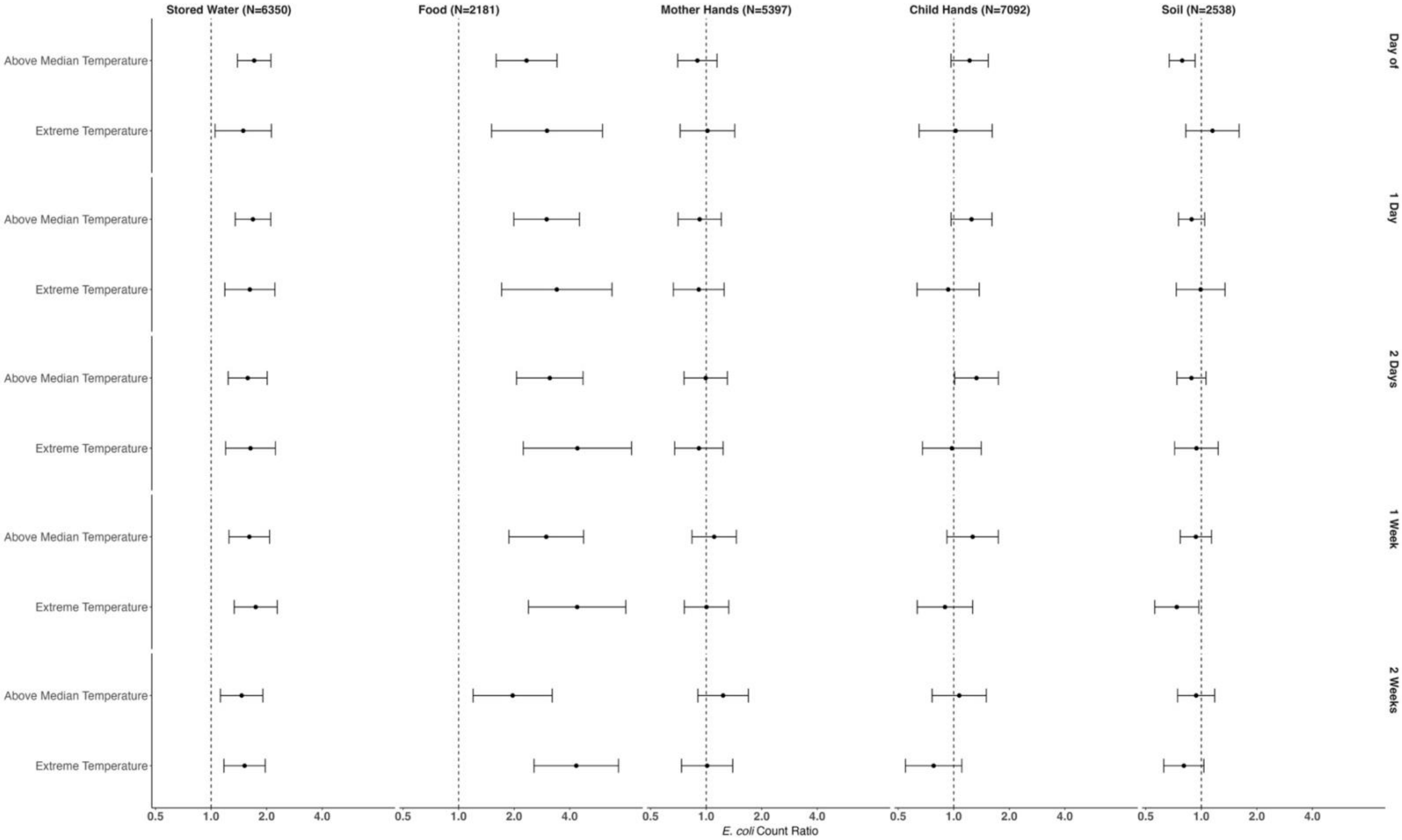


Figure 2. Adjusted *E. coli* count ratios by sample type associated with above-median and extreme temperature, compared to below-median temperature, during different antecedent periods.

All adjusted temperature models controlled for the following variables: Rolling mean rainfall for the same antecedent period, binary intervention variable (intervention or control), sex of index child, age of index child (in days), number of children under the age of 18 in the household, number of people in the compound, mother's age (in years), mother's educational status, food security category (using HFIAS scale), minutes to water source, household having improved walls, household having improved floors, household wealth quintile based on owned assets, number of cows, goats and chickens/ducks in the compound, source water origin from a tubewell. Food models included hours since stored food was prepared and stored drinking water models included covered storage container, narrow-mouth storage container, and hours water has been stored. Temperature categories were defined as below-median temperature (<27·1˚C), above-median temperature (≥27·1 and <30·2˚C), and extreme temperature (≥30·2˚C). We could not estimate associations between extreme temperature and source water (tubewells), ponds and flies due to data sparsity.



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CHAPTER 2

Do Rainfall and Temperature Modify Effects of On-Site Sanitation Intervention on *E. coli* Contamination in Bangladeshi Households?

Introduction

Higher temperatures and rainfall have been linked to increased risk of infectious disease, potentially through increasing the dissemination and survival of pathogens in environmental compartments, such as water and soil[1–4]. Water, sanitation and hygiene (WASH) interventions, such as improved access to clean water, sanitation facilities that isolate fecal waste from the environment, and adequate hygiene practices, are fundamental to preventing the spread of disease. However, the efficacy of these interventions can be influenced by environmental conditions, including weather fluctuations[4]. For example, heavy rainfall and/or flooding may impact service delivery or overwhelm sanitation systems, leading to increased fecal contamination of the environment, thereby undermining the effectiveness of sanitation interventions[5]. Alternatively, WASH interventions may deliver larger benefits during periods of increased rainfall or temperature, which can support pathogen dissemination and survival in environmental compartments in the absence of effective barriers[3,6]. Resilient interventions that continue to interrupt pathogen transmission and reduce disease outcomes under weather-related stressors can ensure sustained access to clean water and effective sanitation in the face of climate change. In low- and middle-income countries vulnerable to failure in fragile WASH systems during extreme weather events, it is important to understand how the efficacy of WASH interventions may vary under different weather conditions[7].

A recent meta-analysis of WASH intervention trials found larger diarrhea reductions in dry seasons compared to wet seasons for water treatment and handwashing but not sanitation interventions[8]. Another systematic review suggested that the use of unimproved water and sanitation services exacerbated rainfall-associated increases in diarrhea risk among young children[4]. In the WASH Benefits Bangladesh trial (the parent trial for the data used in the current analysis), the WASH interventions reduced diarrhea and enteric infections among young children[9,10]. However, a longitudinal analysis focused on the sanitation intervention demonstrated that the health benefits were confined to the rainy seasons; the intervention did not affect child diarrhea during dry seasons[11]. Similarly, a recent re-analysis of the trial data using daily rainfall and temperature values found that the WASH interventions reduced diarrhea prevalence by 51% following periods with heavy rainfall, compared to 13% following periods without heavy rainfall, and by 40% following periods with above-median temperature, compared to 9% following periods with below-median temperature[12].

Investigating the underlying environmental routes of fecal contamination under different weather conditions is important for interpreting these health effects and understanding how intervention effectiveness can be improved under adverse weather conditions. Previous evaluations of the effects of the WASH Benefits interventions on fecal contamination found that the water treatment, handwashing and combined WASH interventions reduced *E. coli* in stored drinking water and food, with evidence of greater reductions during the dry season[13,14]. The sanitation intervention did not reduce *E. coli* in the domestic environment when measured approximately 4 months after intervention initiation[13]. In a longitudinal study conducted between 1 and 3.5 years after intervention initiation, the sanitation intervention slightly reduced *E. coli* in stored drinking water and child hand rinses, with no effect modification by season[15]. However, two of these studies defined seasons based on calendar month, and one study defined the monsoon season based on spatiotemporal rainfall data. It is important to consider granular rainfall and temperature measurements rather than general/binary seasonality as this approach can capture discrete weather events as well as intra-annual variation in the onset and duration of dry and wet seasons, which are expected to shift with climate change. One study in Kenya used daily rainfall and temperature data to show that increases in drinking water contamination associated with increased rainfall were mitigated if households treated their water[16]. No study has evaluated the influence of daily weather parameters on the effect of WASH improvements on a comprehensive set of fecal-oral pathways.

This current study re-analyses data from environmental samples collected over 3.5 years in the sanitation and control arms of the WASH Benefit Bangladesh trial using daily weather data to investigate whether rainfall and temperature modify the effectiveness of the sanitation intervention on fecal contamination in the domestic environment.

Methods

Study Design and Population

The WASH Benefits randomized controlled trial in rural Bangladesh (NCT01590095) aimed to assess the impact of individual and combined WASH and nutrition interventions on child health. The trial was conducted in contiguous rural subdistricts in Gazipur, Mymensingh, Tangail and Kishoreganj districts of central Bangladesh. These four districts span a combined area of approximately 3,300 square miles. The study areas were chosen to have no other ongoing WASH/nutrition programs. Trained field staff from the International Centre for Diarrheal Disease Research, Bangladesh (icddr,b) screened the areas for enrollment; women were eligible to enroll if they were in the first or second trimester of pregnancy and did not plan to move in the next two years. The trial enrolled pregnant women and followed their birth cohort (index children) for two successive years. Six to eight enrolled households were grouped geographically to form a cluster, and eight adjacent clusters formed a block. A total of 5551 households were enrolled and grouped into 720 clusters and 90 blocks[10]. Within each block, clusters were randomly assigned to intervention arms or a double-sized control arm. Further details of the study design and enrollment criteria have been previously published[17].

The current study uses data from the sanitation intervention group and control group of the WASH Benefits trial to isolate the effectiveness of the sanitation improvements implemented by the trial. The sanitation intervention included installing new or upgraded double-pit latrines with concrete-lined pits, concrete slabs and water seals, providing sani-scoops to remove animal and child feces from the compound, and plastic potties for children that were too young to use the latrine. The hardware was accompanied by regular visits by trained community health promoters to intervention households to promote improved sanitation practices. Intervention uptake was high and sustained[18,19]. Further details of the interventions and uptake assessment have been previously published[17].

Ethics

Primary caregivers of children provided written informed consent. The study protocol was approved by human subjects committees at the icddr,b (PR11063), University of California, Berkeley (2011-09-3652), and Stanford University (25863).

Environmental Data Collection

Selected households were enrolled in two sub-studies focused on environmental assessment. The first sub-study enrolled all households in the sanitation intervention group and one of the two control groups and visited them once starting approximately 4 months after intervention initiation. The second sub-study enrolled a random subset of households in the same two study groups and visited them approximately quarterly between 1-3.5 years after intervention initiation. The current analysis combines data from these two sub-studies.

Among households enrolled in the sub-studies, icddr,b field staff trained in sterile technique collected samples from the domestic environment. Sampling pathways included index child and mother hand rinses, stored food for children under five years old (primarily rice), stored drinking water, source water, ponds, courtyard soil, and captured flies. In our study setting, source water primarily refers to groundwater from tubewells, which is typically stored at home prior to consumption. Ponds refer to small lagoons used for domestic chores (e.g. washing dishes, laundry), bathing or fishing[20]; in our previous work in the same study area, approximately half of households had a pond[13]. Samples were transported on ice to the icddr,b field laboratory and processed within 24 hours of collection. icddr,b lab staff enumerated the most probable number (MPN) of *E. coli* using IDEXX Quanti-Tray/2000 with Colilert-18 media and incubation at 45˚C[21]. For quality control, 10% field blanks, 10% lab blanks and 5% replicates were processed. Additional sample collection and processing details have been previously reported[13,15,22].

Weather Data

Daily rainfall (in mm) was obtained from the GloH2O's Multi-Source Weighted-Ensemble Precipitation dataset at a resolution of 1.0° updated every 3 hours. Daily temperature (in °C) was obtained from the National Aeronautics and Space Administration's Famine and Early Warning Systems Network Land Data Assimilation System for Central Asia dataset at a resolution of 0.01° updated daily. Weather observations were missing for 0.3% (2/652) of study days. Data for these days were imputed using available data for the same date from nearest neighboring household in the study[23].

Statistical Analysis

We generated dichotomous and categorical variables to classify rainfall and temperature for antecedent periods of 2 and 7 days before sample collection. In a prior analysis, we assessed associations between weather fluctuations across a range of antecedent periods (0, 1, 2, 7 and 14 days) and *E. coli* levels using the same dataset. This prior work showed similar effects on *E. coli* from rainfall and temperature occurring 0-2 days before sampling, and attenuated effects from rainfall and temperature occurring 7-14 days before sampling[23]. Therefore, we selected 2 and 7 days as representative of the range of possible effects for the current analysis. These periods are also consistent with expected pathogen survival in the environment[24,25].

We identified threshold values commonly used in the literature to classify rainfall and temperature intensity. Using these thresholds, we classified rainfall observations as 'extreme rain' if any day in the antecedent period exceeded the 90th percentile of all daily rainfall values occurring during the 3.5-year study period in the study area; we used the same approach to classify temperature observations as 'extreme temperature' [23]. As a sensitivity analysis, we classified rainfall observations as 'heavy rain' if any day in the antecedent period exceeded the 80th percentile of daily rainfall values; we used the same approach to classify temperature observations as 'elevated temperature' [23]. We used these classifications to generate dichotomous variables for the occurrence of extreme rain, extreme temperature, heavy rain and elevated temperature for both antecedent periods. We also generated a categorical rainfall variable using a combination of these thresholds (no rain, some but not heavy rain, heavy but not extreme rain, extreme or more rain) during each antecedent period. Additionally, we considered rolling average rainfall and temperature across the antecedent periods because using the 80th and 90th percentiles can lead to data sparsity when observations are further stratified by study arm and sample type. Specifically, we generated a dichotomous variable for whether the rolling average rainfall was above vs. below the median of rolling average values and a categorical variable for tertiles of rolling average rainfall over each antecedent period; we used the same approach to generate dichotomous and categorical variables for rolling average temperature.

To assess effect modification by weather, we compared log10-transformed *E. coli* counts between sanitation and control groups, separately within strata of rainfall and strata of temperature. We conducted separate comparisons for the 2-day and 7-day antecedent periods.

For each antecedent period, the rainfall strata included (1) extreme vs. no extreme rain, (2) heavy vs. no heavy rain, (3) no rain, some but not heavy rain, heavy but not extreme rain, extreme or more rain, (4) above- vs. below-median rolling average rain, (5) tertiles of rolling average rain. The temperature strata included (1) extreme vs. no extreme temperature, (2) elevated vs. no elevated temperature, (3) above- vs. below-median rolling average temperature, (4) tertiles of rolling average temperature. We included an interaction term between the study group and each of these weather variables. We compared the direction, magnitude and precision of intervention effects across the different strata and interpreted p-values <0.20 for the interaction variable as evidence of effect modification. This p-value threshold is conventionally used to detect effect modification and reflects the additional statistical uncertainty associated with comparing differences between groups across strata of a third variable[26].

We used generalized linear models (GLM) with a Gaussian distribution and robust standard errors to account for geographical clustering of households by study block and repeated collection of environmental samples from the same households. Non-detects were imputed as half of the lower detection limit and values above the upper detection limit were imputed as the upper detection limit; detection limits varied by sample type due to differences in processed sample amounts and dilutions (Appendix B Table S1). Models included an indicator variable for study block to account for geographical matching. Randomized assignment of households into intervention vs. control groups balanced baseline covariates (e.g. socio-demographic indicators, water access, animal ownership) between the study groups, as previously demonstrated both among all trial participants[10,15]. Therefore, our analyses comparing *E. coli* counts between the sanitation intervention and control groups did not adjust for additional variables. Analyses were conducted in R (version 4.3.1, RStudio 2023.06.0+421). The source code and all data used for the analysis are publicly available at Open Science framework (https://osf.io/6u7cn/), and the code is also available as a supplemental file.

Results

E. coli Measurements

Between July 2013 and December 2016, we collected 1928 soil, 557 pond, 395 fly, 1098 source water (tubewell), 5740 stored drinking water, 1629 stored food, 5397 mother hand rinse, and 6494 child hand rinse samples from 1243 unique households in the control and sanitation arms of the WASH Benefits Bangladesh trial (Appendix B Table S2). Log10-transformed mean *E. coli* counts were 5.11 per dry gram (SD=1.06) of soil, 3.76 per 100 mL (SD=0.79) of pond water, 2.77 MPN per fly (SD=1.34), -0.03 per 100 mL (SD=0.65) of source water, 0.98 per 100 mL (SD=1.05) of stored drinking water, 0.83 per dry gram (SD=1.43) of food, 1.47 per two mother hands (SD=1.00) and 1.36 per two child hands (SD=0.99) (Appendix B Table S1).

Weather Classifications

The 90th percentile of daily rainfall (classified as extreme rainfall) corresponded to 28.20 mm and the 80th percentile (classified as heavy rainfall) corresponded to 16.44 mm. The median of rolling average rainfall values for two- and seven-day periods were 0.27 mm and 1.10 mm, respectively. The 90th percentile of daily mean temperature (classified as extreme temperature) corresponded to 30.21˚C and the 80th percentile (classified as elevated temperature) corresponded to 29.29˚C. The median of rolling daily average temperature values for two- and seven-day periods were 27.46˚C and 27.52˚C, respectively. The highest rainfall occurred between the months of April–October and the highest temperatures occurred between the months of March–September (Appendix B Figure S1). Of 23,238 total samples, 12.0% (2779) were collected within two days and 23% (5342) within seven days after extreme rainfall, and 14.1% (3282) were collected within two days and 20.5% (4765) within seven days after extreme temperature (Appendix B Table S3).

Unstratified Intervention Effects

Across all observations (without stratification by weather), the sanitation intervention was associated with an approximately a 0.1-log reduction in *E. coli* counts in stored drinking water (Δlog10 = -0.08 (-0.14, -0.01), p-value= 0.03) and on child hands (Δlog10 = -0.06 (-0.13, 0.00), p-value=0.05) (Table 1). The intervention did not significantly reduce *E. coli* contamination in food, mother hands, soil, tubewell water, ponds, and flies.

Effect Modification by Rainfall

Across the different classifications, rainfall modified the effect of the sanitation intervention on *E. coli* counts on mother hands, on child hands, in ponds, and carried by flies. Overall, the intervention consistently led to larger reductions in *E. coli* in these sample types following periods of higher rainfall (Figures 3 and 4 Appendix B Figure S2, Tables S4-S6). Rainfall of any classification over either antecedent period did not modify intervention effects on *E. coli* in stored drinking water, food, soil and tubewell water.

Extreme or heavy rainfall. When no extreme rainfall occurred within 7 days before sampling, the intervention was associated with small (<0.10-log) reductions in *E. coli* in stored water and on child hands, but there was no evidence of effect modification (interaction p-values>0.20) compared to periods with extreme rainfall, indicating statistically indistinguishable intervention effects between the two rain strata (Figure 3, Appendix B Table S4). There were no other intervention effects distinguishable from chance when no extreme rainfall occurred within 7 days (Figure 3, Table S4). In contrast, when extreme rainfall occurred within 7 days before sampling, the intervention was associated with approximately 1-log reduction in *E. coli* carried by flies (Δlog10 = -0.91 (-1.65, -0.17), interaction p-value=0.03 compared to no extreme rainfall) (Figure 3, Appendix B Table S4). Trends were similar for extreme rain within 2 days and heavy rain within 2 or 7 days before sampling (Figure 3, Appendix B Figure S2, Tables S4 and S5). Extreme or heavy rainfall did not modify intervention effects on sample types other than flies for either antecedent period (interaction p-values>0.20) (Figure 3, Appendix B Figure S2, Tables S4 and S5). Analysis by categories of rainfall (no, some, heavy and extreme rain) showed that intervention effects primarily occurred in the heavy and extreme rain strata (Appendix B Figure S3).

Rolling average rainfall. There were no intervention effects that could be distinguished from chance for any sample type when rolling average rainfall within 7 days before sampling was below median (Figure 4, Appendix B Table S6). In contrast, when rolling average rainfall within 7 days was above median, the intervention was associated with 0.25-log reduction in *E. coli* in ponds (Δlog10 = -0.25 (-0.48, -0.03), interaction p-value=0.10) and small (approximately 0.10-log) reductions in *E. coli* on child hands and in stored water; there was evidence of effect modification for child hands (interaction p-value=0.11) but not for stored water (interaction p-value>0.20) compared to below-median rain (Figure 4, Appendix B Table S6). There was also evidence of effect modification for mother hands and flies (interaction p-values <0.20), and intervention effects appeared stronger following above-median rain but effect estimates could not be distinguished from chance in either rain stratum (Figure 4, Table S6). Trends were similar for above- vs. below-median rolling average rain in the last 2 days (Figure 4, Appendix B Table

S6). When analyzed by tertiles of rolling average rainfall, intervention effects primarily occurred in the top tertile (Appendix B Figure S4).

Effect Modification by Temperature

Across the different classifications, temperature modified the effect of the sanitation intervention on *E. coli* counts in food, on mother hands, on child hands, in soil, and in ponds. Overall, the intervention consistently leading to larger reductions in *E. coli* in these sample types following periods of higher temperature (Figures 3 and 4, Appendix B Figure S2, Tables S4-S6). Temperature of any classification over either antecedent period did not modify intervention effects on *E. coli* in stored drinking water, tubewell water, or flies.

<u>Extreme or elevated temperature</u>. When no extreme temperature occurred within 7 days before sampling, the intervention was associated with a small (<0.10-log) reduction in *E. coli* in stored water, but there was no evidence of effect modification (interaction p-value=0.68) compared to periods with extreme temperature. When extreme temperature occurred within 7 days before sampling, the intervention was associated with a 0.19-log reduction in *E. coli* on child hands (Δlog10 = -0.19 (-0.31, -0.07), interaction p-value=0.01) and 0.33-log reduction in *E. coli* in soil (Δlog10 = -0.33 (-0.54, -0.11), interaction p-value=0.01) (Figure 3, Appendix B Table S4). There was also evidence of effect modification for food (interaction p-value=0.12), and the intervention effect appeared stronger following extreme temperature, but the effect estimate could not be distinguished from chance in either temperature stratum (Figure 3, Appendix B Table S4). Trends were similar for extreme temperature within 2 days and elevated temperature within 2 or 7 days before sampling (Figure 3, Appendix B Figure S2, Tables S4 and S5). Additionally, when elevated temperature occurred within 7 days before sampling, the intervention was associated with 0.31-log reduction in *E. coli* in ponds (Δlog10 = -0.31 (-0.50, -0.13), interaction p-value=0.01 compared to no elevated temperature), with similar findings for the 2-day period (Appendix B Figure S2, Table S5).

<u>Rolling average temperature</u>. There were no intervention effects that could be distinguished from chance for any sample type when rolling average temperature within 7 days before sampling was below median (Figure 4, Appendix B Table S6). When rolling average temperature within 7 days was above median, the intervention was associated with approximately 0.20-log reduction in *E.*

coli in soil (Δlog10 = -0.17 (-0.31, -0.03), interaction p-value=0.05 compared to below-median temperature) (Figure 4, Appendix B Table S6). In this temperature stratum, the intervention was also associated with small (<0.10-log) reductions in *E. coli* in stored water and on child hands, but there was no evidence of effect modification (interaction p-values>0.20) compared to below-median temperature, indicating statistically indistinguishable intervention effects between the two temperature strata (Figure 4, Appendix B Table S6). Trends for rolling average rain in the last 2 days were similar and additionally indicated effect modification for mother hands (Figure 4, Appendix B Table S6). When analyzed by tertiles of rolling average temperature, intervention effects for soil, stored water and child hands primarily occurred in the top tertile (Appendix B Figure S5). Additionally, the intervention was associated with reduced *E. coli* in ponds in the second and top temperature tertiles (Appendix B Figure S5).

Discussion

The WASH Benefits sanitation intervention, including free provision of double-pit latrines, potties and scoops for feces disposal along with intensive promotion for their use, reduced fecal contamination in rural Bangladeshi households more effectively for several sample types following higher rainfall and temperature. Rain modified intervention effects for four sample types (mother and child hands, ponds, flies). Compared to the control group, the sanitation intervention group had 0.91-log lower *E. coli* carried by flies following extreme rainfall, as well as 0.25-log lower *E. coli* in ponds and approximately 0.10-log lower *E. coli* in stored water and on child hands following above-median rolling average rainfall. Temperature modified effects for five sample types (food, mother and child hands, soil, and ponds). Compared to the control group, the sanitation intervention group had 0.19-0.22 log lower *E. coli* on child hands, 0.33-0.40 log lower *E. coli* in soil and 0.31-0.38 log lower *E. coli* in ponds following extreme or elevated temperature, as well as approximately 0.10-log lower *E. coli* in stored water and on child hands following above-median rolling average temperature. In contrast, analyses without stratifying by daily weather only found small (<0.10-log) reductions in *E. coli* for stored drinking water and child hands and no intervention effects on other sample types. These findings indicate that averaging across the study period concealed intervention effects that occurred following increased rainfall and temperature for pathways such as flies, soil and ponds. For rainfall, trends were driven by rolling average rainfall across the antecedent period rather than the occurrence of extreme or heavy rain during the antecedent period, while for temperature, trends were driven by the occurrence of extreme or elevated temperature during the antecedent period, suggesting nuances in how weather fluctuations influence intervention effectiveness (e.g. cumulative effects from accumulating water fluxes vs. acute response to elevated temperatures).

Higher rainfall can lead to increased initial dissemination (e.g. overflowing latrine pits) and subsequent dilution of contamination in the environment[27,28]. We previously found that increased rainfall was associated with higher *E. coli* levels in ponds but lower levels in tubewell water and courtyard soil[29]. These patterns may indicate that, during heavy rain, latrine pits overflow into the surroundings and/or leak into the subsurface but fecal waste is then flushed out of the soil matrix into ponds with run-off [30]. Our current findings suggest that the intervention latrines may reduce rainfall-associated flushing of latrine contents into ponds (while both intervention and control group latrines may similarly contain fecal waste during dry conditions), explaining the larger protective effect from the intervention on pond water quality following increased rainfall. Possible mechanisms include that the concrete lining of the improved pits reduced leakage or that the double-pit design prevented overly full pits that are more likely to overflow with rain. Reduced rainfall-associated flushing of fecal waste from latrines into the environment would in turn reduce fecal contact by flies and hands, consistent with the larger reductions we observed from the intervention in *E. coli* carried by flies and on mother and child hands following rainfall.

We previously also found increased contamination of stored drinking water and food following extreme rainfall[29]. However, the sanitation intervention was not any more or less effective against contamination of these pathways following increased rainfall, and the larger reductions in hand contamination after rainfall did not translate to larger reductions of stored water and food contamination[31]. These findings suggest that the dominant mechanisms for rainfall-associated contamination of stored water and food (e.g. handling and storage conditions) were not influenced by sanitation improvements. Drinking water treatment and safe storage of water and food may protect against rainfall-associated contamination; a recent study in Kenya found that household water treatment mitigated the adverse effects of rainfall on drinking water quality[16].

Warmer temperatures can support bacterial growth as well as breeding of flies that can spread contamination; these effects may be mitigated by sanitation interventions that isolate feces from the environment[3,32]. Conversely, warmer temperatures can be associated with more sun exposure, which can inactivate microorganisms[3,6]. Our findings of larger reductions in *E. coli* in soil and ponds following higher temperatures may indicate that improved containment of fecal waste curbed the bacterial proliferation that would have occurred in the environment during warmer conditions in the absence of containment. Curbing bacterial proliferation may in turn lead to fewer opportunities for contamination of downstream pathways, consistent with the larger reductions we observed from the sanitation intervention in *E. coli* counts on mother and child hands and in stored food following higher temperatures.

Higher rainfall and temperature may also affect sanitation practices[33], as individuals may alter their latrine usage behavior, due to damage or resource conservation, or change their defecation location to avoid discomfort or inconvenience[28,34]. During heavy rain or on hot days, young children may defecate in a potty indoors and older children and adults may be more likely to use latrines than open defecate outdoors. Domestic animals might be confined to different spaces during higher rainfall or temperatures, impacting their feces disposal. If adherence to the sanitation intervention components was higher on wetter or hotter days, this could explain our findings. Understanding the user convenience of sanitation hardware and any behavior changes during different weather conditions can help improve the implementation and adoption of sanitation practices[35]. Weather can also influence hygiene behaviors in ways that can modify the observed effectiveness of the sanitation intervention. For example, if higher temperatures were associated with less handwashing, reduced hand contamination in the sanitation intervention group from reduced fecal contact may be more apparent during hotter periods.

Our findings are consistent with a recent meta-analysis that found that, when households lack access to improved latrines, increasing temperature and rainfall are associated with increased diarrhea[4]. In contrast, a meta-analysis of intervention trials found no effect modification by dry vs. wet seasons on the effectiveness of sanitation interventions against diarrhea[8]. Our findings can also shed light on the mechanisms behind the larger reductions in child enteric infections observed in the WASH Benefits trial during rainy seasons and following higher rainfall and temperature[12]. The largest health benefits occurred among the lowest socioeconomic strata during the monsoon season, indicating joint effects from socioeconomic position and vulnerability to climate-sensitive pathogen transmission[36]. The current analysis adds nuance to previous assessments that used calendar-based and/or binary definitions of season to assess WASH Benefits intervention effects on environmental contamination[13–15]. These definitions do not capture rainfall/temperature fluctuations within the same season and cannot differentiate between joint variations in rainfall and temperature (e.g., warmer temperatures generally coincide with the wet season in Bangladesh). As weather patterns shift under climate change and longstanding definitions of season no longer hold empirically, using finer grained weather data can provide improved insights over relying on season definitions. However, in regions like Bangladesh, where a distinct monsoon season can be reliably identified from rainfall data, using season as an effect modifier could still be valuable[36]. This approach can distill a complex set of environmental/temporal factors into a single variable and capture the combined influence of rainfall and temperature which might be missed if each is modelled separately. Operationally defining a monsoon season can also simplify program implementation and messaging (e.g. deliver and emphasize interventions only or more heavily during the monsoon season).

This study leveraged a large longitudinal dataset across eight fecal-oral pathways, used daily weather data and investigated a multi-faceted sanitation intervention that achieved health benefits. One limitation is that we could not assess effect modification by extreme temperature for tubewells, ponds, and flies because only a small number of samples coincided with periods of extreme temperature for these sample types. However, our sensitivity analysis using elevated temperature supported our primary conclusions. Also, environmental contamination is likely influenced by additional environmental and infrastructure factors; our results average over variation in such factors across our study data. However, our study areas in central Bangladesh had relatively homogenous environmental conditions. Because the four study districts were geographically contiguous, we expect limited spatial variability in weather parameters but our data collection period spanning 3.5 years captured temporal variability. Our findings may not generalize to other settings with different environmental factors, socioeconomics, infrastructure, and cultural practices where the underlying mechanisms driving intervention effects during different weather patterns may differ from our study setting. We did not adjust for multiple hypothesis testing because these adjustments can be overly conservative for correlated outcomes[37]. Therefore, some of the reported effects could have arisen by chance. However, effects for a given sample type were consistent across different weather classifications (e.g.

extreme vs. heavy rain) and antecedent periods (2 vs. 7 days). These trends are unlikely to be explained by chance. Additionally, while the weather datasets we used (NASA's FLDAS-Central Asia temperature dataset and GloH2O's MSWEP precipitation dataset) utilize observational data, modeling techniques, and data assimilation methods to enhance accuracy, they are still subject to uncertainties associated with spatial resolution constraints and potential biases in the process of data assimilation. Compared to empirically measured values, these datasets provide high temporal and spatial coverage but may still not fully capture localized temperature and precipitation variations, particularly in areas with complex terrain or limited ground-based observations. Further, we relied on *E. coli* as a proxy for fecal pathogens, which does not correlate well with actual pathogens[38] nor capture how non-bacterial pathogens respond to rainfall, temperature and humidity. While hotter and wetter conditions are associated with increased bacterial and protozoan (e.g. *Cryptosporidium*) infections[39,40], infections with enteric viruses (e.g., norovirus, rotavirus) are more common during colder periods[41]. Therefore, the influence of weather on intervention effects on specific pathogens may differ from our findings.

Additionally, measuring *E. coli* in the environment is not sufficient to quantify child fecal exposure and subsequent health risks without knowing the frequency/duration of exposure behaviors, such as hand and mouth contact with specific environmental compartments[42]. When contact frequencies from structured and video observations among a subset of trial participants were combined with our measured *E. coli* levels, soil emerged as a dominant contributor to children's ingestion of fecal bacteria, along with hands, objects and food[43,44]. In our current analysis, following extreme temperature, the sanitation intervention was associated with 0.33-0.40 log10-MPN reduction in *E. coli* in soil and 0.19-0.22 log10-MPN reduction in *E. coli* on child hands. *E. coli* on child hands and objects has been linked to increased risk of diarrhea and growth faltering, with each log10 increase in *E. coli* on child hands increasing the risk of diarrhea 11-23%[45,46]. The reductions we report may therefore meaningfully reduce child ingestion of fecal bacteria from soil and hands and reduce associated health risks. Following above-median rainfall and elevated temperature, the intervention was also associated with 0.25-0.38 log10-MPN reduction in *E. coli* in ponds. In rural Bangladesh, using ponds to bathe and wash utensils and clothes has been associated with increased risk of cholera[47] while others found that washing utensils and clothes with pond water does not increase diarrhea risk[48]; the health impacts from the observed reductions in *E. coli* in ponds in our study are unclear. We also note that, despite the observed reductions, *E. coli* counts in soil (5.08 log10-MPN/dry gram) and ponds (3.74 log10-MPN/100 ml) remained high among intervention recipients[13]. Also, while the intervention significantly reduced contamination along some fecal-oral pathways under some weather conditions, other pathways showed no or small reductions. Therefore, our environmental measurements are unlikely to fully explain the health benefits observed among trial participants following increased rainfall and temperature, suggesting that additional mechanisms may have mediated these findings.

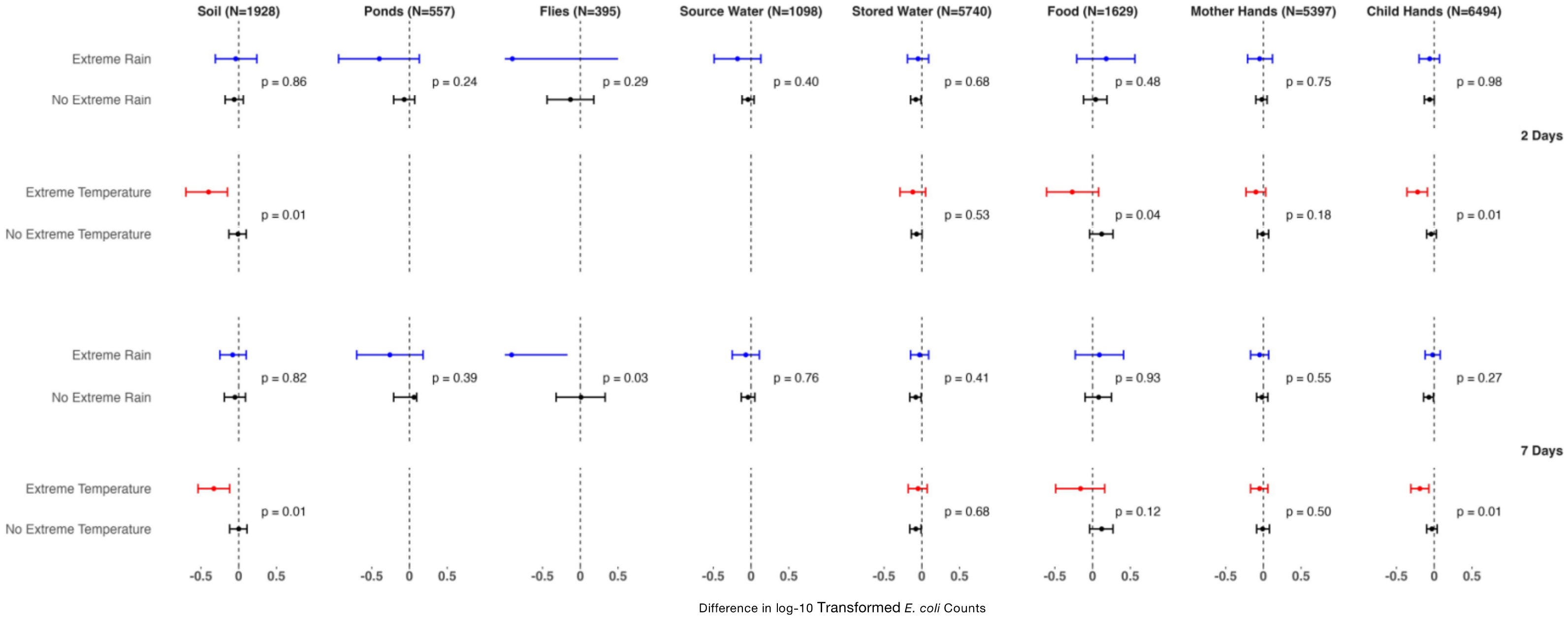
The WASH Benefits on-site sanitation interventions in rural Bangladesh more effectively reduced fecal contamination of soil, ponds, flies and hands following periods of higher rainfall and temperature. These intervention effects were not discernible in previous analyses that did not stratify by daily weather, where average reductions in *E. coli* levels were minimal. Future WASH trials studies should conduct longitudinal environmental assessments spanning a range of seasons and weather conditions, use fine-grained spatiotemporal weather data and consider targeted environmental sampling following periods of higher rainfall and temperatures.

Table 1. Differences in mean log10-transformed most probable number (MPN) of *E. coli* between randomized sanitation intervention and control groups by sample type, using all study observations without stratification by weather. Estimates and p-values compare the sanitation intervention group to the control group using unadjusted generalized linear models with robust standard errors. Estimates <0 indicate a protective effect from the intervention and estimates >0 indicate a harmful effect from the intervention.

Sample type	N	Δlog10-MPN (95% CI)	p-value
Soil	1928	-0.06 (-0.17, 0.05)	0.28
Ponds	557	0.08 (-0.21, 0.05)	0.24
Flies	395	-0.20 (-0.52, 0.12)	0.22
Source water	1098	-0.05 (-0.13, 0.03)	0.20
Stored water	5740	-0.08 (-0.14, -0.01)	0.03
Food	1629	0.06 (-0.08, 0.21)	0.39
Mother hands	5397	-0.02 (-0.10, 0.05)	0.51
Child hands	6494	-0.06 (-0.13, 0.00)	0.05

Δlog10-MPN=Difference in mean log10-transformed most probable number (MPN) of *E. coli* between intervention vs. control groups; CI: Confidence interval.

Figure 3. **Effect modification by extreme rainfall and temperature.** Forest plot of differences in mean log10-transformed most probable number (MPN) of *E. coli* between randomized sanitation intervention and control groups in strata of extreme rainfall and temperature during 2- and 7-day antecedent periods.

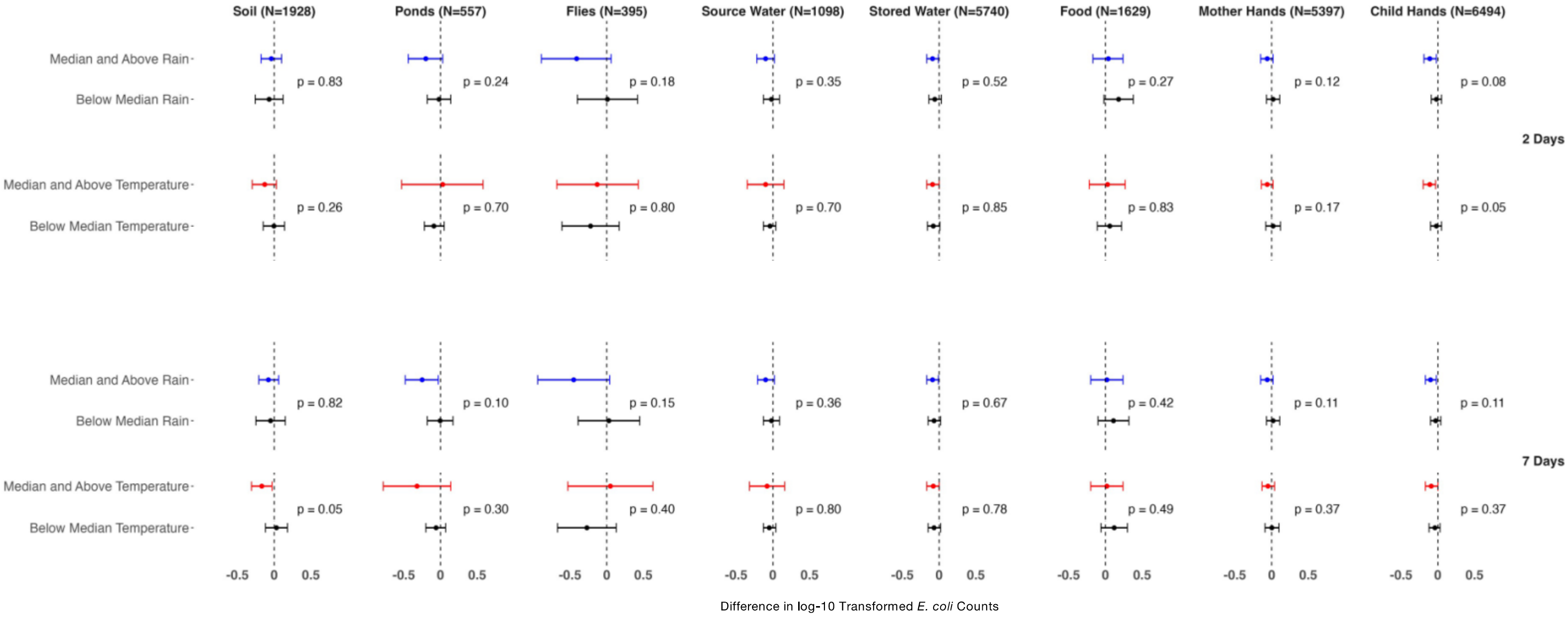


Extreme rainfall was defined as ≥ 90th percentile of daily rainfall values (28.20 mm). Extreme temperature was defined as ≥ 90th percentile of daily temperature values (30.21˚C).

Estimates compare the sanitation intervention group to the control group within each weather stratum using unadjusted generalized linear models with robust standard errors. Estimates <0 indicate a protective effect from the intervention, and estimates >0 indicate a harmful effect from the intervention. Circles indicate point estimates for differences in log10-transformed *E. coli* counts. Horizontal lines indicate 95% confidence intervals. Shown p-values refer to the p-value for the interaction term between the study group (intervention vs. control) and binary weather variable. We interpreted interaction p-values <0.20 as evidence of effect modification. The number of samples in each weather stratum is provided in Appendix B Table S4.

We could not estimate intervention effects for ponds, flies and source water (tubewells) following periods of extreme temperature due to data sparsity. Confidence intervals shown are truncated for flies in the extreme rainfall stratum for the 2-day antecedent period (Δlog10 = -0.90, 95% CI: -2.30, 0.50) and the 7-day antecedent period (Δlog10 = -0.91, 95% CI: -1.65, -0.17).

Figure 4. Effect modification by above- vs. below-median rolling average rainfall and temperature. Forest plot of differences in mean log10-transformed most probable number (MPN) of *E. coli* between randomized sanitation intervention and control groups in strata of above- and below-median rolling average rainfall and temperature during 2- and 7-day antecedent periods.



Above-median 2-day rolling average rain was defined as ≥ 0.27 mm, above-median 2-day rolling average temperature as ≥ 27.46˚C, above-median 7-day rolling average rain as ≥ 1.10 mm and above-median 7-day rolling average temperature as ≥27.52˚C.

Estimates compare the sanitation intervention group to the control group within each weather stratum using unadjusted generalized linear models with robust standard errors. Estimates <0 indicate a protective effect from the intervention, and estimates >0 indicate a harmful effect from the intervention. Circles indicate point estimates for differences in log10-transformed *E. coli* counts. Horizontal lines indicate 95% confidence intervals. Shown p-values refer to the p-value for the interaction term between the study group (intervention vs. control) and binary weather variable. We interpreted interaction p-values <0.20 as evidence of effect modification. The number of samples in each weather stratum is provided in Appendix B Table S6.

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CHAPTER 3

Associations between water supply intermittencies and drinking water quality, child health outcomes, and caregiver emotional stress in peri-urban Malawi

Introduction

The United Nations Sustainable Development Goals aim to achieve universal access to safe and affordable drinking water by 2030; meeting this goal remains a significant global challenge. The WHO/UNICEF Joint Monitoring Programme (JMP) estimated that 2.2 billion individuals lacked access to safely managed drinking water in 2022.[1] A recent study using household-level estimates from geospatial earth observation data rather than national-scale assessments estimated that up to 4 billion individuals do not have safely managed drinking water at home.[2] The JMP defines "safely managed" water service as water from an improved source that is on premises, free of fecal and priority chemical contamination, and available when needed[1]; for piped supplies, they define "available when needed" as ≥12 hours/day of water service. The WHO emphasizes that an improved water source must not only be safe but also continuously available on the premises.[3] However, intermittent piped supplies serve over one billion individuals, approximately 12.5% of the global population,[4] and non-piped supplies such as boreholes can have prolonged interruptions due to wellhead malfunction, water scarcity or both.[5]

Lack of continuous water access has profound implications for water security and quality, hygiene, health, and emotional well-being. Water insecurity at the household level refers to the inability to access adequate, reliable, and safe water for everyday use, including drinking, washing, cooking, and cleaning.[6,7] For piped supplies, intermittencies allow pathogens to intrude into pipes during non-pressurized periods, compromising water quality. Microbiological contamination levels can be up to 45 times higher in intermittently supplied taps, compared to continuously supplied taps.[8] Intermittent water supplies can also force households to store water for extended periods, ration water usage, or supplement their primary supply with unsafe/unprotected sources.[9] Opportunities for contamination during water collection and storage increase the risk of waterborne diseases. These contamination events may also foster the proliferation of antimicrobial-resistant bacteria in drinking water due to contamination with human or animal waste in stagnant pipes and/or under suboptimal water storage conditions.[10–12] Though antimicrobial resistance has been evaluated extensively in aquatic environments, few studies to date have assessed the effect of water intermittencies on contamination of drinking water with antimicrobial-resistant bacteria.[13–16]

Further, water intermittency and limited water availability can contribute to water-washed diseases by impeding on essential hygiene practices (e.g. handwashing), as households may have to prioritize the use of clean water for other household tasks.[17] Lack of handwashing has been linked to enteric and acute respiratory infections (ARIs).[18–21] While intermittencies in water service have been associated with increased risk of gastrointestinal diseases like diarrhea, typhoid fever and enteric infections[22,23] studies examining their effect on respiratory infections remain scarce.[24,25] Diarrhea and ARIs are drivers of antibiotic use,[26–28] therefore, increased enteric and respiratory infections associated with intermittent water supplies can plausibly lead to increased antibiotic use and consequently increase community carriage of antimicrobial resistance.

The direct and indirect effects of lacking continuous access to water extend beyond physical health, and can significantly impact mental and emotional health through increased psychosocial stress and emotional burdens. Daily challenges in finding an adequate water supply, ensuring sufficient water is stored, and reserving or rationing water for priority purposes can contribute to chronic stress and anxiety.[30–34] Women and girls, who are primarily responsible for water-related chores, particularly in sub-Saharan Africa, often bear the greatest emotional and physical burden.[33,35,36] Studies in sub-Saharan Africa have found women must balance responsibilities with the burden of water-related chores such as fetching, treating, boiling, storing.[37,38] The physically demanding task of fetching and managing water can contribute to significant stress, especially when caregivers must make difficult decisions about prioritizing limited water for essential household needs. Chronic stress, anxiety, and a sense of helplessness are common among those facing uncertainty about access to safe and sufficient water.[31–33,36,39] A study in Ethiopia found that up to 60% of caregivers reported anxiety and social conflict related to water scarcity.[33] Moreover, water insecurity does not exist in isolation, it is compounded by other stressors such as lack of access to safe sanitation, increased risks of waterborne diseases, conflicts over scarce resources and food insecurity.[40,41] The cumulative impact of these challenges – heightened disease risks, physical demands, and emotional strain – demonstrates how water insecurity, including intermittent water access, is both a physical threat and a significant psychosocial burden.

Malawi is a landlocked country in Southern Africa with a population of over 20 million, ranking 172 out of 193 on the Human Development Index, placing it among the poorest 8% of countries globally.[42] More than half the population lives in poverty and one-fifth in extreme poverty[43], with over a quarter unable to afford the recommended daily food intake—putting many individuals at risk for elevated stress and adverse health outcomes.[44,45] Water insecurity is also widespread: 3.8 million Malawians lack access to clean drinking water, with rural access (65%) lagging behind urban areas (90%).[44] Previous studies in Malawi have highlighted several challenges with water services. For example, piped water systems face sustainability issues due to logistical, technical, and infrastructural constraints.[46] In informal settlements in Lilongwe, the capital city, limited and unreliable water kiosks force households to endure long queues and service gaps.[47] At the utility level, water boards struggle with high levels of unaccounted-for water, mainly from leaks, undermining supply reliability.[48,49]

This study aims to examine the relationship between intermittencies in water supplies and a range of outcomes, including drinking water contamination with fecal indicators and antimicrobial-resistant bacteria, child health outcomes (diarrhea, ARI, antibiotic use), and caregiver emotional stress, within peri-urban Malawian households. While previous research has individually explored associations between water intermittency and some of these outcomes, this study builds on existing literature by investigating multiple outcomes along the causal chain to corroborate mechanisms.

Materials and Methods

Study Design and Population

We systematically enrolled 237 households in Bangwe, a peri-urban town in Blantyre, Malawi. We used GIS to select random starting points within town boundaries and systematically approached every third household in each direction to ensure representative geographic coverage. Households were eligible for enrollment if they had at least one child <5 years, and if an adult >18 years that was responsible for those children was available and consented to participate. Enrolled households were visited once to conduct a structured questionnaire and collect samples of drinking water.

Data Collection

Trained enumerators from Mzuzu University (MZUNI) and Malawi University of Science and Technology (MUST) administered a structured questionnaire among the primary caregivers in the enrolled households to record water intermittencies, child health outcomes and antibiotic use, perceived respondent stress, as well as relevant demographic information and water, sanitation and hygiene indicators. Water intermittency was enumerated using the 12-item Household Water InSecurity Experiences (HWISE) scale that assesses the frequency of experiences related to water insecurity and associated negative emotional responses, using a five-point Likert scale ranging from never (0) to always (20+ times) in the last four weeks.[7] One HWISE item is specifically focused on intermittency, asking how often the household's primary water source has been interrupted or limited in the last four weeks. We also asked an additional question on how long the last interruption lasted before water service was restored. Recorded child health outcomes included the reported occurrence of diarrhea (as defined by caregiver), loose stools, constant cough, difficulty breathing, and fever within the last seven days. We also recorded two negative control outcomes (outcomes theoretically not associated with water intermittency),[50,51] including ear infection and a rash anywhere on the child's body within the last seven days. Respondent stress was recorded using the 10-item Perceived Stress Scale (PSS) that evaluates feelings and thoughts in the past month as they pertain to how unpredictable, uncontrollable or overwhelming events are in life using a five-point Likert scale ranging from never (0) to very often (4).[52,53]

Sample Collection and Processing

Enumerators trained in aseptic technique collected drinking water samples from enrolled households. Enumerators asked the respondent for a glass of drinking water in the same way they would give it to a child. Approximately 200 mL of sample was transferred into a sterile WhirlPak bag that contained sodium thiosulfate to remove any residual chlorine (Whirl-Pak Filtration Group, USA). The enumerators recorded whether the sample was obtained from a storage container, the source of the water and whether it had been treated to make it safer for consumption. Field blanks were collected by placing a WhirlPak bag pre-filled with 100 mL sterile DI water into the field cooler of a randomly selected enumerator and asking them to return it to the laboratory along with the samples. One field blank was collected for approximately every 30 water samples (3.0%, 7/236). Samples were transported on ice to the MUST laboratory and processed within five hours.

We used IDEXX Quanti-Tray/2000 with Colilert-18 media (IDEXX Laboratories, Westbrook, ME, USA) with and without antibiotic supplementation to enumerate the most probable number (MPN) of *E. coli* and cefotaxime-resistant *E. coli*. Cefotaxime-resistant *E. coli* was used as a presumptive indicator for extended-spectrum beta-lactamase (ESBL)-producing *E. coli*, which are of particular concern due to their resistance to broad-spectrum beta-lactam antibiotics and form the basis of the WHO's Tricycle global surveillance initiative.[54] 100 mL of sample was added to a sterile WhirlPak, to which Colilert was added and gently dissolved before dispensing the sample into a Quanti-Tray. A second 100 mL aliquot from the same sample was analyzed using the same process plus the addition of 80 µL of 5 mg/mL filter-sterilized cefotaxime solution.[55] Lab blanks were analyzed using the same steps with 100 mL of sterile DI water. One lab blank was processed for approximately every 10 water samples (11.9%, 28/236). Following incubation for 18 hours between 35-36ºC, Quanti-Trays were read by counting the number of wells that were yellow and fluoresced under long-wave UV light, indicating the presence of *E. coli*.

Ethics

The research protocol was approved by the Research Ethics Committee (MZUNIREC) at Mzuzu University (MZUNIREC/DOR/24/38) and University of North Carolina, Greensboro (20-0245), with additional ethical oversight from North Carolina State University via Inter-Institutional Agreement. All participants provided written informed consent in the local language (Chichewa).

Statistical Analysis

<u>Exposure variables</u>. We considered the occurrence, frequency, and duration of water intermittencies. Using the HWISE question, we generated a binary variable for whether the household experienced any intermittencies in their water service and a categorical variable for the frequency of intermittencies, including none, rarely (1-2 times), and sometimes/often/always (3-20+ times) in the last four weeks. We generated a categorical variable for the duration of the last intermittency, including none, below-median duration, and above-median duration.

<u>Outcome variables</u>. Outcomes across the causal chain included water quality, child health and caregiver stress (Figure S1). Water quality outcomes included the prevalence and log-10

transformed most probable number (MPN) of generic and cefotaxime-resistant *E. coli*. We replaced non-detects with half the detection limit (0.5 MPN/100 mL) and values above the detection limit of 2419.6 MPN/100 mL with 2420 MPN/100 mL before taking the logarithm. For samples that were positive for cefotaxime-resistant *E. coli*, we calculated the relative percent abundance as the ratio of cefotaxime-resistant *E. coli* counts to generic *E. coli* counts for the same sample. Child health outcomes included the caregiver-reported 7-day prevalence of diarrhea, ARIs, ARIs with fever, and negative control outcomes (ear infection, rash).[56] Caregiver-defined diarrhea recorded the caregivers' response to the question whether their child had diarrhea, capturing their personal perception of what would constitute illness in their child. WHO-defined diarrhea was classified as ≥3 loose or liquid stools within 24 hours, based on the caregiver-reported symptoms. ARI was defined as a constant cough coupled with panting, wheezing, or difficulty breathing; ARI with fever included the same symptoms with fever occurring in parallel. Additional child health outcomes were whether and how many times the child took antibiotics in the last four weeks. For caregiver stress, we summed the scores to the individual Likert-scale questions to calculate a PSS score, and we also generated a binary variable to define high stress (PSS score ≥27 out of 40).[57] Additionally, we generated a binary version of each individual Likert-scale stress indicator by grouping responses of never, rarely and sometimes into a low-stress category and often and always into a high-stress category.[58]

Analysis approach. We used generalized linear models to assess the relationship between the different water intermittency definitions and each outcome variable. We used a Poisson error distribution with a log link for binary outcomes, negative binomial error distribution with a log link for over-dispersed count outcomes, a Gaussian error distribution with an identity link for continuous outcomes. Each model adjusted for relevant covariates to control for potential confounding, including sociodemographic factors (e.g., household wealth quintile, education level, floor material), water, sanitation and hygiene indicators (e.g., use of an improved latrine and improved drinking water source according to JMP definitions, presence of a handwashing station with soap), and animal ownership (Text S1). We did not control for covariates on water use and hygiene practices as we hypothesized these to be on the causal pathway (Figure S1). We excluded binary and categorical confounders that did not sufficiently vary across our sample (<5% prevalence in any stratum). Models implemented robust standard errors to account for clustered outcomes. A cluster was defined as a geographic grouping of households that is at least 100 meters distant from the next group of clustered households.[59] We used ArcGIS (ESRI, Redlands, California) to define the clusters using the defined distance (DBBSCAN) method based on GPS coordinates of enrolled households. Statistical analyses were conducted in R (version 4.3.1, RStudio (2023.06.0+421).

Results and Discussion

Participant characteristics. We enrolled 237 households between June 20-July 11, 2024. Study households were located within 38 unique spatial clusters based on their GPS coordinates. The mean age of respondents was 31.1 years, and households had on average 1.2 children <5 years (Appendix C Table S1). Approximately 40% of respondents had some primary education. On average, households spent $15-18 USD on weekly expenditures. Almost all households had floors made of cement/concrete, walls made of brick and roofs made of tin. The most common fuel type was charcoal, and the most common stove type was traditional solid fuel stoves (Appendix C Table S1). Almost all households reported having a latrine, and 65.4% of households had an improved latrine; the most common latrine type was a twin pit latrine with a slab (Appendix C Table S1). The primary source of drinking water was an improved source for 84.4% of households, including piped supplies (in own dwelling, own yard/plot or outside the compound) (56.6%) and boreholes (21.5%) (Appendix C Table S1).

Water intermittencies. Approximately one third (32.5%, 77/237) of households reported experiencing at least one water intermittency in the last four weeks. Specifically, 15.2% (36) of households experienced an intermittency rarely (1– 2 times), 12.2% sometimes (3–10 times), 3.8% often (11–20 times) and 1.3% always (>20 times). The mean intermittency duration was 4.53 days, and the median duration was 1.27 days (range: 0.02–90.31 days). Among the 77 households who experienced a water intermittency, 13.0% (10) of households were notified of the intermittency in advance, 2.6% (2) could predict the intermittency based on season or previous pattern of intermittencies, and 84.4% (64) were unaware of the upcoming intermittency.

Households with vs. without water intermittencies were similar in their overall characteristics (Appendix C Table S1). However, households that experienced intermittencies were more likely to obtain their primary drinking water from a piped connection outside the compound (39.0% vs. 24.4%) and less likely to obtain it from a borehole (11.7% vs. 26.3%) (Appendix C Table S1). Households with intermittencies appeared less likely to have at least one household member with complete secondary education (36.4% vs. 45.9%), to own a mosquito net (63.6% vs. 73.1%) and to own animals (13.0% vs. 29.4%) but more likely to own a television (49.4% vs. 41.9%) and a fridge (29.9% vs. 20.6%) and to report animals living on their compound (80.0% vs. 75.6%) than households without intermittencies (Appendix C Table S1).

Water-related behaviors.

Domestic and personal hygiene. Households with vs. without water intermittencies reported similar access to water for handwashing; approximately 10% households in both groups had a designated handwashing station and 9% had a handwashing station with available water observed at the time of the enumerators' visit (Table 2). Intermittent households had higher mean household water insecurity scores than non-intermittent households (8.1 vs. 1.9 out of 36) and were more likely to be classified as water-insecure (HWISE score ≥12) (20.8% vs. 4.4% of households). This trend remained using a truncated HWISE score that excludes the water intermittency question from the total score (Table 2). Households with frequent intermittencies had higher mean truncated HWISE scores than those with rare intermittencies (7.1 vs. 5.6), while households with longer vs. shorter intermittencies had similar mean scores (6.2 vs. 6.6) (Appendix C Table S2).

Water insecurity was reflected in specific domestic hygiene behaviors reported in response to individual HWISE questions. Households with intermittencies were substantially more likely to go without doing laundry (36.4% vs. 9.4%) and bathing (10.4% vs. 1.3%) and slightly more likely to go without handwashing after dirty activities, such as defecating or changing diapers and cleaning animal dung (5.2% vs. 3.1%), sometimes, often, or always (3 to 20+ times) in the last four weeks (Table 2). When asked an unprompted question about when they wash their hands, respondents in both groups reported similar handwashing prevalence after defecating or handling child feces, and before eating or handling food or water (Table 2). However, intermittent households were less likely to report handwashing after handling animals (3.9% vs. 10.0%), handling animal feces (3.9% vs. 8.8%), or working outside (e.g. garden, market) (15.6% vs. 25.0%) than non-intermittent households (Table 2). Households with frequent intermittencies were more likely to go without doing laundry, bathing and handwashing after dirty activities than those with rare intermittencies (Appendix C Table S2). Households with long intermittencies were less likely to report handwashing after handling domestic animals, handling animal feces, after working, before handling water, and before breastfeeding than those with short intermittencies (Appendix C Table S2). However, they were more likely to have a handwashing station with water compared to both households with short or no intermittencies (Appendix C Table S2).

Water storage, handling and use of secondary sources. A higher percentage of intermittent households provided drinking water samples from storage containers than non-intermittent households (96.1% vs. 87.5%) (Table 2). Approximately 80% of storage containers in both groups were observed to be covered but intermittent households were less likely to use narrow-mouthed containers (5.2% vs. 17.5%). The mean duration of water storage was slightly shorter in intermittent households compared to non-intermittent households (29.9 vs. 32.6 hours) (Table 2). The reported prevalence of treating drinking water in the home was low in both groups, but lower in intermittent households (2.6% vs. 5.6%). Intermittent households were also somewhat less likely to rate their primary drinking water source as acceptable (84.4% vs. 89.4%) and more likely to use secondary drinking water sources (32.5% vs. 24.4%) (Table 2). Households with rare and short intermittencies were more likely to provide drinking water samples from storage containers, have longer storage duration and obtain drinking water from secondary sources than those with frequent or long intermittencies (Appendix C Table S2).

Water quality. Of 236 drinking water samples, 65.7% (155) contained *E. coli* at a mean count of 0.74 log10-MPN/100 mL. Of 226 samples processed for with cefotaxime supplementation, 8.4% (19) contained cefotaxime-resistant *E. coli* at a mean count of -0.23 log10-MPN/100 mL. Among the 19 positive samples, the relative abundance of cefotaxime resistance (ratio of cefotaxime-resistant to generic *E. coli* counts for the same sample) ranged from 0.1% to 70%. Water source types with the highest mean levels of contamination ranged from 866.4 log10-MPN/100 mL for protected spring (n=1), 217.3 log10-MPN/100 mL for boreholes (n=51), 135.6 log10-MPN/100 mL for piped water into the dwelling (n=20), and 81.3 log10-MPN/100 mL for piped water outside the compound (n=69) (Appendix C Table S3).

In adjusted analyses, intermittent and non-intermittent households had similar prevalence and counts of both generic and cefotaxime-resistant *E. coli* (Appendix C Table S4). There were no significant differences in *E. coli* prevalence or counts between households that experienced intermittencies rarely (1-2 times), often/sometimes/always (3 to 20+ times) versus never (Appendix C Table S5) or between households that experienced intermittencies of above-median duration (≥1.27 days), below-median duration (<1.27 days) versus never (Appendix C Table S6). We could not assess associations between the categorical intermittency frequency/duration variables and cefotaxime-resistant *E. coli* because of the small number of positive samples.

Child health. Among children in non-intermittent households, the 7-day prevalence of health outcomes was 16.3% for caregiver-defined diarrhea, 13.9% for WHO-defined diarrhea, 40.6% for ARI and 17.3% for ARI with fever, while 29.7% of children were reported to have taken antibiotics at least once in the last four weeks (Appendix C Table S7). Children in intermittent households had higher prevalence of both for caregiver-defined diarrhea (prevalence ratio [PR]= 1.94 (1.11–3.39), p=0.02) and WHO-defined diarrhea (PR=1.63, (0.78–3.39), p=0.19) but the association for WHO-defined diarrhea could not be distinguished from chance (Appendix C Table S7, Figure 5). Children in intermittent households also had 2 times higher prevalence of ARI with fever (PR=2.00, (1.11–3.60), p=0.02) and though borderline significant, higher prevalence of ARI (PR=1.43 (0.99–2.09), p=0.06) (Appendix C Table S8, Figure 5). There were no significant associations between water intermittency and child antibiotic use (Appendix C Table S7, Figure 5). Among our negative control outcomes, water intermittency was not associated with the prevalence of having a rash (PR=1.25, (0.60-2.62), p=0.55) (Appendix C Table S7, Figure 5). We could not assess associations for our second negative control outcome, because only 2.4% (7) of children were reported to have ear infections.

When analyzed by categories of intermittency frequency, children in households with rare intermittencies had approximately 2 times higher prevalence of caregiver-defined diarrhea and WHO-defined diarrhea and used antibiotics twice as many times compared to children in non-intermittent households but the association for WHO-defined diarrhea could not be distinguished from chance (Appendix C Appendix C Table S8). Children in households with frequent intermittencies had between 1.70–2.3 times higher prevalence of ARI and ARI with fever than those in non-intermittent households; there were no associations with other health outcomes (Appendix C Appendix C Table S8).

When analyzed by categories of intermittency duration, children in households experiencing an intermittency of below-median duration had two times higher prevalence of caregiver-defined diarrhea compared to those with no intermittency (PR=2.21 (1.05–4.65), p=0.04) (Appendix C Appendix C Table S9). They also appeared to have higher prevalence of WHO-defined diarrhea and number of antibiotic use episodes, but these associations could not be distinguished from chance (Appendix C Appendix C Table S9). Children in households experiencing an intermittency of above-median duration had significantly higher prevalence of ARI (PR=1.61 (1.02–2.55), p=0.04) and ARI with fever (PR=2.58 (1.53–4.34), p<0.0005) compared to those in non-intermittent households; there were no associations with other health outcomes (Appendix C Appendix C Table S9).

Caregiver stress. Caregivers in households with water intermittencies had higher PSS composite scores (21.6 vs. 18.8 out of 40) and higher probability of experiencing high stress (PSS score ≥27) (22.4% vs. 9.4%) but these associations could not be distinguished from chance after adjusting for confounders (Appendix C Appendix C Table S10, Figure S2). Caregivers in intermittent households were less likely to report feeling unable to control irritations (PR=0.36 (0.19, 0.71), p=0.003) but more likely to report feeling unable to control things, though this association was borderline significant (PR=1.73 (0.99, 3.00), p=0.05). There were no associations between water intermittency and other stress indicators (Appendix C Appendix C Table S10, Figure S2).

When analyzed by categories of intermittency frequency, caregivers in households with rare intermittencies had similar composite PSS scores and likelihood of experiencing high stress as non-intermittent households (Appendix C Appendix C Table S11). They were twice as likely to report feeling angry (PR=2.21 (1.06, 4.61), p=0.04) but less likely to report feeling unable to control irritations (PR=0.30 (0.09, 0.94), p=0.039) than caregivers in non-intermittent households (Appendix C Appendix C Table S11). Caregivers experiencing intermittency rarely were also over 2.5 times more likely to report never/rarely feeling confident to solve problems, though this association was borderline significant (PR=2.56 (0.95, 6.95), p=0.06); there were no other associations with stress indicators in this group after adjusting for confounders (Appendix C Appendix C Table S11). Caregivers in households with frequent intermittencies had higher composite PSS scores (ΔPSS=2.15 (0.24–4.06), p=0.03) and were twice as likely to be experiencing high stress (PR=2.05, (0.99-4.25), p=0.05) compared to caregivers in non-intermittent households, but the latter association was only borderline significant (Appendix C Appendix C Table S11). They were also more likely to report feeling upset by unexpected events but less likely to report things not going their way and being unable to control irritations; these associations were only borderline significant (Appendix C Table S11).

When analyzed by categories of intermittency duration, caregivers in households experiencing short intermittencies had higher PSS scores than those in non-intermittent households (ΔPSS=1.74 (0.08–3.40), p=0.04) (Appendix C Table S12). Short intermittencies were also significantly associated with 2-3 times higher likelihood of caregivers feeling unable to control things (PR=1.95 (1.09, 3.50), p=0.03), nervous or stressed (PR=2.12 (1.09, 4.13), p=0.03), not confident to solve problems (PR=3.39 (1.30, 8.81), p=0.01) and angry (PR=2.18 (1.07, 4.43), p=0.03) compared to non-intermittent households (Appendix C Table S12). In contrast, caregivers in households experiencing longer intermittencies were less likely to report feeling unable to control irritations (PR=0.34 (0.13, 0.88), p=0.026) compared to non-intermittent households; there were no other associations between long water intermittencies and stress indicators.

Discussion. One third of households in our study experienced at least one intermittency in the last four weeks, aligning with prior evidence that intermittencies in water supply are common in urban and peri-urban settings in low- and middle-income countries.[34,40,60–62] Households experiencing a water intermittency were more likely to de-prioritize hygiene practices, especially around animal management, and had higher water insecurity scores. They were also more likely to rely on stored drinking water and alternative water sources, but drinking water quality, as measured by *E. coli,* was not adversely affected by intermittencies. Children in households experiencing a water intermittency had higher prevalence of diarrhea, ARIs and ARIs with fever, while caregivers in these households reported higher stress, but primarily for short and frequent intermittencies. Our findings are broadly consistent with prior studies that have documented adverse effects of water intermittencies individually on water use behaviors, water quality, health or stress outcomes.

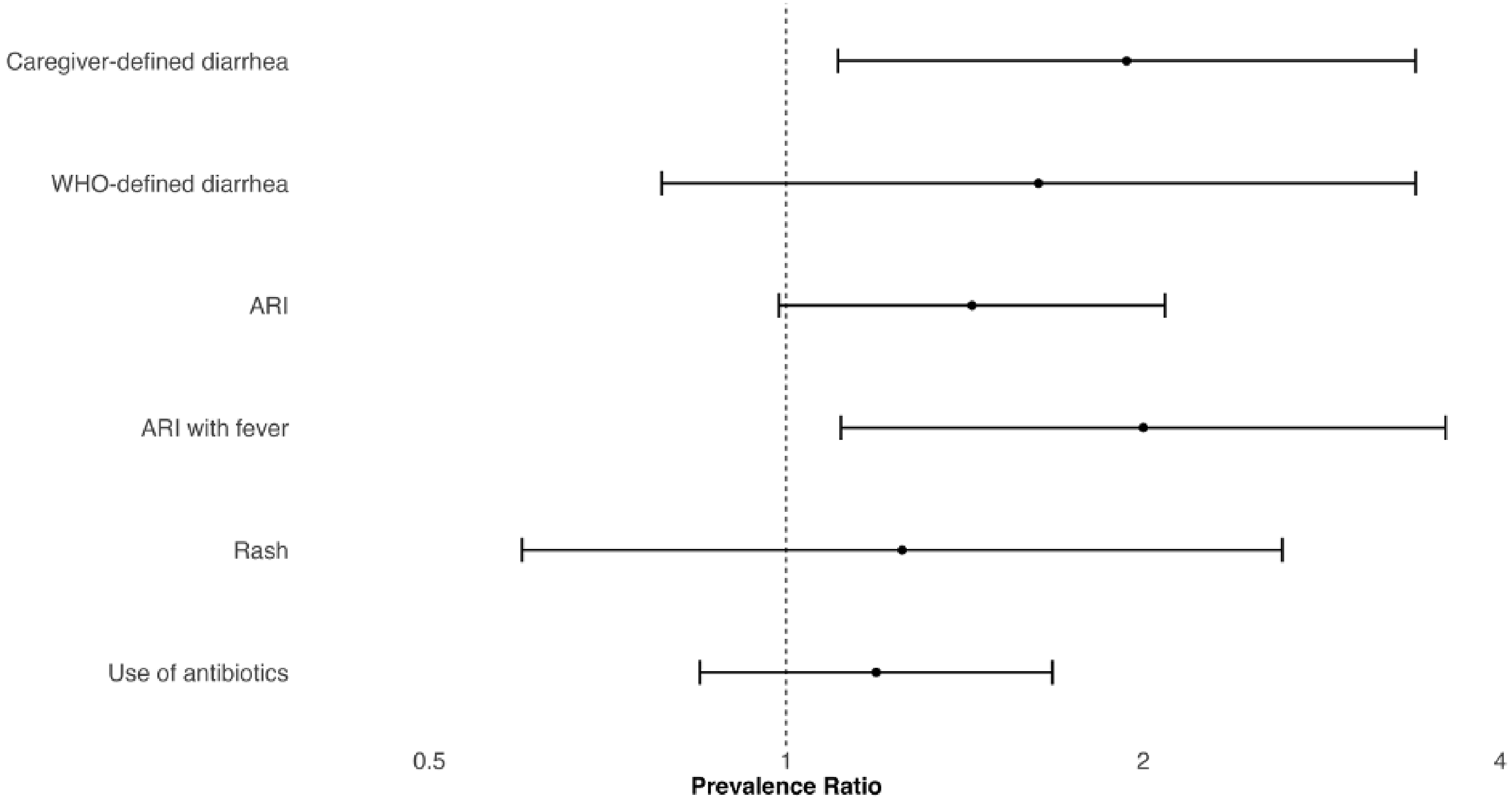
Prior research suggests that water access inequities often align with wealth disparities, with lower-income households disproportionately affected due to a reliance on communal sources.[6,60] In our study, households experiencing intermittencies were socioeconomically similar to those not experiencing intermittencies within the same geographic area. 17% of all intermittencies occurred within a single geographic cluster, while the remaining intermittencies were spread across the other study clusters. This suggests that water intermittency may not be solely driven by socioeconomic status but also by additional external geographic and infrastructural challenges, highlighting a more complex relationship between wealth and water intermittency.[60]

Table 2. Hygiene practices, water storage and secondary water sources among households experiencing at least one water intermittency vs. no water intermittency in the last four weeks

	No Intermittency N=160	Intermittency N=77
Domestic and hand hygiene		
Household has handwashing station, % (n)	9.4% (15)	11.7% (9)
Household has handwashing station with water, % (n)	8.8% (14)	9.1% (7)
Household water insecurity score, mean (SD)	1.9 (4.2)	8.1 (5.9)
Truncated household water insecurity score, mean (SD) a	1.9 (4.2)	6.4 (5.8)
Had to go without sometimes/often/always, % (n)		
Washing clothes	9.4% (15)	36.4% (28)
Bathing	1.3% (2)	10.4% (8)
Washing hands after dirty activities	3.1% (5)	5.2% (4)
Reported handwashing occasions, % (n)		
Never	1.3% (2)	0.0% (0)
After defecation	90.0% (144)	94.8% (73)
After handling child's waste	63.1% (101)	61.0% (47)
After handling domestic animals	10.0% (16)	3.9% (3)
After handling animal feces	8.8% (14)	3.9%(3)
After working (garden, market, etc.)	25.0% (40)	15.6% (12)
After eating	81.3% (130)	79.2% (61)
Before eating	91.9% (147)	94.8% (73)
Before preparing food	69.4% (111)	62.3% (48)
Before feeding child	41.3% (66)	42.9% (33)
Before handling water (storage)	23.8% (38)	24.7% (19)
Before breastfeeding	7.5% (12)	9.1% (7)
Water storage		
Water sample provided from storage container, % (n)	87.5% (140)	96.1% (74)
Stored water container fully or partially covered, % (n)	78.8% (126)	80.5% (62)
Stored water container has narrow mouth, % (n)	17.5% (28)	5.2% (4)
Duration of water storage in hours, mean (SD, range)	32.6 (54.8, 0-577)	29.9 (37.3, 0-194)
Water sample reported to be treated, % (n)	5.6% (9)	2.6% (2)
Secondary water sources		
Primary drinking water source feels acceptable, % (n)	89.4% (143)	84.4% (65)
Household obtains, % (n)		
Drinking water from secondary source	24.4% (39)	32.5% (25)
Drinking water from improved secondary source	8.8% (14)	18.2% (14)
Non-drinking water from improved source	65.6% (105)	64.9% (50)

[a] The truncated household water insecurity (HWISE) score excludes the intermittency question to allow comparing scores between intermittent and non-intermittent households.

Figure 5. **Forest plot of adjusted associations between water intermittency and caregiver-reported child health outcomes**. The circles denote point estimates for prevalence ratios and the horizontal lines denote 95% confidence intervals. Models controlled for age of the respondent, age of the target child, total number of individuals living in household, respondent's highest level of education, highest level of education level for anyone in household, asset-based household wealth quintile, average weekly expenditures by household, household food insecurity score, whether household used piped water for their primary water source, whether household's designated handwashing station had soap, whether household had an improved latrine (as defined by the WHO), flooring material inside household, total number of animals in compound, and respondent's report of the last time it rained.



Water intermittency is recognized as a component of water insecurity. Consistent with prior research, our study found that an intermittent water supply disrupts household water management and increases reliance on potentially unsafe water sources.[13,63] Notably, household water insecurity scores were low in our study, and less than 10% (23) of households were classified as water insecure (HWISE score ≥12 points). Despite being relatively water secure, households that experienced at least one water intermittency in the last four weeks were substantially more likely to skip hygiene practices, such as bathing, laundry and handwashing after dirty activities. This supports previous studies linking water insecurity with reduced hygiene.[18–21,61,62] Importantly, in our study, households experiencing an intermittency had similar reported handwashing during some key moments (after defecation, before eating or handling food or water) as non-intermittent households, consistent with evidence that washing hands after defecation is prioritized despite water limitations.[17,64] However, in our study, intermittent households were substantially less likely to report washing hands after handling animals and their feces or working outside (e.g. in the garden). Backyard animal husbandry is common in low- and middle-income countries and exposure to domestic animals is a risk factor for infectious diseases.[65–67] Between 75-80% of households in our study reported having animals in the compound, and the number of animals per compound ranged from 6 to 9 (Appendix C Table S1). Domestic soil is also increasingly recognized as a disease transmission pathway in settings where fecal waste is not isolated from the environment.[68,69] Our findings indicate that water conservation strategies associated with intermittencies may potentially increase zoonotic and soilborne exposure to enteric pathogens.

Intermittent households were more likely to obtain drinking water from secondary sources and use stored drinking water and less likely to use narrow-mouthed containers, which are more protective against contamination[13,70]. Increased reliance on stored water is a well-documented risk factor for microbial contamination due to prolonged storage and environmental exposure.[8] However, we did not find significant differences in *E. coli* prevalence or counts between intermittent and non-intermittent households. This finding contrasts with studies from other settings that reported a link between intermittency and microbial contamination of drinking water and suggests that, in our context, the increased risk of enteric and respiratory infections associated with water intermittencies may be more strongly driven by changes in hygiene-related behavior and limited water access and quantity than by differences in water quality.

It is possible that differences in water sources partly explain the lack of water quality effects from intermittencies in our study. While approximately 80% of both intermittent and non-intermittent households used an improved primary water source, households that experienced intermittencies were more likely to obtain their primary drinking water from a piped connection outside the compound (with a mean *E. coli* level of 81.3 log10-MPN/100 mL) and less likely to obtain it from a borehole (with a mean *E. coli* level of 217.3 log10-MPN/100 mL). While our analyses controlled for whether the household's drinking water came from a piped source, our findings of no adverse water quality effects from intermittencies may residually reflect the better quality of piped sources, which more commonly experienced intermittencies. Piped water interruptions in Blantyre are driven by a combination of infrastructural, operational, and financial challenges faced by the Blantyre Water Board. Aging infrastructure and widespread leakages account for almost 40% of physical water losses but demand regularly exceeds supply capacity, especially during dry periods.[49] High levels of non-revenue water—exceeding 50%—due to illegal connections, faulty meters, and system leaks further strain the utility's resources.[71] Additionally, water access is highly unequal across zones, with peri-urban and elevated areas experiencing especially short and inconsistent supply due to low pressure and distribution issues.[49,71] Our findings highlight a trade-off between water supply reliability and quality, with boreholes presenting a supply that is less likely to be interrupted but more likely to be contaminated than piped sources.

Children in intermittent households had significantly higher prevalence of diarrhea, ARI, and particularly ARI with fever. This finding strengthens existing evidence linking water intermittency to adverse health outcomes[22,23,35]. Most research on water intermittencies and water insecurity has focused on diarrheal disease. A small number of studies have investigated relationships between water quality improvements and ARI.[18,21,72] Our findings suggest water intermittency may increase ARI risk through pathways such as compromised hygiene, consistent with our findings of impaired handwashing practices in intermittent households. Emerging research has shown associations between water intermittencies and lessened ability to adhere to handwashing recommendations for COVID-19 prevention and higher risk of COVID-19 infections.[24,25,73] Existing disease burden estimates for intermittent water supplies are focused on gastrointestinal infections[22]; our findings on ARIs indicate that these assessments may underestimate the total disease burden from water intermittencies. Additionally, when we analyzed health outcomes by intermittency frequency and duration, children in households with rare or short disruptions had higher prevalence of diarrhea while children with frequent or long disruptions had higher prevalence of ARIs, suggesting that short-term vs. long-term behavioral adaptations may differently impact enteric versus respiratory pathogen exposure. Further, almost one third of children in our study had used antibiotics at least once on the last four weeks, and infrequent and long intermittencies were associated with higher antibiotic use compared to non-intermittent households. Our findings suggest that the increased prevalence of enteric and respiratory infections among children experiencing intermittencies may translate to increased antibiotic use, highlighting antibiotic use and antimicrobial resistance as outcomes to investigate in future studies of water supply intermittencies.

A review conducted in 2016 found that predictable intermittencies, compared to irregular and unpredictable intermittencies, were the most disruptive in the lives of consumers across over 100 empirical case studies [74]. We found that shorter and more frequent intermittencies were associated with higher stress among caregivers, which may be due to greater uncertainty and need for adaptation strategies, supporting that even brief disruptions in water supply can have psychological effects. A recent study found that being able to predict a water intermittency reduced the stress response associated with it.[30] We were not able to test the influence of predictability on caregiver stress because most households who experienced an intermittency reported that they were not notified about it nor able to predict it. These findings align with prior research linking water insecurity to increased psychosocial distress, particularly among caregivers responsible for household water management.[6,29,33,34,37,41] Chronic stress, mental health and emotional wellbeing are important health dimensions to consider in the context of water insecurity. Our findings reinforce calls for integrating mental health considerations into water supply programs.

Climate change is expected to exacerbate water access challenges by increasing the frequency and severity of droughts, rainfall variability and extreme weather events. These stressors can prompt persistent water supply interruptions and disrupt traditional water sources, potentially increasing reliance on unprotected sources, as well as overcrowding and social conflict around water access. Additionally, climate change can alter seasonality, stressing households as protected, piped water may be less available during dry months, while unprotected sources such as surface water may be more accessible during the rainy season.[40,75] While our study did not assess the causes of the observed intermittencies, the water utilities report a complex set of causes, including compromised infrastructure, power shortages that disrupt pumping as well as water shortages and high demand during the dry season[76] . As changing weather patterns, extreme events, and shifting seasonal cycles increasingly disrupt water availability, future research should quantify health and well-being impacts from increasingly unpredictable and intermittent water supplies.[9,34]

Our study integrated microbial, behavioral, health, and psychosocial dimensions of water intermittencies for a comprehensive assessment. This study also had limitations. Both water intermittencies and outcomes of interest were self-reported and may be subject to recall bias, potentially affecting our exposure and outcome classifications. Specifically, households experiencing intermittencies may be aware of health risks and therefore overreport adverse health outcomes. However, our negative control outcome (rash) suggest that recall bias was unlikely to fully explain the observed associations. If recall bias were a major driver of our findings, we would expect to see similarly strong associations between water intermittency and the prevalence of children experiencing a rash, yet we did not observe such an association. We also note that while we selected rash as a negative control outcome under the assumption that it is causally independent of water intermittency, it is possible that hygiene behaviors or water-related stress could influence skin conditions. Further, the observational design of this study limits our ability to draw causal inferences between water intermittency and health/stress outcomes, and our findings may be affected by residual confounding from unaccounted-for differences between intermittent and non-intermittent households. Nevertheless, we recorded outcomes across the causal chain, including potential mediators, and conclude that our findings are internally consistent and biologically plausible because the observed direction of effects on mediating factors supports the observed associations with our study outcomes.

Conclusion. Our findings indicate that water intermittency is significantly associated with impaired hygiene, especially in the context of handling domestic animals, higher risk of respiratory infections and diarrhea in children, and increased psychological stress among caregivers. While our observational findings cannot determine causality, they suggest that improved coping strategies— including safe water storage practices, use of safe alternative water sources during disruptions, low-flow hand hygiene strategies, water reuse for domestic hygiene, and advanced notification on upcoming disruptions—may help reduce health risks during water supply disruptions, while provision of an uninterrupted continuous water supply remains the ultimate goal. Targeted support for caregiver stress may be beneficial, given the increasing evidence on the relationship between water insecurity and psychosocial outcomes. Future research should explore the long-term health consequences of water intermittency, and explore interventions aimed at reducing the occurrence, frequency and duration of water supply intermittencies.

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CONCLUSION

This dissertation investigates how climate variability, water insecurity, and infrastructure limitations influence fecal contamination across environmental pathways in low-resource settings. Through three interconnected studies conducted in rural Bangladesh and peri-urban Malawi, we examined the role of extreme weather, sanitation interventions, and water intermittency in shaping household-level exposure to microbial risks. Each study contributed unique insights, but taken together, they underscore a common reality that the health risks posed by fecal contamination are intricately tied to both environmental exposures and systemic gaps in WASH infrastructure.

Across all three studies, *E. coli* was used as a fecal indicator to assess pathogen contamination. While *E. coli* is a widely accepted indicator of fecal contamination, it is not a perfect proxy for a full range of enteric pathogens, specifically non-bacterial organisms such as viruses and protozoa. This is an important limitation to acknowledge as our findings can likely only be generalizable to trends in fecal exposure and may underestimate risks associated with pathogens that behave differently in the environment.

Another key limitation across this dissertation is our inability to assess other forms of environmental contamination, such as those from chemicals. While our studies focused on microbial contamination, we did not measure or hypothesize about the presence of chemical contaminants such as arsenic, nitrates, pharmaceuticals or pesticides. It is predicted that changes in climate will also affect chemical exposure— such as altering groundwater levels, flooding, and surface water runoff— which emphasizes the importance of future research assessing chemical contaminants. Considering chemicals have similar exposure pathway and health effects to microbial contaminants, understanding their relationship with climate and WASH infrastructure would benefit from integration in future study designs though would require a different methodological approach which was outside of our capacity in all three studies.

A third consideration relates to the risk of identifying statistically significant associations due to multiple hypothesis testing. Given the sheer number of exposures (e.g., rainfall, temperature, water source) and outcomes (e.g., *E. coli*, diarrhea, ARIs, stress levels) explored across these studies, there is an inherent possibility that some significant findings may have arisen by chance. While each analysis was guided by theory and prior evidence, and sensitivity analyses were conducted where possible, the risk of conducting a type I error remains. Therefore, our findings—especially those from our exploratory sensitivity analyses—should be interpreted carefully, in context.

In terms of methodological design, two of the three studies – chapters one and three – were observational, and therefore are subject to potential confounding bias. Despite efforts to adjust for known confounders, residual confounding remains a possibility—especially given the complexity of household behaviors, environmental variability, and social determinants that influence health outcomes. These limitations highlight the value of mixed-methods, longitudinal, and experimental approaches in future research to strengthen causal inference.

Despite the aforementioned challenges, the dissertation produced several key takeaways. Climate variability influences contamination risk - both heavy rainfall and dry periods were associated with increased *E. coli* contamination, reflecting distinct environmental mechanisms like runoff from contaminated areas and stagnation in stored water. Infrastructure quality and behavior matter in WASH interventions - the type and reliability of water sources, storage practices, and sanitation infrastructure all played a role in moderating contamination risks—especially during extreme weather. Sanitation interventions can be resilient - while weather influenced contamination risk, sanitation interventions still provided significant, measurable reductions in environmental contamination. Water intermittency exacerbates health vulnerabilities -an intermittent water supply disrupted hygiene behaviors, was associated with higher risk of child illnesses, and contributed to psychosocial stress among caregivers.

These findings offer practical implications for public health, water resource management, and future climate adaptation efforts. They support the need for integrated, climate-resilient WASH interventions that are grounded in local environmental realities and behavioral patterns. They also underline the value of improving both physical infrastructure and social support systems—especially for caregivers navigating chronic water stress.

This dissertation emphasizes that climate-resilient health strategies must be interdisciplinary, incorporating environmental science, sociology, psychology and behavioral research, engineering, and public health. Addressing microbial contamination is critical—but so is expanding the scope of this work to include chemical exposures, mental health outcomes, and broader sources of vulnerability. By understanding how climate, infrastructure, and human behavior intersect, we can better protect the health of those most vulnerable and at risk in this changing world.

APPENDICES

Appendix A

Table S1. *E. coli* reporting units and detection limits by sample type

	Unit	Lower Limit (MPN)	Upper Limit (MPN)
Stored water	100 mL	1	2419.6
Food	1 dry gram	1–2 [a]	2,494 – 48,392 [a]
Mother hands	2 hands	5	12,098
Child hands	2 hands	5	12,098
Source water	100 mL	1	2,419.6
Soil	1 dry gram	1,000–1887 [b]	2.42×10^6– 4.56×10^6 [b]
Ponds	100 mL	100	241,960
Flies	1 fly	100	241,960

[a] Given a food moisture content range of 3-95%, a lower limit of 1 MPN and upper limit of 2,419·6 MPN per wet gram

[b] Given a soil moisture content range of 0-47%, a lower limit of 1,000 MPN and upper limit of 2,419,600 per wet gram

Table S2. Number of samples collected by sample type and study round

Round	Round 1	Round 2	Round 3	Round 4	Round 5	Round 6	Round 7	Round 8	Round 9	Total
Stored water	1623	641	592	571	599	581	582	574	587	6350
Food	1646	0	0	329	206	0	0	0	0	2181
Mother hands	0	720	705	684	682	668	662	643	633	5397
Child hands	1768	720	705	682	673	653	650	626	615	7092
Source water	1669	0	0	0	0	0	0	0	0	1669
Soil	1795	0	0	402	341	0	0	0	0	2538
Ponds	822	0	0	0	0	0	0	0	0	822
Flies	610	0	0	0	0	0	0	0	0	610
Total	9933	2081	2002	2668	2501	1902	1894	1843	1835	26659

Text S1. Sample collection and processing details

Stored drinking water was collected by asking the participant to provide a glass of water from their storage container, meant for children under five, and approximately 150 mL was poured into a sterile Whirlpak bag. Hand rinse samples were taken from index children - those born to women pregnant at enrollment - or the youngest available child under five, and their mothers. Each hand was placed into a sterile Whirlpak bag prefilled with 250 mL of distilled water, massaged from the outside for 15 seconds, shaken for 15 seconds, and then repeated for the other hand. Soil samples were collected from a 30 cm x 30 cm area in the courtyard near the household entrance. A sterile plastic scoop was used to scrape around 50 g from the top layer of soil into a sterile Whirlpak bag. Stored food samples were collected by asking participants to provide a small amount of food as they would for children under five, which was scooped into a 50 mL sterile tube using a sterile spoon. Tubewell water was collected by removing attached materials from the mouth, flushing the tubewell via pumping five times, and collecting 250 mL. Pond water was collected by submerging a Whirlpak bag into the pond at the household's usual access point to collect 250 mL. Sticky fly tape strips were hung in the food preparation area for 3-6 hours for fly collection. One fly was removed using sterile tweezers and placed into a Whirlpak bag. Clean gloves were worn during all sample collections, and quality control procedures included 10% field blanks and duplicates. Samples were placed on ice and transported to the field laboratory at the International Centre for Diarrhoeal Disease Research, Bangladesh (icddr,b), for processing within 24 hours of collection using IDEXX Quanti-Tray/2000. Stored drinking water was analyzed in 100 mL undiluted aliquots and hand rinses were diluted to 50 mL with 50 mL of distilled water. 20 grams of soil was homogenized with 200 mL distilled water and then diluted to create a 100 mL aliquot. Another 5 g of soil was reserved to determine moisture content by oven-drying at 110 °C for 24 hours. Stored food samples were homogenized by mixing 10 g of food with 100 mL of distilled water and then diluted 1:10. Moisture content for food was carried out in the same manner as for soil. Fly samples were homogenized by mixing with 100 mL of distilled water and diluted 1:100. *E. coli* were enumerated using the most probable number (MPN) method after incubating for 18 hours with Colilert-18 media at 44.5 °C.

Table S3. Number of study observations and geometric mean *E. coli* counts by sample type for each weather category[a] across different antecedent timeframes

	Stored Water (N=6350)		Food (N=2181)		Mother Hands (N = 5397)		Child Hands (N= 7092)		Source Water (N=1669)		Soil (N=2538)		Ponds (N=822)		Flies (N=610)	
	% (n)	Geometric Mean (SD)	% (n)	Geometric Mean (SD)	% (n)	Geometric Mean (SD)	% (n)	Geometric Mean (SD)	% (n)	Geometric Mean (SD)	% (n)	Geometric Mean (SD)	% (n)	Geometric Mean (SD)	% (n)	Geometric Mean (SD)
Day of																
No Rain	52.8% (3356)	5.31 (9.95)	49.4% (1078)	1.63 (14.94)	49.2% (2656)	31.93 (9.88)	52.3% (3706)	18.66 (9.24)	62.1% (1037)	0.82 (3.90)	48% (1218)	121285.80 (13.56)	75.9% (624)	4994.44 (5.84)	56.2% (343)	432.50 (19.49)
Some Rain	37.8% (2401)	10.81 (12.10)	40.4% (881)	11.81 (27.62)	39.8% (2146)	25.17 (9.75)	38.4% (2722)	22.41 (10.34)	33.6% (560)	1.10 (4.86)	41.8% (1062)	139114.00 (10.22)	19.1% (157)	4837.13 (6.78)	39.2% (239)	1429.36 (23.52)
Heavy Rain	4.3% (270)	14.77 (12.61)	5.2% (114)	41.18 (23.45)	4.9% (267)	35.71 (12.90)	4.4% (313)	24.14 (9.87)	2.8% (47)	1.54 (9.10)	5.2% (133)	111340.10 (9.58)	3.4% (28)	27879.14 (4.44)	2.6% (16)	1544.76 (40.20)
Extreme Rain	5.1% (323)	21.60 (11.20)	5% (108)	30.68 (26.77)	6.1% (328)	36.99 (9.26)	4.9% (351)	24.72 (8.91)	1.5% (25)	1.52 (5.24)	4.9% (125)	77025.78 (7.58)	1.6% (13)	24471.59 (6.32)	2% (12)	369.71 (10.10)
Below Median Temp	52.7% (3345)	5.70 (10.29)	62.5% (1363)	2.09 (17.52)	43.7% (2360)	32.88 (9.80)	52.5% (3721)	17.68 (9.19)	79.1% (1320)	0.90 (4.29)	61.5% (1562)	138924.20 (11.58)	90.5% (744)	5550.86 (6.09)	74.4% (454)	579.08 (21.60)
Above Median Temp	38.4% (2442)	11.30 (12.25)	32.2% (703)	19.48 (28.02)	44.2% (2384)	27.23 (9.94)	38.3% (2719)	23.39 (10.23)	20.7% (346)	1.06 (4.79)	33% (838)	97628.63 (10.68)	9.1% (75)	4420.02 (7.12)	25.1% (153)	1337.50 (22.90)
Extreme Temp	8.9% (563)	9.96 (10.96)	5.3% (115)	32.96 (19.41)	12.1% (653)	26.47 (10.51)	9.2% (652)	28.07 (9.76)	0.2% (3)	0.50 (1.00)	5.4% (138)	170818.30 (16.90)	0.4% (3)	761.89 (1.66)	0.5% (3)	304.56 (22.86)
1 Day																
No Rain	45.5% (2888)	4.88 (9.59)	44.8% (978)	1.36 (13.63)	40.9% (2206)	32.58 (9.72)	45.1% (3196)	18.30 (9.33)	58% (968)	0.82 (3.90)	42.9% (1089)	112160.30 (14.03)	70.5% (580)	4893.64 (6.06)	51% (311)	408.03 (18.17)
Some Rain	39.6% (2514)	10.22 (12.26)	39.5% (861)	10.21 (26.57)	41.7% (2252)	24.99 (9.69)	39.8% (2824)	22.32 (10.09)	33.9% (566)	1.07 (4.90)	40.7% (1033)	159589.20 (10.04)	21.8% (179)	5288.68 (5.82)	42.3% (258)	1419.65 (25.28)
Heavy Rain	7% (446)	11.47 (10.91)	8.2% (179)	28.51 (23.57)	8% (432)	28.96 (11.54)	7.2% (512)	21.62 (9.81)	4.9% (81)	1.29 (7.07)	8.2% (207)	121600.30 (11.03)	5.4% (44)	13847.16 (6.23)	3.8% (23)	802.28 (30.00)
Extreme Rain	7.9% (502)	21.15 (11.36)	7.5% (163)	38.26 (25.58)	9.4% (507)	40.22 (10.46)	7.9% (560)	24.83 (9.35)	3.2% (54)	1.17 (3.82)	8.2% (209)	67865.91 (7.23)	2.3% (19)	14685.42 (9.01)	2.9% (18)	468.43 (12.00)
Below Median Temp	48.3% (3065)	5.42 (10.12)	57.2% (1247)	1.82 (14.43)	39.2% (2118)	32.35 (9.58)	47.9% (3396)	17.51 (9.12)	74.5% (1243)	0.90 (4.27)	60% (1421)	137132.80 (12.01)	88.2% (725)	5526.74 (6.10)	70.7% (431)	551.34 (20.99)
Above Median Temp	39.9% (2537)	11.33 (12.13)	35.7% (778)	17.73 (30.44)	45% (2426)	28.61 (10.22)	40.1% (2844)	23.04 (10.32)	25.2% (420)	1.04 (4.80)	36.6% (930)	107046.10 (10.09)	11.3% (93)	4989.69 (6.64)	28.4% (173)	1385.66 (23.97)
Extreme Temp	11.8% (748)	9.71 (11.40)	7.1% (156)	26.66 (19.32)	15.8% (853)	25.56 (10.15)	12% (852)	26.35 (9.49)	0.3% (6)	0.50 (1.00)	7.4% (187)	134374.80 (16.45)	0.5% (4)	458.58 (2.99)	0.9% (6)	316.42 (17.45)
2 Days																
No Rain	41.8% (2655)	4.79 (9.51)	43.5% (950)	1.30 (13.33)	36.5% (1971)	33.18 (9.72)	41.5% (2945)	17.58 (9.21)	56.9% (949)	0.82 (3.90)	41.5% (1054)	112622.60 (14.14)	68.2% (561)	4715.59 (6.06)	50% (305)	389.66 (17.36)
Some Rain	38.3% (2430)	9.73 (12.24)	33.7% (735)	9.83 (26.93)	41.4% (2234)	24.82 (9.72)	38.2% (2712)	23.95 (10.25)	28.3% (473)	1.09 (4.94)	35.1% (892)	152067.20 (10.67)	18.9% (155)	5134.47 (5.84)	35.2% (215)	1325.16 (23.41)
Heavy Rain	8.9% (563)	11.47 (11.28)	10.7% (233)	23.75 (22.31)	9.3% (502)	30.18 (11.73)	8.9% (630)	18.94 (9.39)	7.7% (128)	1.02 (5.28)	10.6% (268)	150455.00 (10.22)	8.5% (70)	11793.15 (6.45)	7.2% (44)	898.60 (34.03)
Extreme Rain	11.1% (702)	16.70 (11.52)	12.1% (263)	23.29 (27.78)	12.8% (690)	36.04 (9.89)	11.4% (805)	22.98 (9.45)	7.1% (119)	1.20 (5.03)	12.8% (324)	88017.53 (7.50)	4.4% (36)	12008.60 (5.99)	7.5% (46)	1704.53 (27.98)
Below Median Temp	46.3% (2940)	5.32 (10.11)	54.6% (1192)	1.71 (14.84)	37.6% (2027)	32.31 (9.46)	45.9% (3258)	17.26 (9.10)	71.7% (1197)	0.85 (4.01)	53.4% (1355)	134851.00 (12.33)	87.1% (716)	5586.98 (6.10)	67.5% (412)	529.80 (20.71)
Above Median Temp	39.9% (2533)	11.18 (12.02)	36.2% (789)	16.67 (30.30)	44.1% (2382)	29.02 (10.36)	40% (2839)	23.35 (10.33)	27.4% (457)	1.18 (5.42)	37.3% (947)	112930.10 (9.66)	12.3% (101)	4643.53 (6.57)	30.3% (185)	1311.68 (23.92)
Extreme Temp	13.8% (877)	9.93 (11.50)	9.2% (200)	23.94 (21.45)	18.3% (988)	25.34 (10.00)	14% (995)	25.13 (9.47)	0.9% (15)	0.64 (2.55)	9.3% (236)	122036.30 (16.00)	0.6% (5)	803.87 (4.82)	2.1% (13)	1406.45 (26.72)
7 Days																
No Rain	31.3% (1989)	4.31 (9.35)	38.8% (847)	1.23 (13.08)	24.7% (1332)	33.58 (9.94)	31.3% (2217)	15.17 (8.93)	51.7% (862)	0.83 (4.02)	36.6% (929)	109019.50 (14.39)	61.6% (506)	4740.81 (6.21)	44% (268)	386.05 (17.94)
Some Rain	34.9% (2216)	8.33 (11.11)	20.3% (442)	6.73 (24.62)	41% (2212)	27.46 (9.76)	34.8% (2467)	25.35 (9.63)	16% (267)	0.93 (4.58)	23.2% (589)	149509.50 (13.03)	13.6% (112)	4887.53 (5.28)	19.3% (118)	729.95 (19.88)
Heavy Rain	12% (763)	13.28 (12.47)	13.8% (300)	20.18 (22.61)	12.1% (655)	29.19 (11.24)	11.9% (842)	19.55 (10.06)	11% (184)	0.95 (4.37)	13.7% (348)	130922.60 (11.03)	12.3% (101)	9288.00 (6.31)	10% (61)	897.81 (21.09)
Extreme Rain	21.8% (1382)	12.27 (12.12)	27.1% (592)	14.35 (29.24)	22.2% (1198)	29.21 (9.67)	22.1% (1566)	23.23 (10.25)	21.3% (356)	1.20 (5.09)	26.5% (672)	126208.70 (7.50)	12.5% (103)	6677.73 (6.38)	26.7% (163)	1755.19 (28.13)
Below Median Temp	42.4% (2691)	4.90 (9.77)	51.4% (1120)	1.58 (14.39)	33.6% (1813)	32.35 (9.31)	41.9% (2972)	16.66 (8.94)	67.5% (1126)	0.83 (3.93)	49.9% (1267)	131726.60 (12.86)	82.2% (676)	5538.48 (6.03)	60.3% (368)	467.07 (19.83)
Above Median Temp	37.8% (2400)	10.80 (12.04)	34.8% (759)	13.03 (29.78)	40% (2158)	30.12 (10.37)	37.9% (2691)	23.51 (10.57)	31.6% (528)	1.19 (5.36)	35.8% (908)	128507.50 (9.14)	17.2% (141)	5102.58 (6.80)	37.5% (229)	1349.39 (23.96)
Extreme Temp	19.8% (1259)	11.28 (11.67)	13.8% (302)	30.69 (21.65)	26.4% (1426)	25.33 (10.15)	20.1% (1429)	24.58 (9.33)	0.9% (15)	0.64 (2.55)	14.3% (363)	97396.32 (13.89)	0.6% (5)	803.87 (4.82)	2.1% (13)	1406.45 (26.72)
No Heatwave	90.6% (5751)	7.63 (11.29)	93% (2028)	4.43 (25.44)	86.9% (4689)	30.99 (10.03)	90.1% (6392)	20.42 (9.76)	100% (1669)	0.93 (4.40)	92.5% (2347)	134597.40 (11.23)	100% (822)	5397.41 (6.18)	100% (610)	712.12 (22.30)
Heatwave	9.4% (599)	9.64 (11.64)	7% (153)	22.37 (14.93)	13.1% (708)	21.11 (9.25)	9.9% (700)	21.65 (9.01)	0% (0)	[b]	7.5% (191)	50619.76 (14.25)	0% (0)	[b]	0% (0)	[b]
14 Days																
No Rain	18.8% (1195)	4.19 (9.63)	23.4% (511)	1.05 (12.29)	14.5% (783)	35.88 (9.71)	18.8% (1334)	14.70 (8.75)	32.5% (543)	0.89 (4.59)	22.7% (576)	89903.28 (15.62)	37% (304)	4239.19 (6.50)	25.7% (157)	410.14 (19.49)
Some Rain	34.1% (2164)	6.35 (10.19)	19.1% (416)	2.06 (17.50)	38.5% (2076)	28.32 (9.78)	33.8% (2396)	23.42 (9.31)	20.5% (342)	0.73 (2.97)	20.7% (525)	142281.80 (13.69)	24.3% (200)	4693.61 (6.00)	20.7% (126)	359.45 (16.39)
Heavy Rain	14.7% (934)	10.00 (11.60)	19.8% (432)	9.28 (22.45)	13.1% (706)	26.88 (10.55)	14.5% (1027)	18.53 (10.72)	18.5% (308)	0.89 (3.98)	19.3% (491)	117548.00 (12.02)	19.7% (162)	8391.78 (5.69)	17.7% (108)	672.08 (18.97)
Extreme Rain	32.4% (2057)	12.40 (12.34)	37.7% (822)	14.67 (28.63)	33.9% (1832)	29.37 (10.03)	32.9% (2335)	22.73 (9.99)	28.5% (476)	1.21 (5.41)	37.3% (946)	146942.20 (8.18)	19% (156)	6536.77 (5.81)	35.9% (219)	1612.75 (26.41)
Below Median Temp	38.7% (2458)	4.67 (9.72)	49.7% (1083)	1.51 (14.10)	29.5% (1590)	32.37 (9.18)	38.3% (2714)	15.99 (8.94)	65.5% (1093)	0.82 (3.94)	47.5% (1205)	125198.60 (13.20)	78.8% (648)	5333.28 (6.03)	58.7% (358)	477.95 (19.88)
Above Median Temp	34.3% (2176)	10.63 (11.81)	28.6% (624)	9.38 (27.31)	36.4% (1966)	32.89 (10.60)	34.3% (2433)	23.40 (10.44)	27.5% (459)	1.25 (5.33)	30.6% (776)	137487.90 (9.19)	16.8% (138)	5539.64 (6.51)	33.6% (205)	1043.56 (22.58)
Extreme Temp	27% (1716)	10.96 (11.74)	21.7% (474)	32.72 (24.55)	34.1% (1841)	24.17 (9.87)	27.4% (1945)	23.47 (9.54)	7.0% (117)	0.89 (4.55)	21.9% (557)	109283.10 (11.79)	4.4% (36)	6057.94 (8.14)	7.7% (47)	2803.68 (29.01)
No Heatwave	87.8% (5576)	7.57 (11.27)	91.6% (1997)	4.29 (25.22)	83.2% (4490)	31.41 (10.04)	87.4% (6195)	20.34 (9.75)	100% (1669)	0.93 (4.40)	90.9% (2308)	135931.00 (11.21)	100% (822)	5397.41 (6.18)	100% (610)	712.12 (22.30)
Heatwave	12.2% (774)	9.64 (11.71)	8.4% (184)	24.24 (16.06)	16.8% (907)	21.49 (9.37)	12.6% (897)	21.91 (9.27)	0% (0)	[b]	9.1% (230)	54121.62 (13.77)	0% (0)	[b]	0% (0)	[b]

[a] Weather classifications are as follows: no rain (0 mm), some rain (<16·4 mm), heavy rain (≥16·4 and <28·2 mm), extreme rain (≥28·2 mm), below-median temperature (<27·1˚C), above-median temperature (≥27·1 and <30·2˚C), extreme temperature (≥ 30·2˚C), no heatwave (<30·9˚C), heatwave (≥ 30·9˚C for 3 consecutive days).

[b] We could not estimate effects of heatwaves on source water (tubewells), ponds and flies due to data sparsity.

Table S4. **Percentages of study observations within each weather category[a] across different antecedent timeframes. Study observation refers to unique combinations of household GPS coordinates and sample collection dates (total n=7253)**

	0 Days	**1 Day**	**2 Days**	**7 Days**	**14 Days**
No Rain	52.4% (3803)	45.1% (3274)	41.6% (3014)	31.3% (2270)	18.8% (1361)
Some Rain	38.2% (2773)	39.8% (2888)	38.3% (2776)	34.8% (2525)	34% (2468)
Heavy Rain	4.4% (319)	7.2% (521)	8.8% (641)	11.8% (858)	14.5% (1051)
Extreme Rain	4.9% (358)	7.9% (570)	11.3% (822)	22.1% (1600)	32.7% (2373)
Below Median Temp	52.6% (3812)	48.0% (3483)	46.1% (3344)	42.1% (3051)	38.4% (2785)
Above Median Temp	38.3% (2778)	40.0% (2903)	39.9% (2896)	37.9% (2748)	34.3% (2486)
Extreme Temp	9.1% (663)	12.0% (867)	14.0% (1013)	20.0% (1454)	27.3% (1982)
No Heatwave	--	--	--	90.2% (6543)	87.5% (6343)
Heatwave	--	--	--	9.8% (710)	12.5% (910)

[a] Weather classifications are as follows: no rain (0 mm), some rain (<16·4 mm), heavy rain (≥16·4 and <28·2 mm), extreme rain (≥28·2 mm), below-median temperature (<27·1˚C), above-median temperature (≥27·1 and <30·2˚C), extreme temperature (≥ 30·2˚C), no heatwave (<30·9˚C), heatwave (≥ 30·9˚C for 3 consecutive days).

Figure S1. Daily precipitation and temperature, and monthly mean most probable number (MPN) of *E. coli* by sample type across the study period

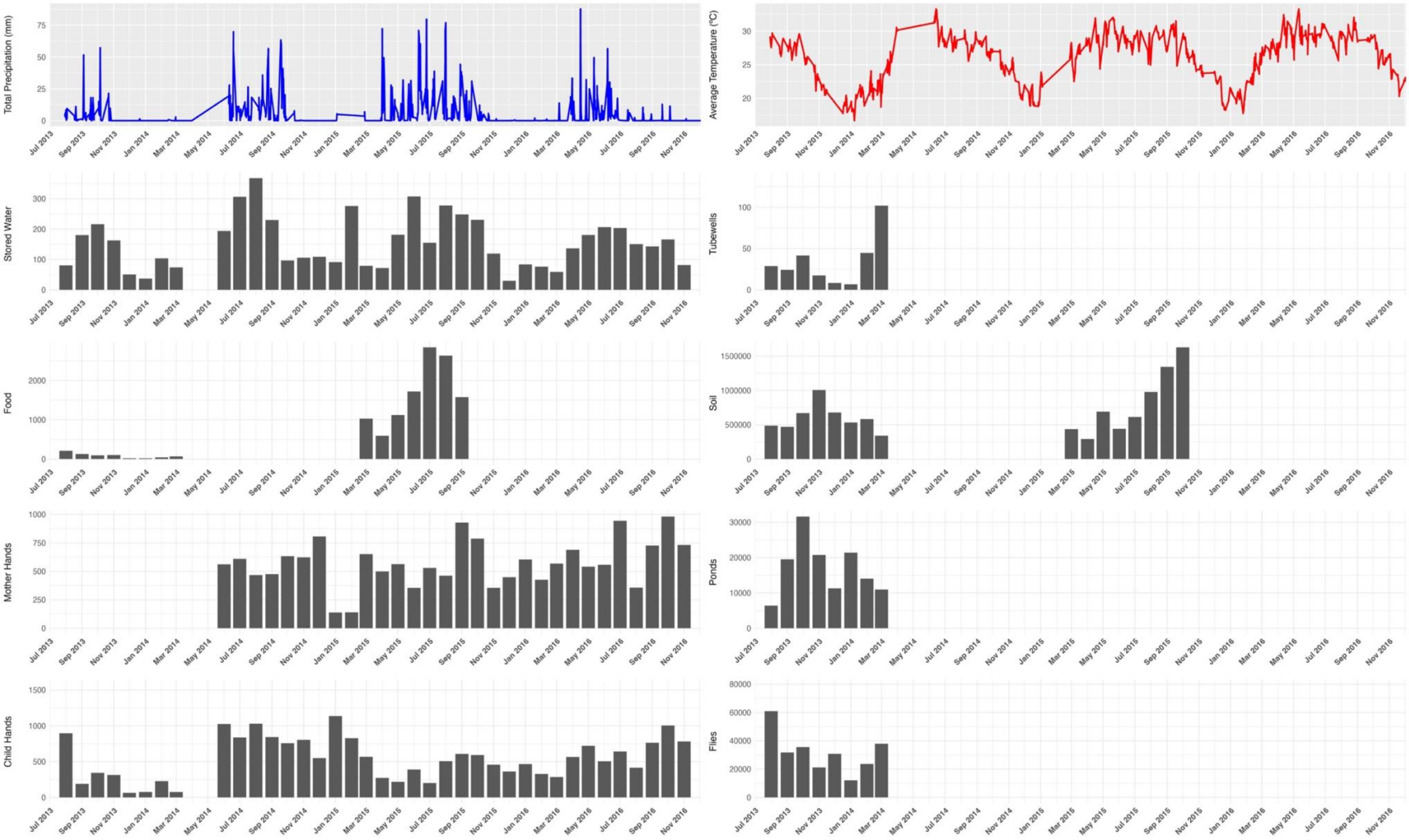


Figure S2. Adjusted generalized additive model plot of *E. coli* counts on child hands vs. continuous rainfall and temperature on the day of sample collection. The red dashed line corresponds to the 90th percentile (28·2 mm) for rainfall plots, and (30·2ºC) for temperature plots.

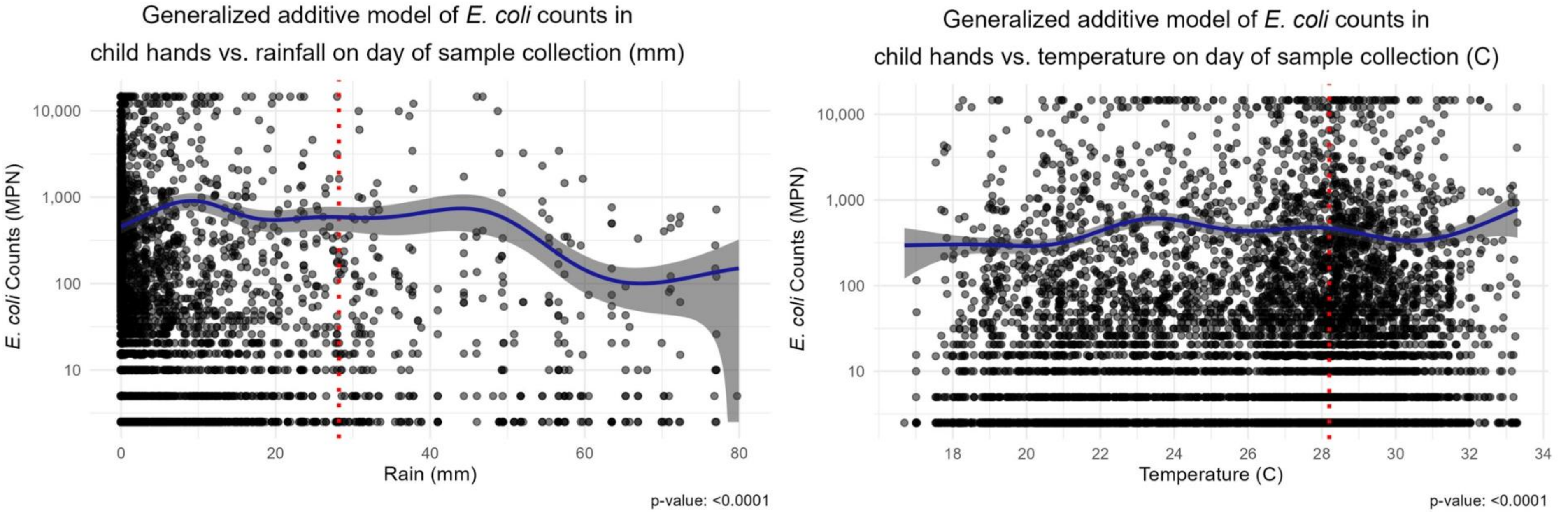


Figure S3. Adjusted generalized additive model plot of *E. coli* counts on mother hands vs. continuous rainfall and temperature on the day of sample collection. The red dashed line corresponds to the 90th percentile (28·2 mm) for rainfall plots, and (30·2ºC) for temperature plots.

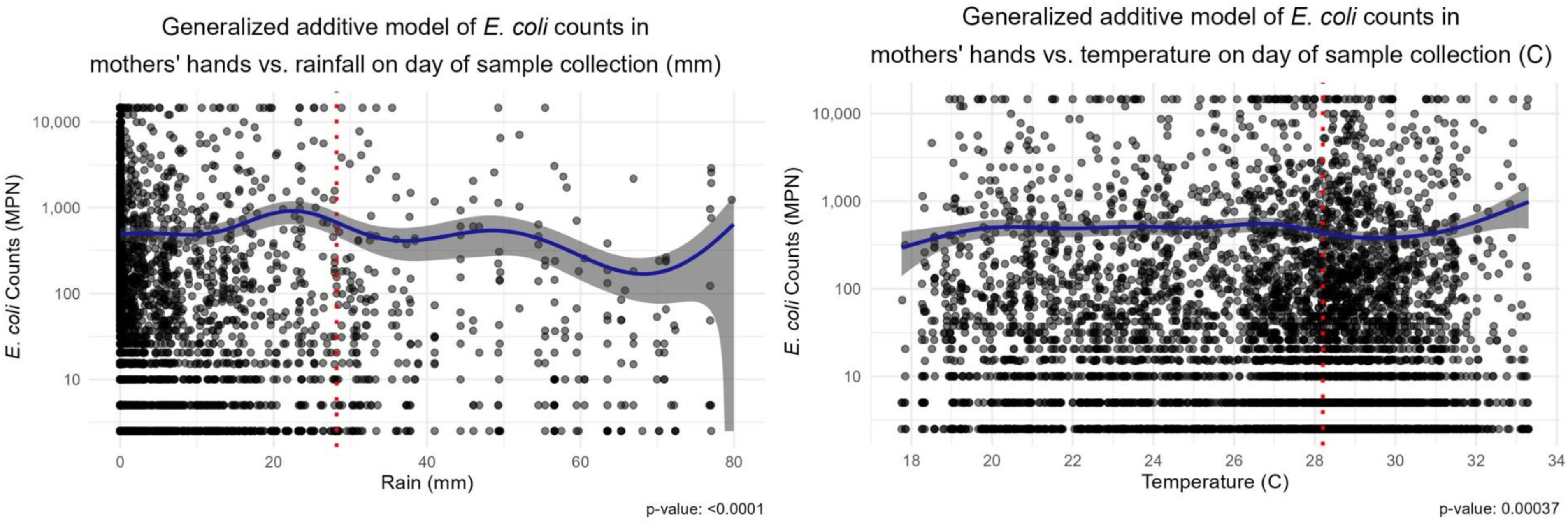
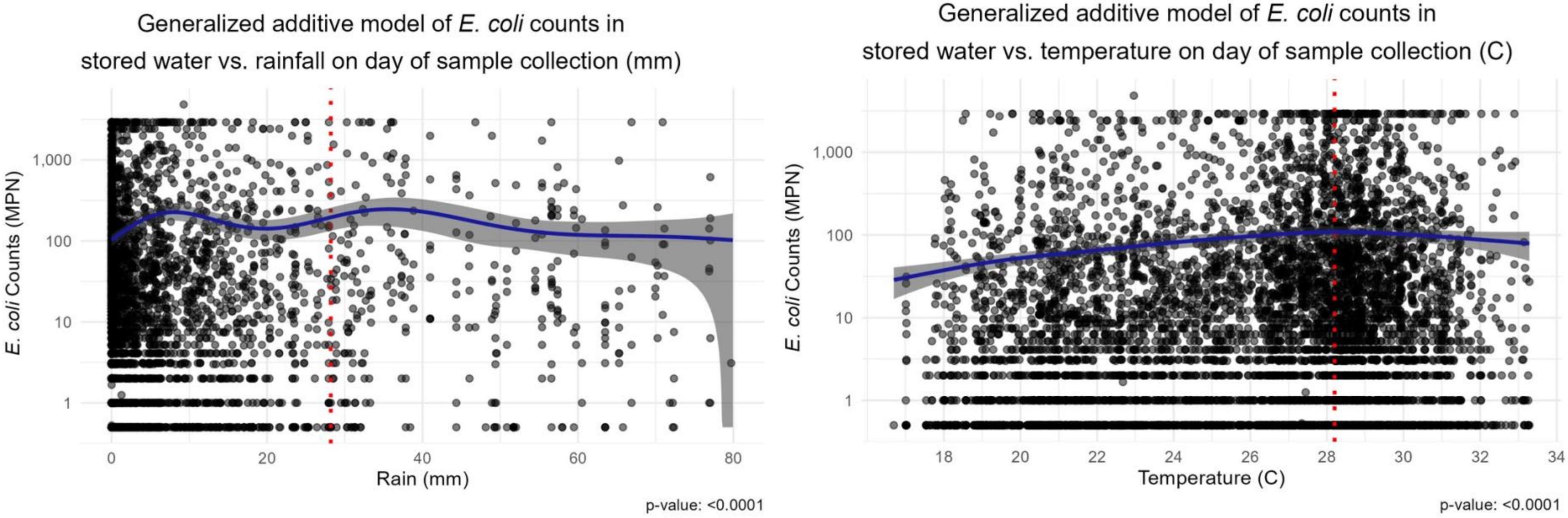


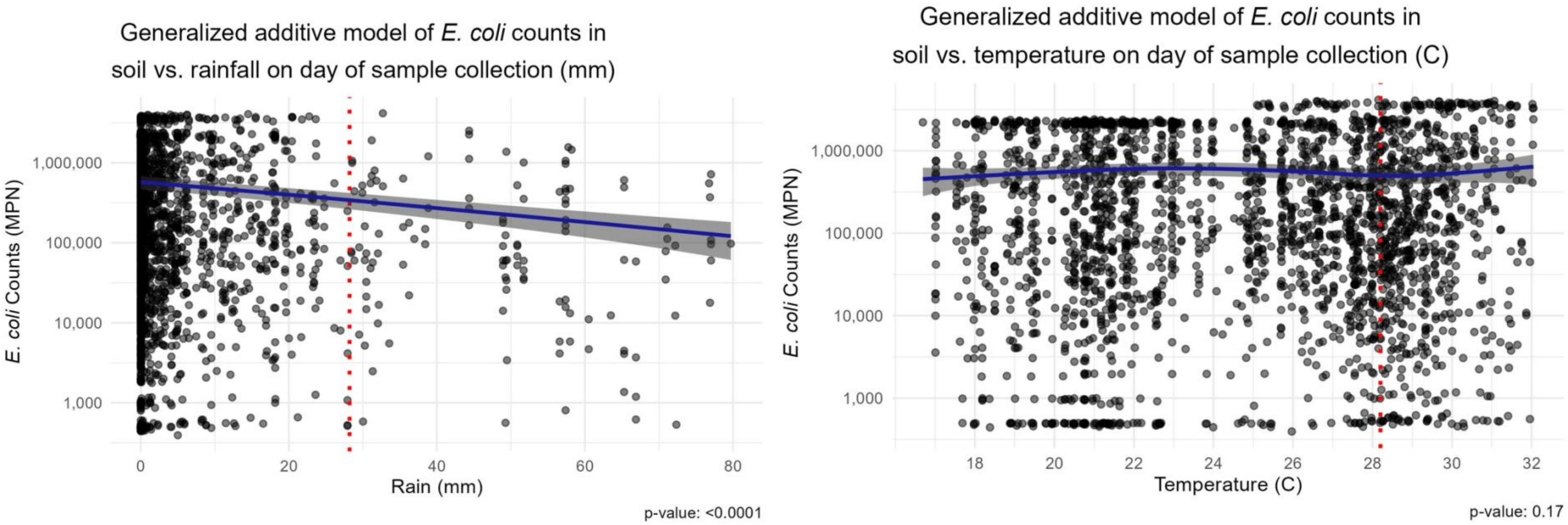
Figure S4. Adjusted generalized additive model plot of *E. coli* counts in stored water vs. continuous rainfall and temperature on the day of sample collection. The red dashed line corresponds to the 90th percentile (28·2 mm) for rainfall plots, and (30·2ºC) for temperature plots.



Generalized additive model of *E. coli* counts in stored water vs. rainfall on day of sample collection (mm)

Generalized additive model of *E. coli* counts in stored water vs. temperature on day of sample collection (C)

Figure S5. Adjusted generalized additive model plot of *E. coli* counts in soil vs. continuous rainfall and temperature on the day of sample collection. The red dashed line corresponds to the 90th percentile (28·2 mm) for rainfall plots, and (30·2ºC) for temperature plots.



Generalized additive model of *E. coli* counts in soil vs. rainfall on day of sample collection (mm)

Generalized additive model of *E. coli* counts in soil vs. temperature on day of sample collection (C)

Figure S6. Adjusted generalized additive model plot of *E. coli* counts in food vs. continuous rainfall and temperature on the day of sample collection. The red dashed line corresponds to the 90th percentile (28·2 mm) for rainfall plots, and (30·2ºC) for temperature plots.

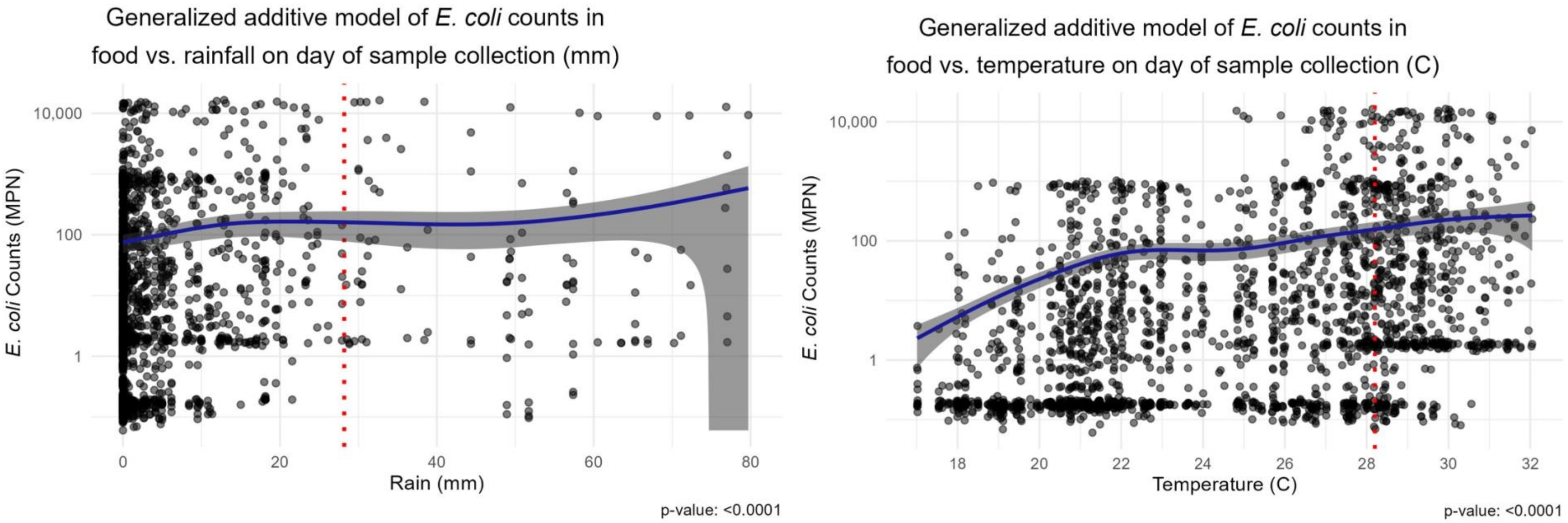
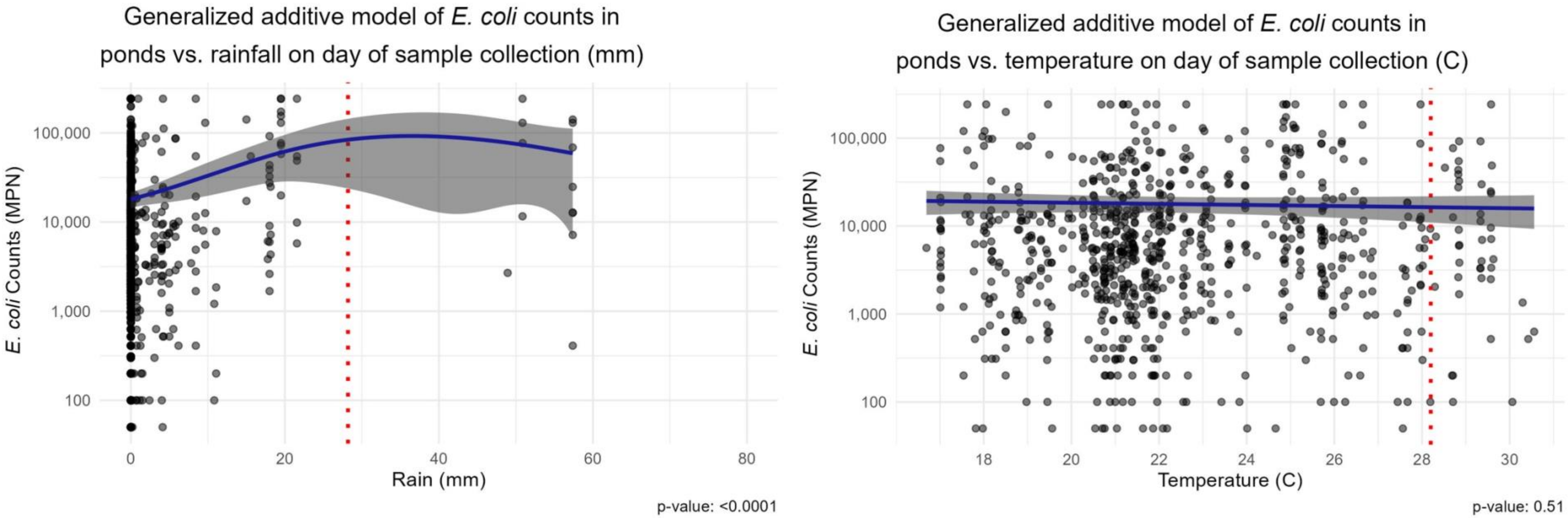


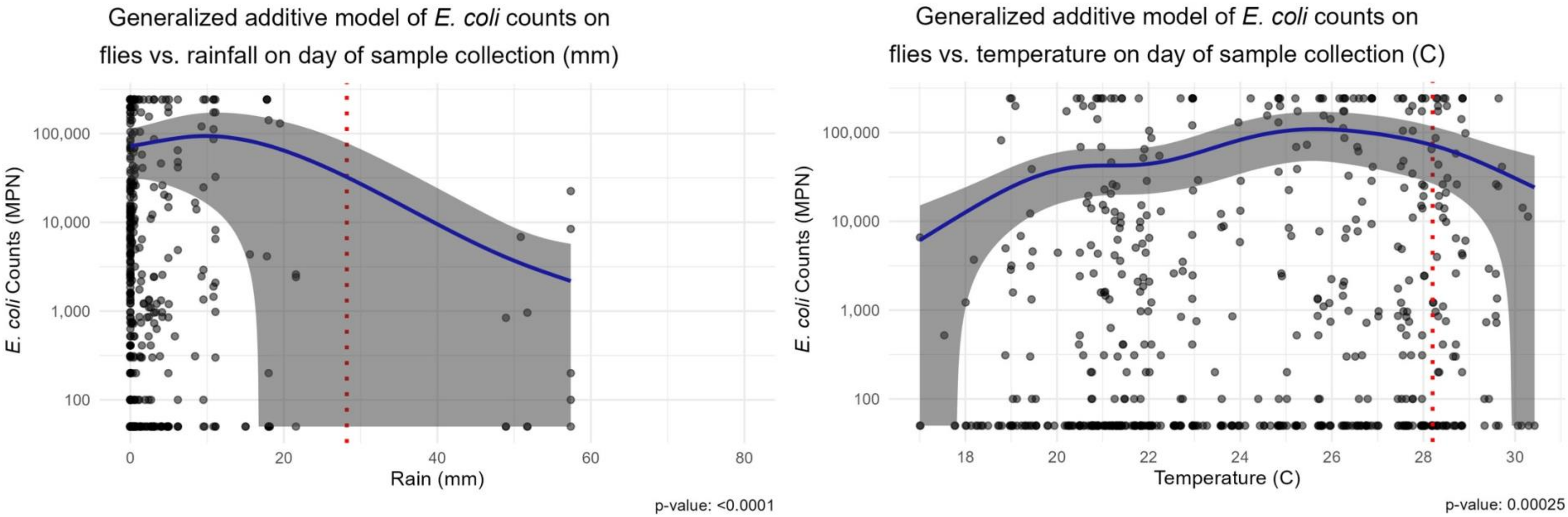
Figure S7. Adjusted generalized additive model plot of *E. coli* counts in ponds vs. continuous rainfall and temperature on the day of sample collection. The red dashed line corresponds to the 90th percentile (28·2 mm) for rainfall plots, and (30·2ºC) for temperature plots.



Generalized additive model of *E. coli* counts in ponds vs. rainfall on day of sample collection (mm)

Generalized additive model of *E. coli* counts in ponds vs. temperature on day of sample collection (C)

Figure S8. Adjusted generalized additive model plot of *E. coli* counts in/on flies vs. continuous rainfall and temperature on the day of sample collection. The red dashed line corresponds to the 90th percentile (28·2 mm) for rainfall plots, and (30·2ºC) for temperature plots.



Generalized additive model of *E. coli* counts on flies vs. rainfall on day of sample collection (mm)

Generalized additive model of *E. coli* counts on flies vs. temperature on day of sample collection (C)

Figure S9. Adjusted generalized additive model plot of *E. coli* counts in tubewell water vs. continuous rainfall and temperature on the day of sample collection. The red dashed line corresponds to the 90th percentile (28·2 mm) for rainfall plots, and (30·2ºC) for temperature plots.

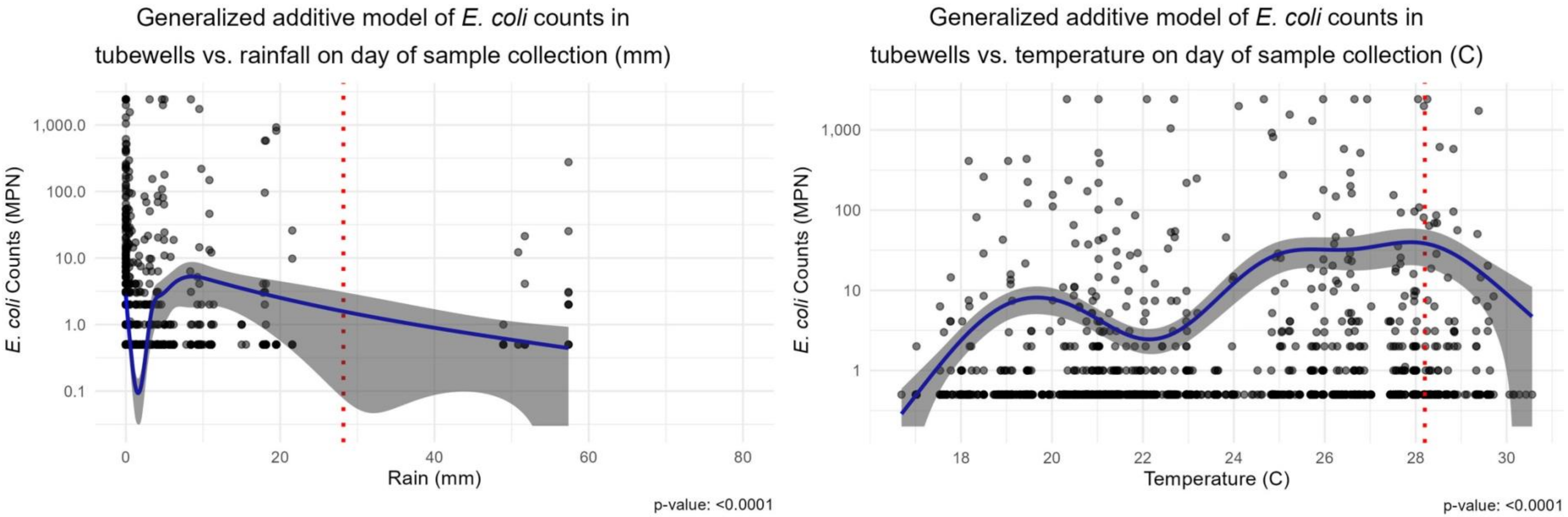


Figure S10. Adjusted *E. coli* count ratios associated with deciles of rain, compared to no rain, on the day of sampling

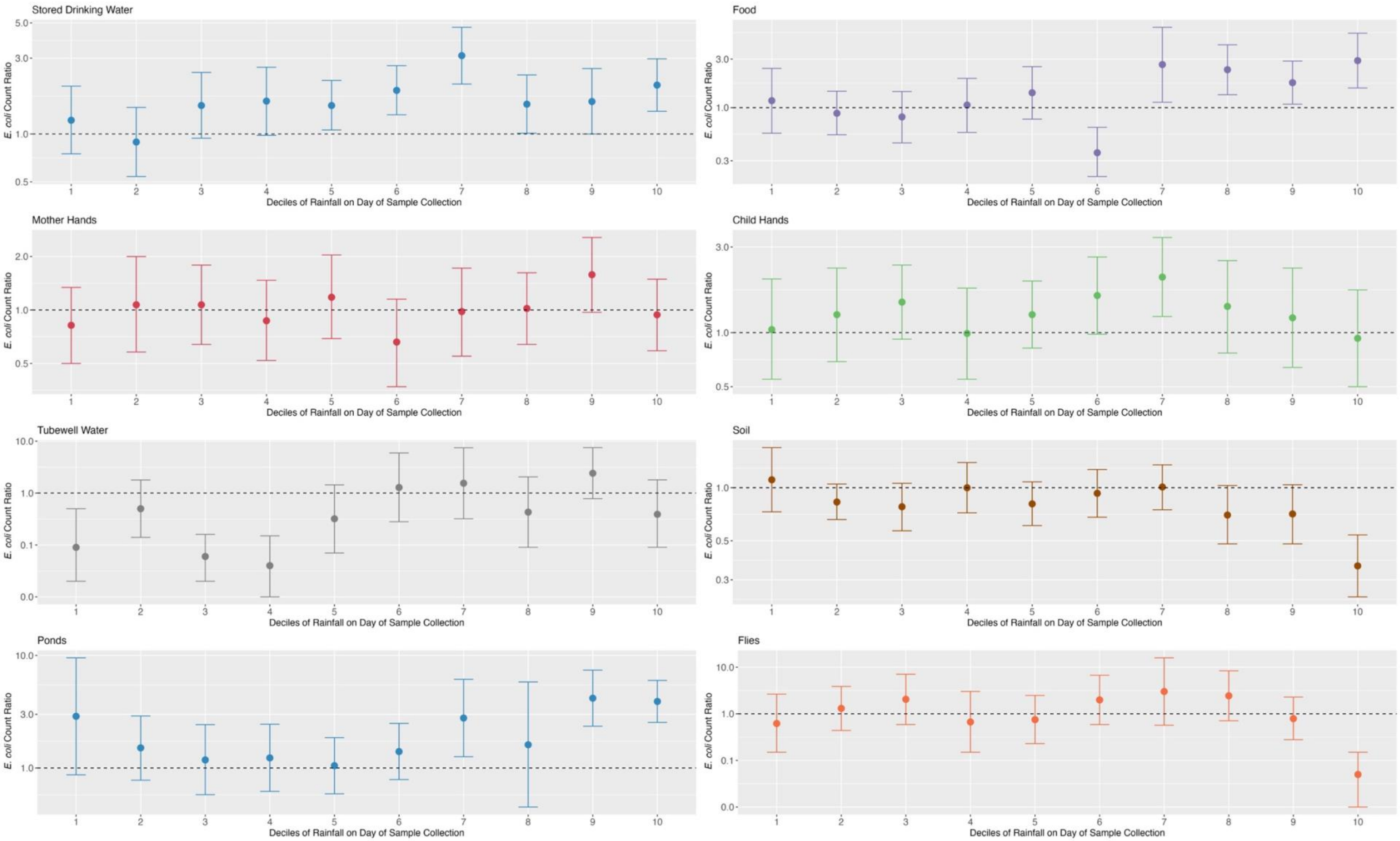


Figure S11. Adjusted *E. coli* count ratios associated with deciles of temperature, compared to 1st decile of temperature, on the day of sampling

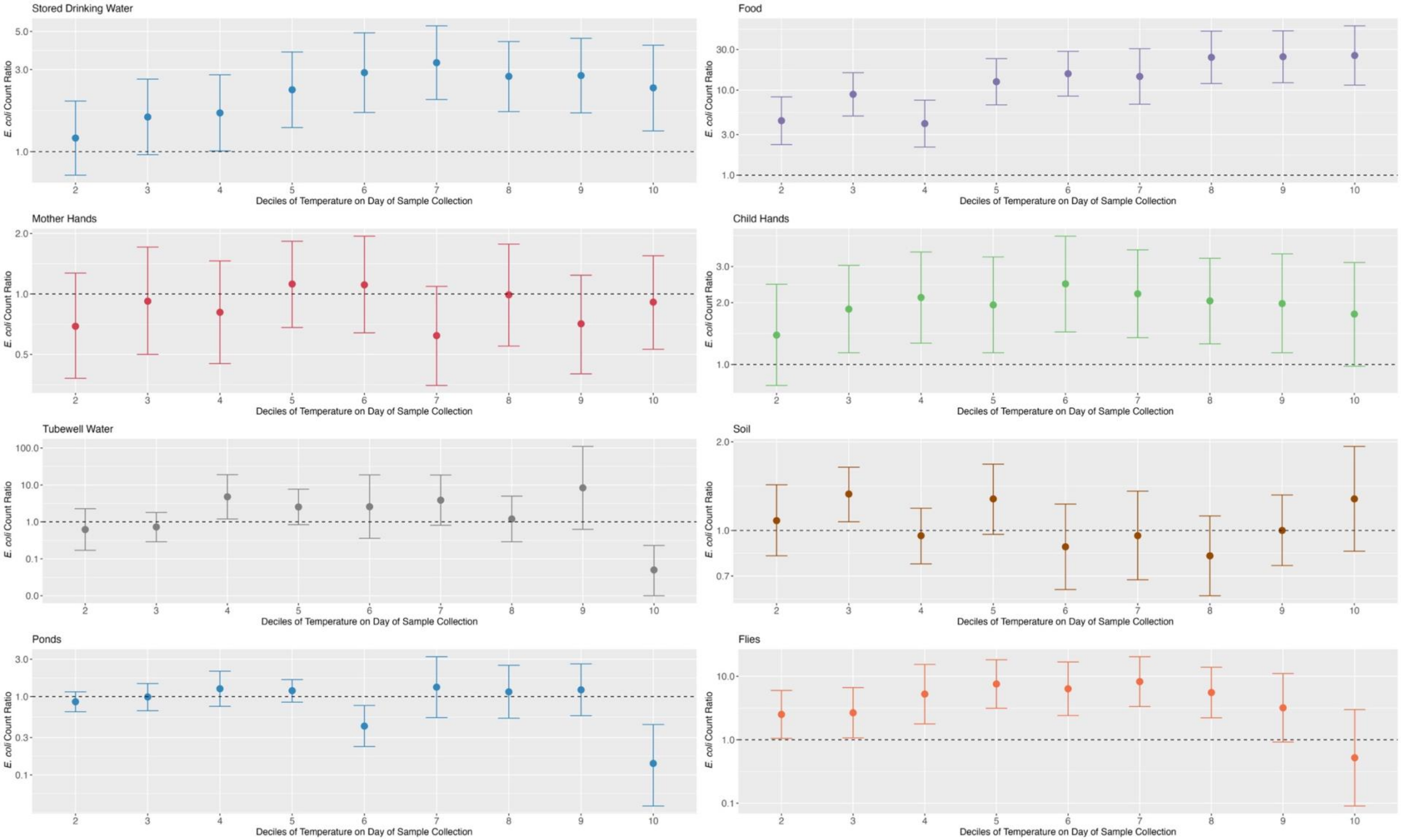


Table S5. Adjusted[a] *E. coli* count ratios by sample type[b] associated with each weather category[c] across different antecedent timeframes

Adjusted	Stored Water (N=6350)		Food (N=2181)		Mother Hands (N = 5397)		Child Hands (N= 7092)		Source Water (N=1669)		Soil (N=2538)		Ponds (N=822)		Flies (N=610)	
	E. coli Ratio (95% CI)	p-value	*E. coli* Ratio (95% CI)	p-value	*E. coli* Ratio (95% CI)	p-value	*E. coli* Ratio (95% CI)	p-value	*E. coli* Ratio (95% CI)	p-value	*E. coli* Ratio (95% CI)	p-value	*E. coli* Ratio (95% CI)	p-value	*E. coli* Ratio (95% CI)	p-value
Day of																
No Rain	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Some Rain	1.67 (1.29, 2.17)	< 0.0005	1.45 (0.89, 2.35)	0.357	0.96 (0.72, 1.28)	0.771	1.38 (1.09, 1.74)	0.008	0.36 (0.12, 1.07)	0.066	0.87 (0.73, 1.05)	0.140	1.52 (1.03, 2.25)	0.036	0.95 (0.27, 3.39)	0.941
Heavy Rain	1.674 (1.02, 2.64)	0.041	2.06 (1.22, 3.49)	0.007	1.62 (1.00, 2.60)	0.049	1.24 (0.68, 2.25)	0.478	1.93 (0.61, 6.13)	0.266	0.74 (0.52, 1.06)	0.101	4.46 (2.42, 8.20)	< 0.0005	0.94 (0.30, 2.99)	0.923
Extreme Rain	1.98 (1.36, 2.88)	< 0.0005	3.13 (1.63, 5.99)	0.001	0.90 (0.57, 1.41)	0.632	0.92 (0.52, 1.60)	0.757	0.34 (0.07, 1.76)	0.198	0.36 (0.24, 0.53)	< 0.0005	3.46 (2.34, 5.11)	< 0.0005	0.03 (0.01, 0.19)	< 0.0005
Below Median Temp	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Above Median Temp	1.71 (1.39, 2.11)	< 0.0005	2.33 (1.60, 3.41)	< 0.0005	0.90 (0.70, 1.15)	0.38	1.22 (0.97, 1.54)	0.095	[c]	[c]	0.79 (0.67, 0.93)	0.004	[c]	[c]	[c]	[c]
Extreme Temp	1.49 (1.05, 2.12)	0.025	3.01 (1.51, 6.01)	< 0.0005	1.02 (0.72, 1.43)	0.927	1.02 (0.65, 1.62)	0.919	[c]	[c]	1.15 (0.82, 1.60)	0.412	[c]	[c]	[c]	[c]
1 Day																
No Rain	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Some Rain	1.77 (1.37 , 2.29)	< 0.0005	1.19 (0.69, 2.07)	0.534	0.97 (0.73, 1.27)	0.798	1.03 (0.80, 1.34)	0.807	0.28 (0.12, 0.68)	0.005	0.95 (0.78, 1.17)	0.634	1.35 (0.93, 1.96)	0.111	0.91 (0.18, 4.75)	0.913
Heavy Rain	1.23 (0.81 , 1.87)	0.324	1.49 (0.80, 2.78)	0.475	1.44 (0.94, 2.20)	0.093	0.80 (0.50, 1.28)	0.345	0.58 (0.09, 3.51)	0.42	0.89 (0.68, 1.16)	0.367	2.91 (1.24, 6.82)	0.014	0.64 (0.15, 2.71)	0.549
Extreme Rain	2.25 (1.57 , 3.21)	< 0.0005	2.13 (1.19, 3.86)	0.011	1.18 (0.84, 1.66)	0.348	0.97 (0.63, 1.49)	0.877	0.10 (0.02, 0.62)	0.014	0.35 (0.25, 0.48)	< 0.0005	2.74 (1.51, 4.95)	0.001	0.28 (0.06, 1.39)	0.119
Below Median Temp	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Above Median Temp	1.69 (1.35, 2.10)	< 0.0005	3.00 (1.99, 4.52)	< 0.0005	0.92 (0.70, 1.21)	0.554	1.25 (0.97, 1.61)	0.088	[c]	[c]	0.89 (0.75, 1.04)	0.145	[c]	[c]	[c]	[c]
Extreme Temp	1.62 (1.19, 2.22)	0.002	3.40 (1.71, 6.77)	< 0.0005	0.91 (0.66, 1.25)	0.565	0.93 (0.63, 1.37)	0.723	[c]	[c]	0.99 (0.73, 1.34)	0.959	[c]	[c]	[c]	[c]
2 Days																
No Rain	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Some Rain	1.64 (1.27 , 2.10)	< 0.0005	1.06 (0.62, 1.83)	0.822	0.85 (0.65, 1.11)	0.233	1.00 (0.76, 1.32)	0.991	0.20 (0.08, 0.50)	0.001	0.93 (0.74, 1.16)	0.506	1.80 (1.32, 2.45)	< 0.0005	5.34 (2.40, 11.89)	< 0.0005
Heavy Rain	1.21 (0.82 , 1.81)	0.339	1.23 (0.68, 2.22)	0.49	1.24 (0.84, 1.83)	0.278	0.67 (0.43, 1.06)	0.087	0.21 (0.03, 1.62)	0.135	0.86 (0.66, 1.13)	0.280	3.36 (1.71, 6.57)	< 0.0005	3.99 (1.64, 9.68)	0.002
Extreme Rain	1.88 (1.34 , 2.65)	< 0.0005	1.40 (0.81, 2.42)	0.226	0.94 (0.67, 1.32)	0.717	0.88 (0.62, 1.27)	0.503	0.34 (0.01, 1.13)	0.079	0.46 (0.34, 0.61)	< 0.0005	2.36 (1.22, 4.57)	0.011	4.10 (1.16, 14.48)	0.028
Below Median Temp	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Above Median Temp	1.58 (1.24, 2.01)	< 0.0005	3.12 (2.06, 4.72)	< 0.0005	0.99 (0.76, 1.30)	0.964	1.33 (1.01, 1.75)	0.042	[c]	[c]	0.88 (0.74, 1.06)	0.183	[c]	[c]	[c]	[c]
Extreme Temp	1.63 (1.20, 2.23)	0.002	4.40 (2.24, 8.65)	< 0.0005	0.91 (0.67, 1.24)	0.555	0.98 (0.68, 1.41)	0.900	[c]	[c]	0.94 (0.72, 1.24)	0.662	[c]	[c]	[c]	[c]
7 Days																
No Rain	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Some Rain	1.42 (1.06 , 1.91)	0.019	0.59 (0.34, 1.02)	0.059	0.72 (0.53, 0.98)	0.039	0.88 (0.61, 1.28)	0.503	0.17 (0.07, 0.45)	< 0.0005	1.11 (0.83, 1.49)	0.494	1.14 (0.79, 66)	0.478	1.30 (0.51, 3.32)	0.582
Heavy Rain	1.47 (0.96, 2.23)	0.072	0.74 (0.36, 1.54)	0.426	0.96 (0.64, 1.44)	0.83	0.82 (0.53, 1.27)	0.372	0.07 (0.01, 0.47)	0.006	0.84 (0.61, 1.16)	0.283	2.34 (1.22, 4.49)	0.011	0.83 (0.26, 2.60)	0.744
Extreme Rain	1.77 (1.22 , 2.57)	0.002	0.81 (0.49, 1.34)	0.418	0.67 (0.48, 0.94)	0.02	1.13 (0.76, 1.68)	0.548	0.13 (0.02, 0.63)	0.012	0.66 (0.49, 0.89)	0.007	1.52 (0.88, 2.63)	0.135	2.62 (0.98, 7.04)	0.056
Below Median Temp	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Above Median Temp	1.61 (1.25, 2.07)	< 0.0005	2.98 (1.87, 4.75)	< 0.0005	1.10 (0.84, 1.46)	0.482	1.27 (0.92, 1.74)	0.150	[c]	[c]	0.93 (0.77, 1.14)	0.497	[c]	[c]	[c]	[c]
Extreme Temp	1.74 (1.33, 2.28)	< 0.0005	4.39 (2.39, 8.05)	< 0.0005	1.00 (0.76, 1.32)	0.979	0.90 (0.63, 1.27)	0.533	[c]	[c]	0.74 (0.56, 0.97)	0.029	[c]	[c]	[c]	[c]
No Heatwave	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Heatwave	1.15 (0.85, 1.55)	0.378	0.81 (0.47, 1.40)	0.452	0.81 (0.59, 1.11)	0.189	0.79 (0.50, 1.27)	0.334	[c]	[c]	0.54 (0.38, 0.78)	0.001	[c]	[c]	[c]	[c]
14 Days																
No Rain	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Some Rain	0.85 (0.60, 1.21)	0.371	0.80 (0.53, 1.21)	0.295	0.78 (0.54, 1.15)	0.210	1.05 (0.71, 1.54)	0.809	0.26 (0.09, 0.75)	0.013	1.16 (0.92, 1.45)	0.204	1.15 (0.86, 1.53)	0.336	0.70 (0.36, 1.35)	0.287
Heavy Rain	0.81 (0.55 , 1.21)	0.312	0.64 (0.36, 1.14)	0.132	0.87 (0.51, 1.46)	0.591	1.18 (0.73 1.90)	0.504	0.11 (0.02, 0.50)	0.004	0.82 (0.61, 1.10)	0.182	1.99 (1.29, 3.07)	0.002	0.66 (0.28, 1.58)	0.352
Extreme Rain	1.04 (0.67 , 1.60)	0.869	0.65 (0.36, 1.15)	0.141	0.81 (0.49, 1.35)	0.422	1.27 (0.82, 1.97)	0.292	0.23 (0.05, 1.07)	0.062	0.78 (0.57, 1.05)	0.102	1.60 (0.99, 2.60)	0.057	1.91 (0.74, 4.90)	0.179
Below Median Temp	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Above Median Temp	1.46 (1.12, 1.91)	0.005	1.96 (1.20, 3.21)	0.007	1.23 (0.90, 1.69)	0.189	1.07 (0.76, 1.50)	0.691	[c]	[c]	0.94 (0.74, 1.18)	0.584	[c]	[c]	[c]	[c]
Extreme Temp	1.52 (1.17, 1.96)	0.001	4.34 (2.56, 7.34)	< 0.0005	1.01 (0.73, 1.39)	0.944	0.78 (0.55, 1.11)	0.162	[c]	[c]	0.80 (0.63, 1.03)	0.088	[c]	[c]	[c]	[c]
No Heatwave	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--	ref	--
Heatwave	1.14 (0.86, 1.51)	0.359	1.58 (0.94, 2.66)	0.086	0.79 (0.57, 1.09)	0.149	0.74 (0.51, 1.08)	0.116	[c]	[c]	0.50 (0.36, 0.70)	< 0.0005	[c]	[c]	[c]	[c]

[a] Models for rainfall adjusted for temperature and vice versa. All adjusted models also controlled for the following variables: Binary intervention variable (intervention or control), sex of index child, age of index child (in days), number of children under the age of 18 in the household, number of people in the compound, mother's age (in years), mother's educational status, food security category (using HFIAS scale), minutes to water source, household having improved walls, household having improved floors, household wealth quintile based on owned assets, number of cows, goats and chickens/ducks in the compound, source water origin from a tubewell. Food models included hours since stored food was prepared and stored drinking water models included covered storage container, narrow-mouth storage container, and hours water has been stored.

[b] We could not estimate effects of extreme temperature and heat waves on source water (tubewells), ponds and flies due to data sparsity.

[c] Weather classifications are as follows: No rain (0 mm), some rain (<16·4 mm), heavy rain (≥16·4 and <28·2 mm), extreme rain (≥28·2 mm), below-median temperature (<27·1˚C), above-median temperature (≥27·1 and <30·2˚C), extreme temperature (≥ 30·2˚C), no heatwave (<30·9˚C), heatwave (≥ 30·9˚C for 3 consecutive days).

Figure S12. Adjusted *E. coli* count ratios by sample type associated with above-median and elevated temperature, compared to below-median temperature, during different antecedent periods. All adjusted temperature models controlled for the following variables: Rolling mean rainfall for the same antecedent period, binary intervention variable (intervention or control), sex of index child, age of index child (in days), number of children under the age of 18 in the household, number of people in the compound, mother's age (in years), mother's educational status, food security category (using HFIAS scale), minutes to water source, household having improved walls, household having improved floors, household wealth quintile based on owned assets, number of cows, goats and chickens/ducks in the compound, source water origin from a tubewell. Food models included hours since stored food was prepared and stored drinking water models included covered storage container, narrow-mouth storage container, and hours water has been stored. Weather classifications are as follows: below-median yemperature (<27·1˚C), above-median temperature (≥27·1 and <30·2˚C), elevated temperature (≥29·3˚C).

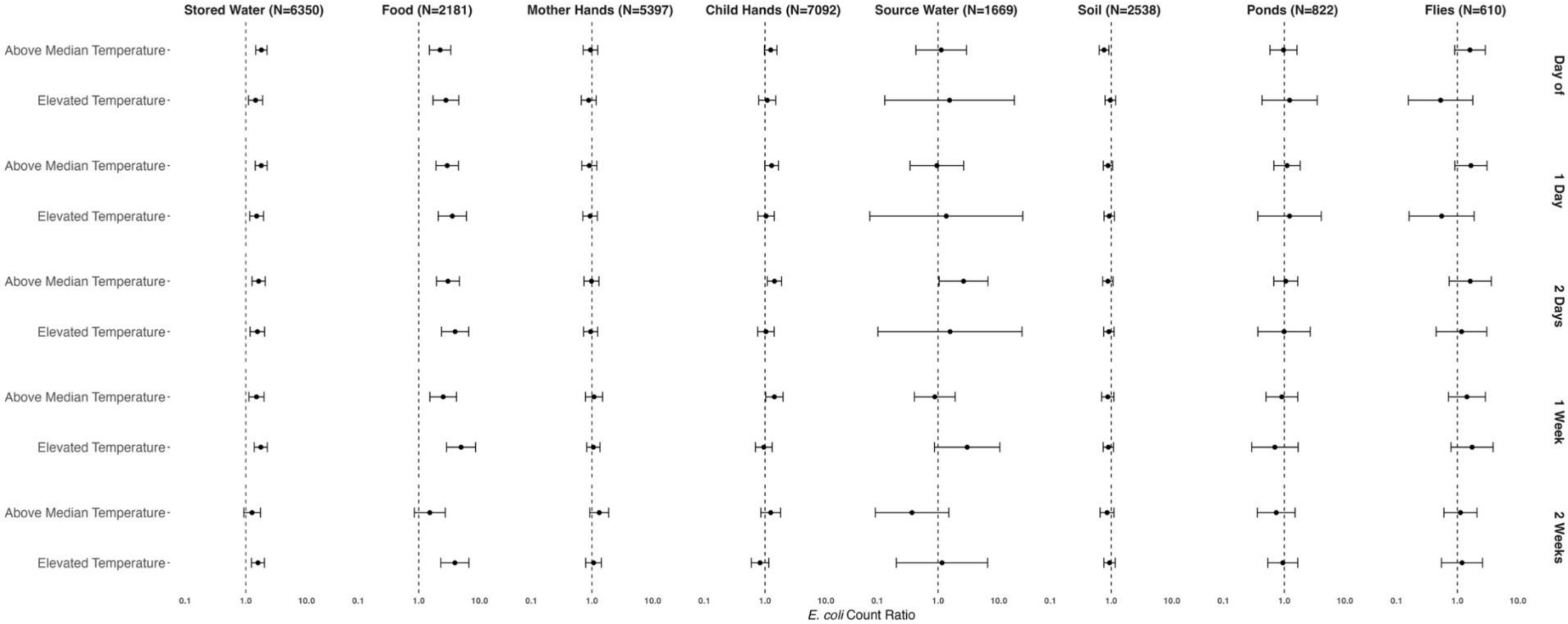


Figure S13. Adjusted *E. coli* count ratios by sample type associated with heatwaves within 7 and 14 days. All adjusted temperature models controlled for the following variables: Rolling mean rainfall for the same antecedent period, binary intervention variable (intervention or control), sex of index child, age of index child (in days), number of children under the age of 18 in the household, number of people in the compound, mother's age (in years), mother's educational status, food security category (using HFIAS scale), minutes to water source, household having improved walls, household having improved floors, household wealth quintile based on owned assets, number of cows, goats and chickens/ducks in the compound, source water origin from a tubewell. Food models included hours since stored food was prepared and stored drinking water models included covered storage container, narrow-mouth storage container, and hours water has been stored. Heatwave was defined as daily maximum temperature values >95th percentile (30·9˚C) for three consecutive days. We could not estimate effects of heatwaves on source water (tubewells), ponds and flies due to data sparsity.

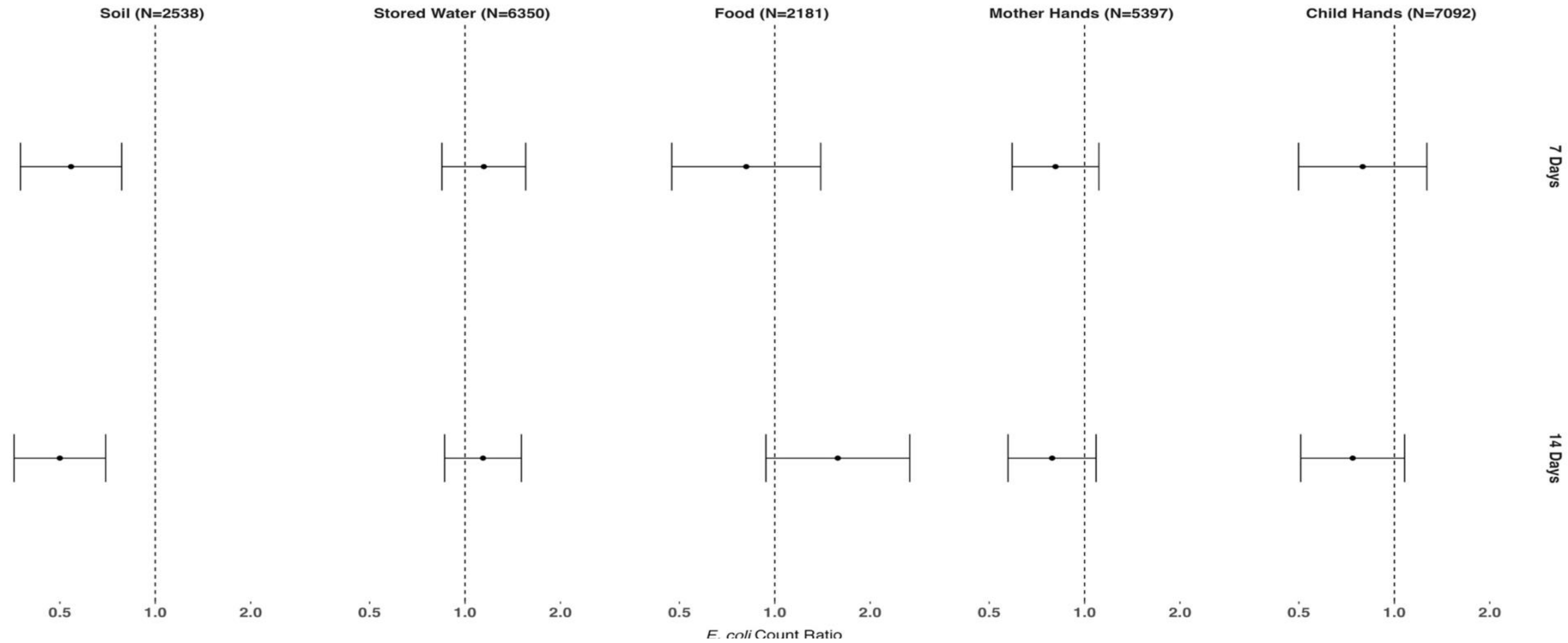


Table S6. Mean *E. coli* (MPN/100 mL) in stored drinking water by storage container type and rainfall, among samples stored for at least 8 hours

	Mean (SD)			
	Covered and narrow mouth	Uncovered and narrow mouth	Covered and wide mouth	Uncovered and wide mouth
Rainy days	100.4 (347.9)	410.6 (847.8)	199.2 (594.1)	618.6 (1088.3)
Dry days	64.9 (351.6)	251.3 (619.5)	89.9 (466.1)	141.3 (493.9)

Appendix B

Table S1. Reporting units, detection limits and *E. coli* prevalence and abundance by sample type

Sample type	**Reporting unit**	**Lower limit of detection (MPN)**	**Upper limit of detection (MPN)**	**Mean log10 MPN (SD)**	**Percent positive**	**Percent above limit of detection**
Soil	1 dry gram	1,000-1,887 [a]	2.42×10^6 - 4.56×10^6 [a]	5.11 (1.06)	94.9%	13.4%
Ponds	100 mL	100	241,960	3.76 (0.79)	98.0%	2.5%
Flies	1 fly	100	241,960	2.77 (1.34)	50.9%	7.5%
Source water	100 mL	1	2419.6	-0.03 (0.65)	23.9%	0.5%
Stored water	100 mL	1	2,419.6	0.98 (1.05)	80.3%	2.7%
Food	1 dry gram	1-20 [b]	2,494-48,392 [b]	0.83 (1.43)	63.7%	8.3%
Mother hands	2 hands	5	12,098	1.47 (1.00)	75.5%	1.9%
Child hands	2 hands	5	12,098	1.36 (0.99)	68.6%	1.9%
Total					73.2%	3.6%

[a] Given a soil moisture content range of 0-47%, a lower limit of 1,000 MPN and upper limit of 2,419,600 per wet gram

[b] Given a food moisture content range of 3-95%, a lower limit of 1 MPN and upper limit of 2,419.6 MPN per wet gram

Table S2. Number of samples collected by sample type and data collection round (R1-R9)

Sample type	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**Total**
Soil	1185	0	0	402	341	0	0	0	0	1928
Ponds	557	0	0	0	0	0	0	0	0	557
Flies	395	0	0	0	0	0	0	0	0	395
Source water	1098	0	0	0	0	0	0	0	0	1098
Stored water	1013	641	592	571	599	581	582	574	587	5740
Food	1094	0	0	329	206	0	0	0	0	1629
Mother hands	0	720	705	684	682	668	662	643	633	5397
Child hands	1170	720	705	682	673	653	650	626	615	6494
Total	6512	2081	2002	2668	2501	1902	1894	1843	1835	23238

Table S3. **Number of samples (total N=23,238) within each weather category across 2- and 7-day antecedent periods.** Extreme rain defined as ≥28.20 mm, extreme temperature defined as ≥30.21˚C, heavy defined as rain ≥16.44 mm, elevated temperature defined as ≥29.29˚C, median 2-day rolling average rain defined as ≥0.27 mm, median 2-day rolling average temperature defined as ≥27.46˚C, median 7-day rolling average rain defined as ≥1.10 mm, and median 7-day rolling average temperature defined as ≥27.52˚C.

	2 Days	**7 Days**
No extreme rain	88.0% (20459)	77.0% (17896)
Extreme rain	12.0% (2779)	23.0% (5342)
No extreme temp	85.9% (19956)	79.5% (18473)
Extreme temp	14.1% (3282)	20.5% (4765)
No heavy rain	78.6% (18274)	64.8% (15062)
Heavy rain	21.4% (4964)	35.2% (8176)
No elevated temp	69.3% (16110)	63% (14641)
Elevated temp	30.7% (7128)	37% (8597)
Below median rain	49.3% (11446)	49.0% (11379)
Above median rain	50.7% (11792)	51.0% (11859)
Below median temp	52.5% (12193)	51.1% (11867)
Above median temp	47.5% (11045)	48.9% (11371)

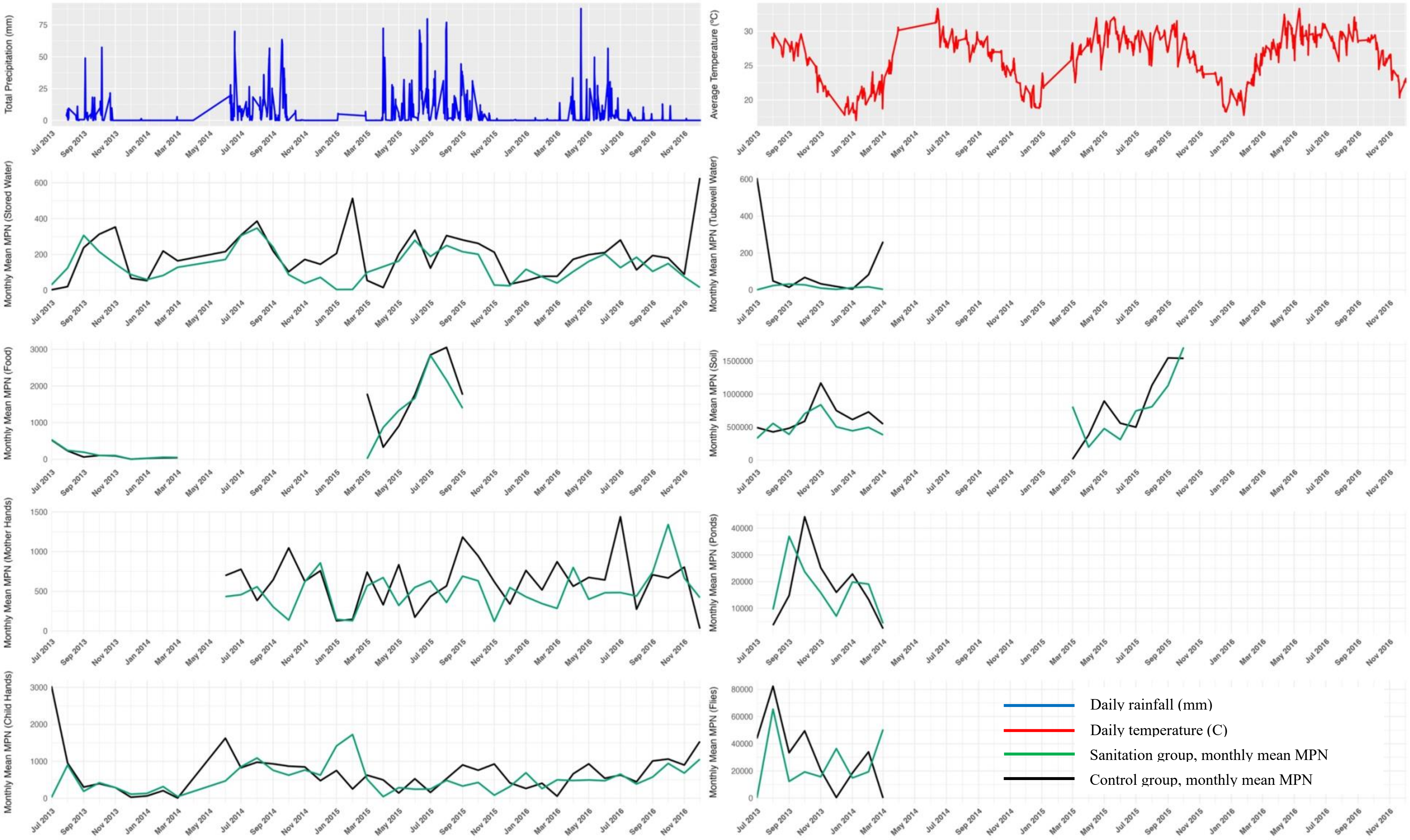


Figure S1. **Daily rainfall, temperature and monthly mean most probable number (MPN) of *E. coli* by sample type and study group across the study period.** Periods with no MPN values plotted indicate that no samples were collected during that period.

Table S4. Effect modification by extreme rainfall and temperature. Differences in mean log10-transformed most probable number (MPN) of *E. coli* between randomized sanitation intervention and control groups in strata of extreme rainfall and temperature during 2- and 7-day antecedent periods. Extreme rainfall was defined as ≥90th percentile of daily rainfall values (28.20 mm). Extreme temperature was defined as ≥90th percentile of daily temperature values (30.21˚C). Estimates compare the sanitation intervention group to the control group within each weather stratum using unadjusted generalized linear models with robust standard errors. Estimates <0 indicate a protective effect from the intervention, and estimates >0 indicate a harmful effect from the intervention. Shown p-values refer to the p-value for the interaction term between study group (intervention vs. control) and binary weather variable. We interpreted interaction p-values <0.20 as evidence of effect modification. We could not estimate intervention effects on ponds, flies and source water (tubewells) following periods of extreme temperature due to data sparsity. The estimates in this table correspond to **Figure 3** in the main text.

	Rainfall							**Temperature**							
	No Extreme Rainfall			Extreme Rainfall				No Extreme Temperature			Extreme Temperature				
	Control n	**Sanitation n**	**Δlog10 (95% CI)**	**Control n**	**Sanitation n**	**Δlog10 (95% CI)**	**p-value**	**Control n**	**Sanitation n**	**Δlog10 (95% CI)**	**Control n**	**Sanitation n**	**Δlog10 (95% CI)**	**p-value**
2 Day															
Soil	834	810	-0.06 (-0.18, 0.06)	138	146	-0.04 (-0.31, 0.24)	0.86	853	847	-0.01 (-0.13, 0.10)	119	109	**-0.40 (-0.70, -0.15)**	**0.01**
Ponds	267	261	-0.07 (-0.21, 0.07)	10	19	-0.40 (-0.94, 0.13)	0.25	276	279	-	1	1	-	-
Flies	173	191	-0.13 (-0.44, 0.18)	20	11	-0.90 (-2.30, 0.50)	0.29	192	196	-0.20 (-0.53, 0.13)	1	6	-	-
Source Water	523	492	-0.04 (-0.12, 0.04)	40	43	-0.18 (-0.49, 0.13)	0.40	561	529	-0.05 (-0.13, 0.03)	2	6	-	-
Stored Water	2496	2581	**-0.08 (-0.15, -0.01)**	318	345	-0.05 (-0.19, 0.09)	0.68	2403	2468	-0.07 (-0.14, 0.00)	411	458	-0.12 (-0.29, 0.05)	0.53
Food	706	690	0.04 (-0.12, 0.19)	116	117	0.18 (-0.21, 0.56)	0.48	722	714	-0.12 (-0.04, 0.27)	100	93	-0.27 (-0.61, 0.08)	**0.05**
Mother Hands	2321	2386	-0.02 (-0.10, 0.05)	335	355	-0.05 (-0.21, 0.12)	0.75	2185	2224	-0.01 (-0.08, 0.07)	471	517	-0.10 (-0.23, 0.03)	**0.18**
Child Hands	2829	2899	**-0.06 (-0.13, 0.00)**	376	390	-0.06 (-0.20, 0.07)	0.99	2737	2770	-0.04 (-0.10, 0.03)	468	519	**-0.22 (-0.36, -0.09)**	**0.01**
7 Day															
Soil	683	692	-0.05 (-0.19, 0.09)	289	264	-0.08 (-0.25, 0.10)	0.82	787	786	0.00 (-0.12, 0.11)	185	170	**-0.33 (-0.54, -0.12)**	**0.01**
Ponds	248	239	0.06 (-0.21, 0.10)	29	41	-0.26 (-0.70, 0.18)	0.39	276	279	-	1	1	-	-
Flies	136	162	0.01 (-0.32, 0.33)	57	40	**-0.91 (-1.65, -0.17)**	**0.03**	192	196	-0.20 (-0.53, 0.13)	1	6	-	-
Source Water	428	430	-0.04 (-0.13, 0.05)	135	105	-0.07 (-0.25, 0.11)	0.76	561	529	-0.05 (-0.13, 0.03)	2	6	-	-
Stored Water	2177	2307	**-0.08 (-0.16, -0.01)**	637	619	-0.03 (-0.15, 0.09)	0.41	2215	2274	**-0.08 (-0.16, -0.01)**	599	652	-0.05 (-0.18, 0.07)	0.68
Food	566	576	0.08 (-0.10, 0.25)	256	231	0.09 (-0.23, 0.41)	0.93	673	661	0.12 (-0.04, 0.27)	149	146	-0.16 (-0.49, 0.16)	**0.12**
Mother Hands	2057	2142	-0.02 (-0.09, 0.06)	599	599	-0.05 (-0.17, 0.07)	0.55	1969	2002	-0.01 (-0.09, 0.08)	687	739	-0.05 (-0.17, 0.06)	0.50
Child Hands	2463	2590	**-0.07 (-0.14, -0.01)**	742	699	-0.02 (-0.12, 0.08)	0.27	2523	2550	-0.03 (-0.10, 0.04)	682	739	**-0.19 (-0.31, -0.07)**	**0.01**

Δlog10=Difference in log10-transfomed *E. coli* counts between intervention vs. control groups; CI: Confidence interval.

Table S5. **Effect modification by heavy rain and elevated temperature.** Differences in mean log10-transformed most probable number (MPN) of *E. coli* between randomized sanitation intervention and control groups in strata of heavy rainfall and elevated temperature during 2- and 7-day antecedent periods. Heavy rainfall was defined as ≥80th percentile of daily rainfall values (16.44 mm). Elevated temperature was defined as ≥80th percentile of daily temperature values (29.29˚C). Estimates compare the sanitation intervention group to the control group within each weather stratum using unadjusted generalized linear models with robust standard errors. Estimates <0 indicate a protective effect from the intervention, and estimates >0 indicate a harmful effect from the intervention. Shown p-values refer to the p-value for the interaction term between study group (intervention vs. control) and binary weather variable. We interpreted interaction p-values <0.20 as evidence of effect modification. The estimates in this table corresponds to **Figure S2**.

	Rainfall							**Temperature**						
	No Heavy Rainfall			Heavy Rainfall				No Elevated Temperature			Elevated Temperature			
	Control n	**Sanitation n**	**Δlog10 (95% CI)**	**Control n**	**Sanitation n**	**Δlog10 (95% CI)**	**p-value**	**Control n**	**Sanitation n**	**Δlog10 (95% CI)**	**Control n**	**Sanitation n**	**Δlog10 (95% CI)**	**p-value**
2 Day														
Soil	704	717	-0.07 (-0.20, 0.06)	268	239	-0.04 (-0.25, 0.16)	0.83	729	733	0.00 (-0.12, 0.12)	243	223	**-0.26 (-0.45, -0.06)**	**0.03**
Ponds	233	246	-0.04 (-0.19, 0.11)	44	34	-0.13 (-0.32, 0.05)	0.45	270	275	-0.08 (-0.22, 0.05)	7	5	**-0.38 (-0.59, -0.17)**	**0.01**
Flies	154	183	-0.11 (-0.44, 0.22)	39	19	-0.71 (-1.56, 0.13)	**0.20**	187	186	-0.22 (-0.56, 0.12)	6	16	0.20 (-0.63, 1.03)	0.37
Source Water	467	463	-0.04 (-0.12, 0.04)	96	72	-0.10 (-0.35, 0.15)	0.64	0	41	-0.05 (-0.13, 0.04)	545	512	-0.23 (-0.69, 0.23)	0.44
Stored Water	2214	2345	**-0.08 (-0.15, -0.01)**	600	581	-0.04 (-0.15, 0.07)	0.53	2027	2114	-0.05 (-0.13, 0.02)	787	812	**-0.13 (-0.26, -0.01)**	0.27
Food	598	604	0.03 (-0.14, 0.20)	224	203	0.21 (-0.08, 0.50)	0.28	625	616	0.16 (-0.01, 0.32)	197	191	-0.22 (-0.50, 0.06)	**0.02**
Mother Hands	2062	2143	-0.02 (-0.10, 0.05)	594	598	-0.02 (-0.14, 0.10)	0.95	1777	1838	-0.01 (-0.10, 0.07)	879	903	-0.05 (-0.14, 0.04)	0.50
Child Hands	2518	2623	-0.06 (-0.13, 0.00)	687	666	-0.07 (-0.18, 0.04)	0.94	2317	2375	-0.04 (-0.11, 0.03)	888	914	**-0.13 (-0.24, -0.02)**	**0.14**
7 Day														
Soil	544	560	-0.04 (-0.20, 0.11)	428	396	-0.08 (-0.23, 0.08)	0.76	632	640	0.00 (-0.13, 0.14)	340	316	**-0.18 (-0.33, -0.03)**	**0.06**
Ponds	214	203	-0.03 (-0.20, 0.13)	63	77	-0.22 (-0.47, 0.03)	0.24	261	273	-0.08 (-0.22, 0.05)	16	7	**-0.31 (-0.50, -0.13)**	**0.04**
Flies	115	143	0.01 (-0.35, 0.37)	78	59	**-0.62 (-1.19, -0.05)**	**0.07**	179	183	-0.22 (-0.57, 0.13)	14	19	-0.04 (-0.75, 0.66)	0.67
Source Water	369	377	-0.02 (-0.12, 0.07)	194	158	-0.10 (-0.26, 0.06)	0.42	521	493	-0.05 (-0.14, 0.03)	42	42	-0.06 (-0.42, 0.31)	0.98
Stored Water	1830	1967	**-0.08 (-0.16, 0.00)**	984	959	-0.05 (-0.14, 0.04)	0.58	1714	1777	-0.07 (-0.15, 0.01)	1100	1149	-0.09 (-0.18, 0.01)	0.79
Food	450	463	0.09 (-0.10, 0.28)	372	344	0.08 (-0.15, 0.32)	0.99	547	546	0.16 (-0.01, 0.32)	275	261	-0.09 (-0.36, 0.18)	**0.11**
Mother Hands	1735	1809	-0.01 (-0.09, 0.07)	921	932	-0.05 (-0.14, 0.04)	0.44	1442	1478	-0.01 (-0.10, 0.08)	1214	1263	-0.04 (-0.12, 0.05)	0.60
Child Hands	2084	2199	-0.06 (-0.12, 0.01)	1121	1090	-0.08 (-0.17, 0.01)	0.62	1958	1997	-0.05 (-0.12, 0.02)	1247	1292	**-0.08 (-0.17, 0.01)**	0.56

Δlog10=Difference in log10-transfomed *E. coli* counts between intervention vs. control groups; CI: Confidence interval

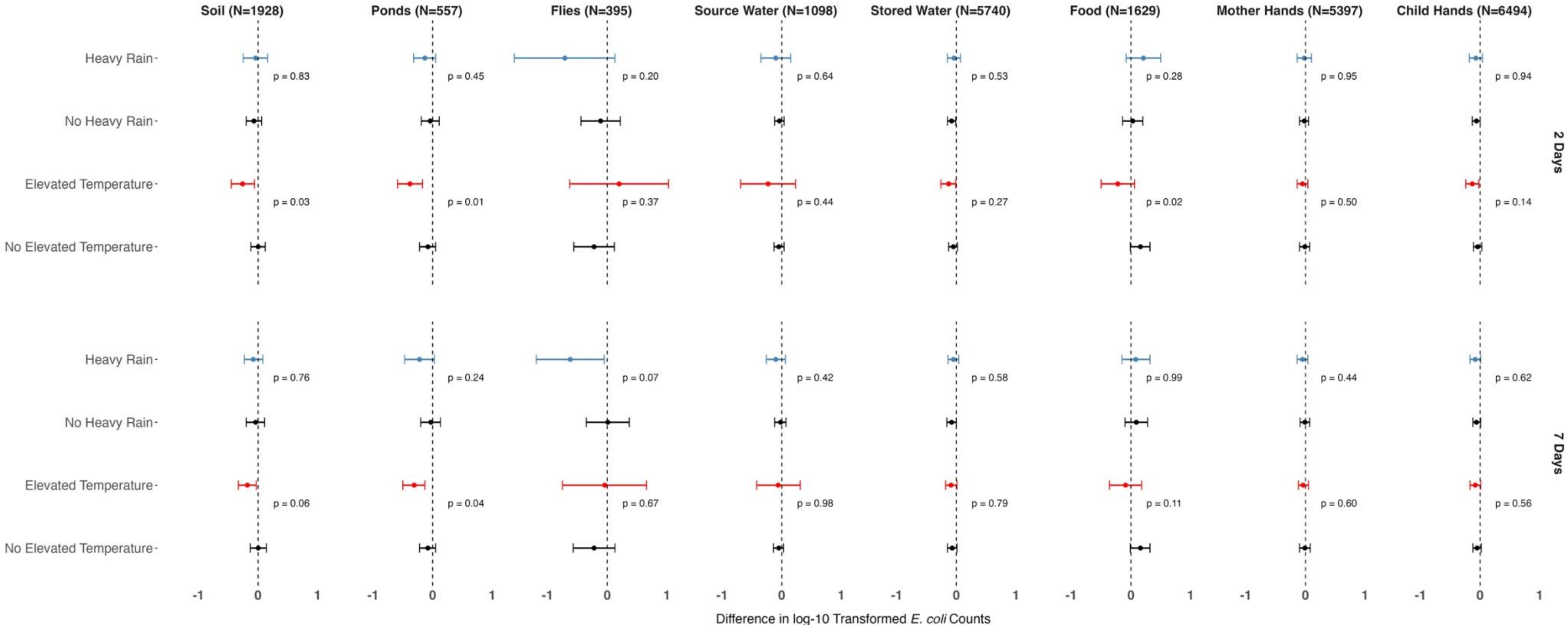


Figure S2. Effect modification by heavy rainfall and elevated temperature. Forest plot of differences in mean log10-transformed most probable number (MPN) of *E. coli* between randomized sanitation intervention and control groups in strata of heavy rainfall and elevated temperature during 2- and 7-day antecedent periods. Heavy rainfall was defined as ≥80th percentile of daily rainfall values (16.44 mm). Elevated temperature was defined as ≥80th percentile of daily temperature values (29.29˚C). Estimates compare the sanitation intervention group to the control group within each weather stratum using unadjusted generalized linear models with robust standard errors. Estimates <0 indicate a protective effect from the intervention, and estimates >0 indicate a harmful effect from the intervention. Circles indicate point estimates for differences in log10-transformed *E. coli* counts. Horizontal lines indicate 95% confidence intervals. Shown p-values refer to the p-value for the interaction term between the study group (intervention vs. control) and binary weather variable. We interpreted interaction p-values <0.20 as evidence of effect modification. The number of samples in each weather stratum is provided in Table S5.

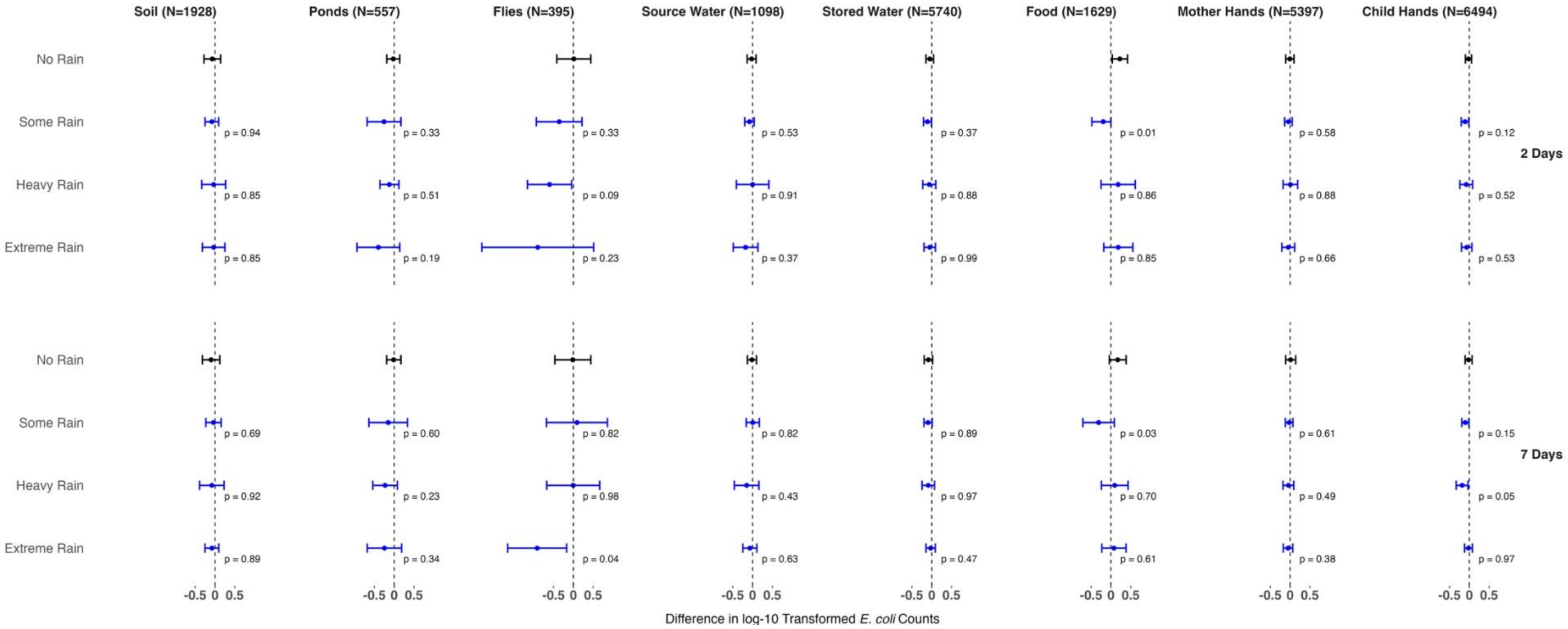


Figure S3. Effect modification by categories of rainfall. Forest plot of differences in mean log10-transformed most probable number (MPN) of *E. coli* between randomized sanitation intervention and control groups in strata of rainfall categories during 2- and 7-day antecedent periods. Extreme rainfall was defined as ≥90th percentile of daily rainfall values (28.20 mm). Heavy rainfall was defined as ≥80th percentile of daily rainfall values (16.44 mm). Estimates compare the sanitation intervention group to the control group within each weather stratum using unadjusted generalized linear models with robust standard errors. Estimates <0 indicate a protective effect from the intervention, and estimates >0 indicate a harmful effect from the intervention. Circles indicate point estimates for differences in log10-transformed *E. coli* counts. Horizontal lines indicate 95% confidence intervals. Shown p-values refer to the p-value for the interaction term between the study group (intervention vs. control) and binary weather variable. We interpreted interaction p-values <0.20 as evidence of effect modification.

Table S6. Effect modification by above- vs. below-median rolling average rainfall and temperature. Differences in log10-transformed *E. coli* counts between randomized sanitation intervention and control groups in strata of above or below-median rolling average rainfall and temperature during 2- and 7-day antecedent periods. Median 2-day rolling average rain was defined as ≥0.27 mm, median 2-day rolling temperature as ≥27.46˚C, median 7-day rolling average rain as ≥1.10 mm and median 7-day rolling average temperature as ≥27.52˚C. Estimates compare the sanitation intervention group to the control group within each weather stratum using unadjusted generalized linear models with robust standard errors. Estimates <0 indicate a protective effect from the intervention, and estimates >0 indicate a harmful effect from the intervention. Shown p-values refer to the p-value for the interaction term between study group (intervention vs. control) and binary weather variable. We interpreted interaction p-values <0.20 as evidence of effect modification. The estimates in this table correspond to **Figure 4** in the main text.

	Rainfall							**Temperature**						
	Below Median Rainfall			Median and Above Rainfall				Below Median Temperature			Median and Above Temperature			
	Control n	**Sanitation n**	**Δlog10 (95% CI)**	**Control n**	**Sanitation n**	**Δlog10 (95% CI)**	**p-value**	**Control n**	**Sanitation n**	**Δlog10 (95% CI)**	**Control n**	**Sanitation n**	**Δlog10 (95% CI)**	**p-value**
2 Day														
Soil	482	458	-0.07 (-0.26, 0.12)	490	498	-0.04 (-0.18, 0.10)	0.83	523	494	0.00 (-0.15, 0.14)	449	462	-0.13 (-0.30, 0.03)	0.26
Ponds	130	125	-0.02 (-0.18, 0.14)	147	155	-0.20 (-0.44, 0.03)	0.24	145	139	-0.09 (-0.22, 0.05)	132	141	0.03 (-0.53, 0.58)	0.70
Flies	108	95	0.01 (-0.40, 0.42)	85	107	-0.41 (-0.89, 0.06)	0.19	108	102	-0.22 (-0.61, 0.17)	85	100	-0.13 (-0.68, 0.43)	0.80
Source Water	277	241	-0.02 (-0.13, 0.09)	286	294	-0.10 (-0.22, 0.02)	0.35	311	265	-0.04 (-0.13, 0.04)	252	270	-0.10 (-0.35, 0.15)	0.71
Stored Water	1408	1422	-0.06 (-0.14, 0.03)	1406	1504	-0.09 (-0.17, -0.01)	0.52	1507	1490	-0.08 (-0.16, 0.01)	1307	1436	-0.09 (-0.17, 0.00)	0.85
Food	398	392	0.18 (-0.02, 0.38)	424	415	0.04 (-0.17, 0.24)	0.27	444	428	0.06 (-0.11, 0.22)	378	379	0.03 (-0.22, 0.27)	0.83
Mother Hands	1325	1368	0.02 (-0.07, 0.11)	1331	1373	-0.06 (-0.15, 0.02)	0.12	1410	1424	0.02 (-0.08, 0.12)	1246	1317	-0.06 (-0.14, 0.02)	0.17
Child Hands	1601	1616	-0.02 (-0.09, 0.05)	1604	1673	-0.11 (-0.19, -0.02)	0.08	1710	1693	-0.02 (-0.10, 0.05)	1495	1596	-0.11 (-0.20, -0.03)	0.05
7 Day														
Soil	473	455	-0.05 (-0.25, 0.15)	499	501	-0.08 (-0.21, 0.06)	0.82	499	493	0.03 (-0.12, 0.18)	473	463	-0.17 (-0.31, -0.03)	0.05
Ponds	131	118	0.00 (-0.18, 0.17)	146	162	-0.25 (-0.48, -0.03)	0.10	136	138	-0.06 (-0.20, 0.07)	141	142	-0.32 (-0.78, 0.14)	0.30
Flies	96	104	0.03 (-0.39, 0.45)	97	98	-0.45 (-0.94, 0.04)	0.15	102	100	-0.27 (-0.67, 0.13)	91	102	0.05 (-0.53, 0.63)	0.40
Source Water	278	244	-0.02 (-0.13, 0.09)	285	291	-0.10 (-0.21, 0.02)	0.36	294	262	-0.05 (-0.13, 0.04)	269	273	-0.08 (-0.32, 0.16)	0.80
Stored Water	1402	1414	-0.07 (-0.15, 0.02)	1412	1512	-0.09 (-0.17, -0.01)	0.67	1461	1463	-0.07 (-0.15, 0.02)	1353	1463	-0.08 (-0.17, 0.00)	0.78
Food	392	387	0.11 (-0.10, 0.32)	430	420	0.00 (-0.20, 0.20)	0.42	416	428	0.12 (-0.06, 0.30)	406	379	0.02 (-0.20, 0.24)	0.49
Mother Hands	1313	1370	0.02 (-0.07, 0.11)	1343	1371	-0.06 (-0.15, 0.02)	0.11	1363	1399	0.00 (-0.09, 0.10)	1293	1342	-0.05 (-0.13, 0.04)	0.37
Child Hands	1589	1613	-0.03 (-0.10, 0.04)	1616	1676	-0.10 (-0.17, -0.02)	0.11	1648	1665	-0.04 (-0.12, 0.03)	1557	1624	-0.09 (-0.17, 0.00)	0.37

Δlog10=Difference in log10-transfomed *E. coli* counts between intervention vs. control groups; CI: Confidence interval.

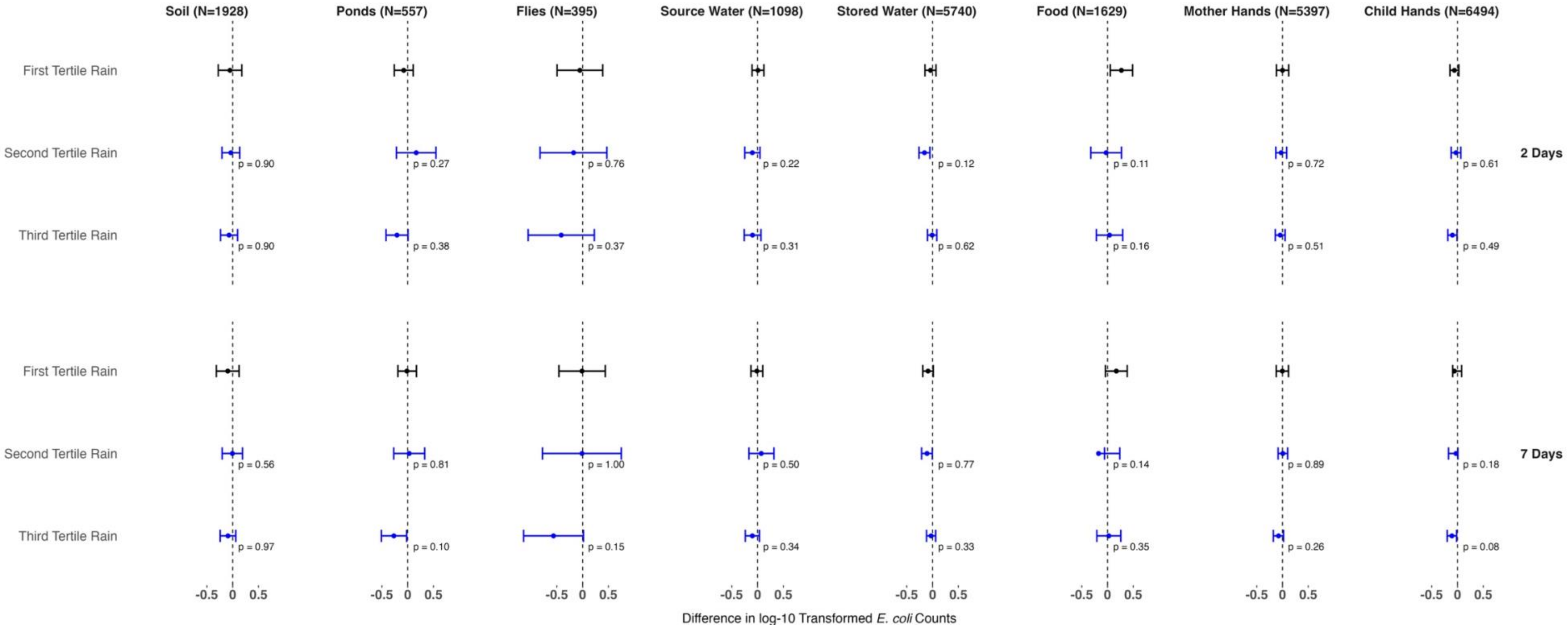


Figure S4. Effect modification by tertiles of rolling average rainfall. Forest plot of differences in mean log10-transformed most probable number (MPN) of *E. coli* between randomized sanitation intervention and control groups in strata of tertiles of rolling average rainfall during 2- and 7-day antecedent periods. Estimates compare the sanitation intervention group to the control group within each weather stratum using unadjusted generalized linear models with robust standard errors. Estimates <0 indicate a protective effect from the intervention, and estimates >0 indicate a harmful effect from the intervention. Circles indicate point estimates for differences in log10-transformed *E. coli* counts. Horizontal lines indicate 95% confidence intervals. Shown p-values refer to the p-value for the interaction term between the study group (intervention vs. control) and binary weather variable. We interpreted interaction p-values <0.20 as evidence of effect modification.

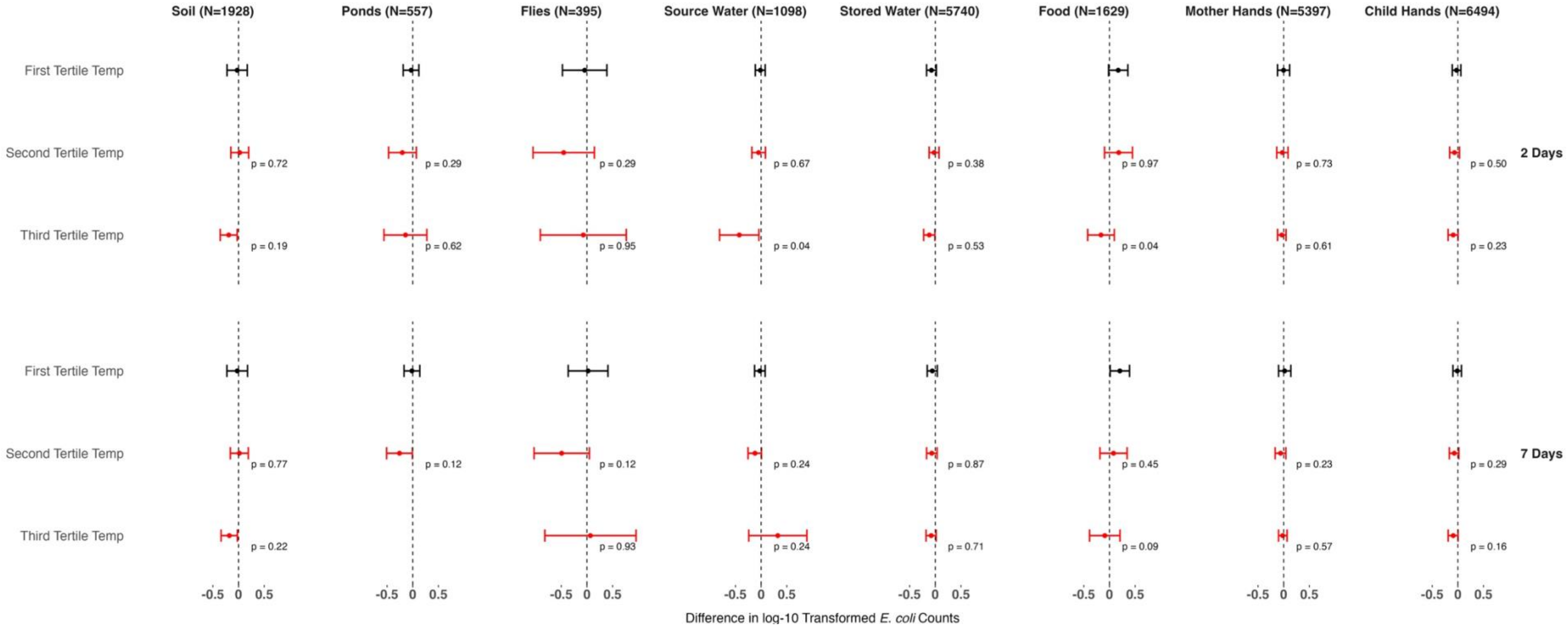


Figure S5. Effect modification by tertiles of rolling average temperature. Forest plot of differences in mean log10-transformed most probable number (MPN) of *E. coli* between randomized sanitation intervention and control groups in strata of tertiles of rolling average temperature during 2- and 7-day antecedent periods. Estimates compare the sanitation intervention group to the control group within each weather stratum using unadjusted generalized linear models with robust standard errors. Estimates <0 indicate a protective effect from the intervention, and estimates >0 indicate a harmful effect from the intervention. Circles indicate point estimates for differences in log10-transformed *E. coli* counts. Horizontal lines indicate 95% confidence intervals. Shown p-values refer to the p-value for the interaction term between the study group (intervention vs. control) and binary weather variable. We interpreted interaction p-values <0.20 as evidence of effect modification.

Appendix C

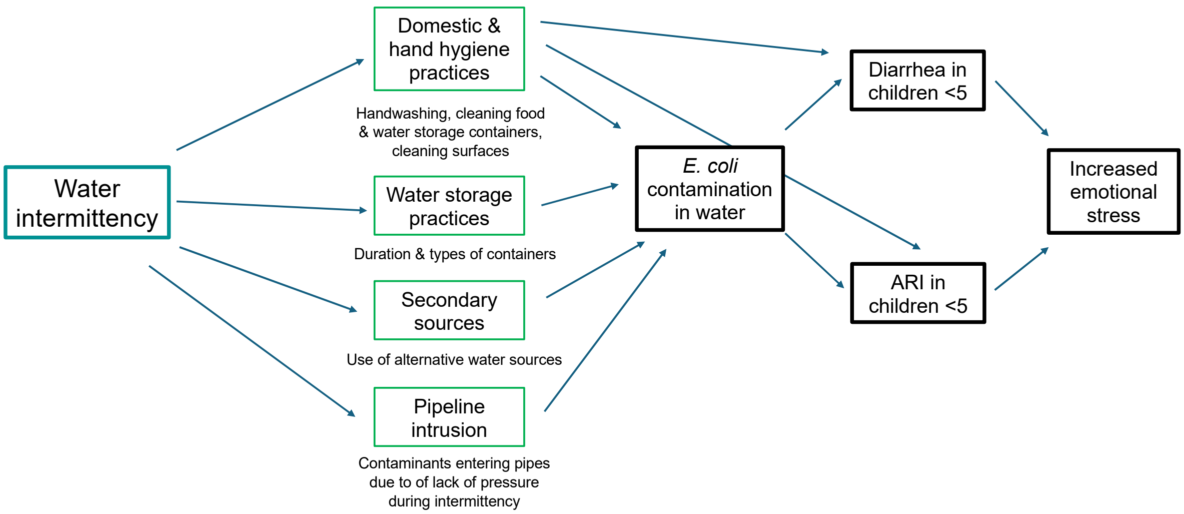


Figure S1. Directed acyclic graph (DAG) illustrating the hypothesized causal pathway between water intermittencies (in teal), mediating behaviors (in green) and our measured outcomes (in black) of water quality, child health, and respondent emotional stress.

Text S1. Adjusted model covariates. We also considered the following adjustment covariates but did not control for them because they had <5% variation in the study sample (i.e. one category dominated across all households): Roof material, wall material, and for respiratory outcomes, fuel type, stove type and presence of windows in the dwelling as predictors of indoor air quality.

All models controlled for:
Household's primary water source piped
Household has an improved latrine
Household has handwashing station with soap (observed)
Number of animals living on the compound
Age of respondent
Total number of people living in the household
Respondent's highest level of education
Highest education level in the household
Household wealth index quintile
Amount of money spent per week by the household, in USD
Floor material in the household
Respondent's report of last time it rained
Models for water quality outcomes additionally controlled for:
Water sample obtained from piped source
Water sample reported to be treated
Models for health and stress outcomes additionally controlled for:
Child age, in months
Food insecurity index (HFIAS score)

Table S1. Demographic, socioeconomic and water and sanitation indicators among households experiencing at least one water intermittency vs. no water intermittency in the last four weeks

	No Intermittency	**Intermittency**
	N=160	**N=77**
Demographics		
Respondent's age, mean (SD)	31.1 (10.5)	31.1 (9.8)
Number of individuals living in household, mean (SD)		
Children <5 years	1.2 (0.5)	1.2 (0.4)
Children 5-16 years	1.4 (1.3)	1.3 (1.1)
Adults >16 years	2.7 (1.2)	2.8 (1.5)
Socio-economic indicators		
Respondent's highest level of education, % (n)		
Never attended	1.9% (3)	1.3% (1)
Incomplete primary	24.4% (39)	35.1% (27)
Complete primary	19.4% (31)	5.2% (4)
Incomplete secondary	25.0% (40)	28.57% (22)
Complete secondary	24.4% (39)	22.1% (17)
Post-secondary	5.0% (8)	7.8% (6)
Highest level of education by any household member, % (n)		
Never attended	0.6% (1)	0% (0)
Incomplete primary	9.6% (15)	15.6% (12)
Complete primary	6.4% (10)	5.2% (4)
Incomplete secondary	20.4% (32)	22.1% (17)
Complete secondary	45.9% (72)	36.4% (28)
Post-secondary	17.2% (27)	20.8% (16)
Household owns, % (n)		
Mobile phone	86.3% (138)	87.0% (67)
Television	41.9% (67)	49.4% (38)
Refrigerator	20.6% (33)	29.9% (23)
Mosquito net	73.1% (117)	63.6% (49)
Animal presence		
Household owns animals, % (n)	29.4% (47)	13.0% (10)
Animals live on the compound, % (n)	75.6% (121)	80.0% (56)
Number of animals owned by household, mean (SD)	2.0 (5.0)	1.6 (8.4)
Number of animals living on the compound, mean (SD)	6.1 (6.38)	9.2 (11.87)
Housing characteristics, %(n)		
Floors made out of cement/concrete	88.1% (141)	88.3% (68)
Walls made out of brick	89.4% (143)	94.8% (73)
Roof made out of tin	97.5% (156)	97.4% (75)
Dwelling has windows	95.0% (152)	98.7% (76)
Household uses charcoal (made from wood, traditional) for any purpose	95.0% (152)	94.8% (73)
Household uses traditional solid fuel stove (non-manufactured)	95.0% (152)	94.8% (73)
Money spent per week by household in USD, mean (SD)	18.2 (15.9)	14.7 (14.5)
Asset-based wealth quintiles, % (n)		
Bottom quintile	19.4% (31)	16.9% (13)
2nd quintile	21.3% (34)	18.2% (14)
3rd quintile	18.1% (29)	22.1% (17)
4th quintile	23.8% (38)	19.5% (15)
Top quintile	17.5% (28)	23.4% (18)
Water access		
Primary drinking water from improved source, % (n)	85.6% (137)	81.8% (63)
Type of water source, % (n)		
Tubewell/ borehole	26.3% (42)	11.7% (9)
Protected spring (has concrete lining)	0% (0)	1.3% (1)
Unprotected dug well	1.3% (2)	0% (0)
Protected dug well (has concrete lining)	6.9% (11)	3.9% (3)
Surface water (river, dam, lake, pond, stream, canal, channel)	0% (0)	2.6% (2)
Piped water into dwelling	7.5% (12)	10.4% (8)
Piped water into yard/plot	20.6% (33)	15.6% (12)
Piped water outside the compound	24.4% (39)	39.0% (30)
Vendor water (kiosk)	12.5% (20)	13.0% (10)
Other	0.6% (1)	2.6% (2)
Sanitation access		
Household has latrine, % (n)	98.8% (158)	98.7% (76)
Household has improved latrine, % (n)	66.3% (106)	63.6% (49)
Type of latrine, % (n)		
Flush / pour flush	1.9% (3)	0% (0)
Flush to piped sewer system	0% (0)	1.3% (1)
Flush to septic tank	8.9% (14)	4.0% (3)
Flush to pit latrine	0.6% (1)	1.3% (1)
Pit latrine without slab / Open pit	0.6% (1)	0% (0)
Twin pit with slab	67.1% (106)	63.2% (48)
Twin pit without slab	26.0% (41)	32.9% (25)

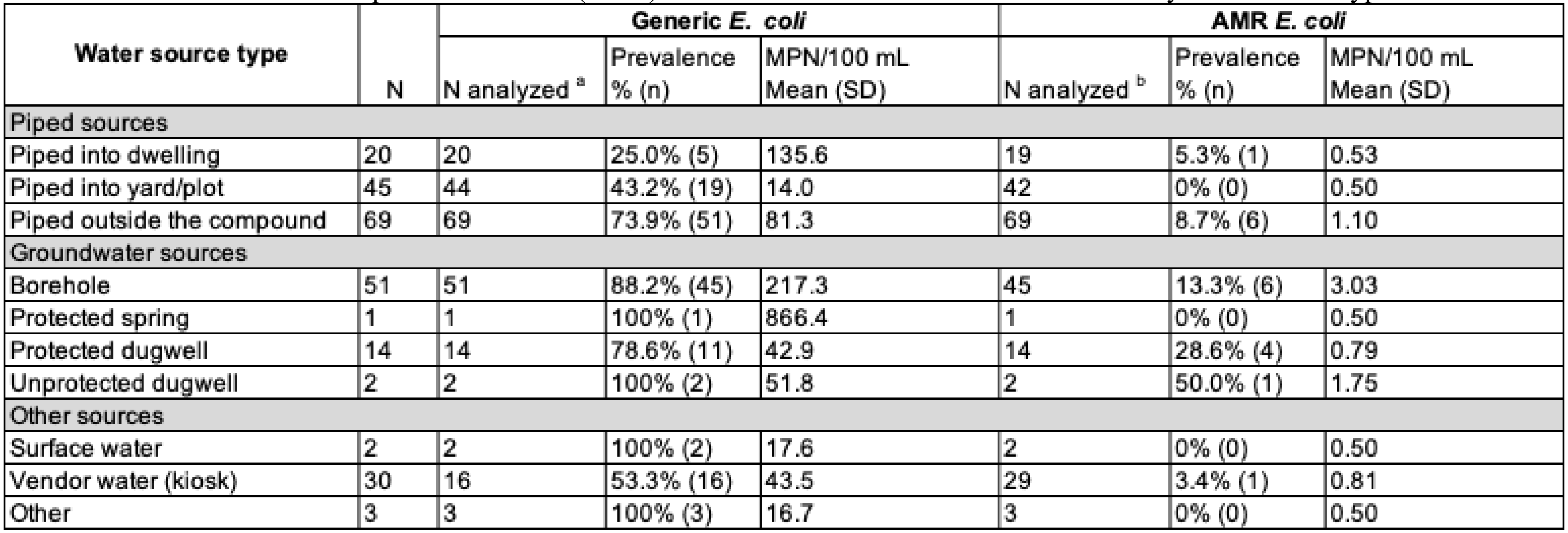
Table S2. Hygiene practices, water storage and secondary water sources by intermittency frequency and duration

	No	Frequency		Duration[a]	
	Intermittency	Rare	Frequent	Short	Long
	N=160	N=36	N=41	N=36	N=37
Domestic and hand hygiene					
Household has handwashing station, % (n)	9.4% (15)	11.1% (4)	12.2% (5)	5.6% (2)	16.2% (6)
Household has handwashing station with water % (n)	8.8% (14)	8.3% (3)	9.8% (4)	2.8% (1)	13.5% (5)
Household water insecurity score, mean (SD)	1.9 (4.2)	6.6 (5.2)	9.4 (6.3)	8.3 (6.8)	7.9 (5.2)
Truncated household water insecurity score, mean (SD)[b]	1.9 (4.2)	5.6 (5.2)	7.1 (6.3)	6.6 (6.7)	6.2 (5.1)
Had to go without sometimes/often/always, % (n)					
Washing clothes	9.4% (15)	30.6% (11)	41.5% (17)	33.3% (12)	37.8% (14)
Bathing	1.3% (2)	5.6% (2)	14.6% (6)	11.1% (4)	10.8% (4)
Washing hands after dirty activities	3.1% (5)	2.8% (1)	7.3% (3)	0% (0)	8.1% (3)
Reported handwashing occasions, % (n)					
Never	1.3% (2)	0% (0)	0% (0)	0% (0)	0% (0)
After defecation	90% (144)	100% (36)	90.2% (37)	91.7% (33)	97.3% (36)
After handling child's waste	63.1% (101)	47.2% (17)	73.2% (30)	63.9% (23)	56.8% (21)
After handling domestic animals	10% (16)	2.8% (1)	4.9% (2)	8.3% (3)	0% (0)
After handling animal feces	8.8% (14)	2.8% (1)	4.9% (2)	8.3% (3)	0% (0)
After working (garden, market, etc.)	25% (40)	11.1% (4)	19.5% (8)	27.8% (10)	5.4% (2)
After eating	81.3% (130)	91.7% (33)	68.3% (28)	69.4% (25)	86.5% (32)
Before eating	91.9% (147)	100% (36)	90.2% (37)	97.2% (35)	91.9% (34)
Before preparing food	69.4% (111)	69.4% (25)	56.1% (23)	58.3% (21)	62.2% (23)
Before feeding child	41.3% (66)	33.3% (12)	51.2% (21)	44.4% (16)	43.2% (16)
Before handling water (storage)	23.8% (38)	19.4% (7)	29.3% (12)	44.4% (16)	8.1% (3)
Before breastfeeding	7.5% (12)	2.8% (1)	14.6% (6)	11.1% (4)	5.4% (2)
Water storage					
Water sample provided from storage container, % (n)	87.5% (140)	100% (36)	92.7% (38)	100% (36)	91.9% (34)
Stored water container fully or partially covered, % (n)	78.8% (126)	83.3% (30)	78.0% (32)	88.9% (32)	75.7% (28)
Stored water container has narrow mouth, % (n)	17.5% (28)	11.1% (4)	0% (0)	2.8% (1)	8.1% (3)
Duration of water storage in hours, mean (SD, range)	32.6 (54.8, 0-577)	36.8 (47.4, 0-194)	23.3 (23.1, 0-72)	35.1 (44.9, 0-194)	25.6 (29, 0-146)
Water sample reported to be treated, % (n)	5.6% (9)	5.6% (2)	0% (0)	2.8% (1)	2.7% (1)
Secondary water sources					
Primary drinking water source feels acceptable, % (n)	89.4% (143)	91.7% (33)	78.0% (32)	80.6% (29)	89.2% (33)
Household obtains, % (n)					
Drinking water from secondary source	24.4% (39)	41.7% (15)	24.4% (10)	36.1% (13)	29.7% (11)
Drinking water from improved secondary source	8.8% (14)	27.8% (10)	9.8% (4)	22.2% (8)	16.2% (6)
Non-drinking water from improved source	65.6% (105)	66.7% (24)	63.4% (26)	66.7% (24)	59.5% (22)

[a] 4 households dropped from analysis because of missing data on intermittency duration.

[b] The truncated household water insecurity (HWISE) score excludes the intermittency question to allow comparing scores between intermittent and non-intermittent household.

Table S3. Prevalence and most probable number (MPN) of *E. coli* and cefotaxime-resistant *E. coli* by water source type



Water source type	N	Generic *E. coli*			AMR *E. coli*		
		N analyzed [a]	Prevalence % (n)	MPN/100 mL Mean (SD)	N analyzed [b]	Prevalence % (n)	MPN/100 mL Mean (SD)
Piped sources							
Piped into dwelling	20	20	25.0% (5)	135.6	19	5.3% (1)	0.53
Piped into yard/plot	45	44	43.2% (19)	14.0	42	0% (0)	0.50
Piped outside the compound	69	69	73.9% (51)	81.3	69	8.7% (6)	1.10
Groundwater sources							
Borehole	51	51	88.2% (45)	217.3	45	13.3% (6)	3.03
Protected spring	1	1	100% (1)	866.4	1	0% (0)	0.50
Protected dugwell	14	14	78.6% (11)	42.9	14	28.6% (4)	0.79
Unprotected dugwell	2	2	100% (2)	51.8	2	50.0% (1)	1.75
Other sources							
Surface water	2	2	100% (2)	17.6	2	0% (0)	0.50
Vendor water (kiosk)	30	16	53.3% (16)	43.5	29	3.4% (1)	0.81
Other	3	3	100% (3)	16.7	3	0% (0)	0.50

AMR: Antimicrobial-resistant, SD: Standard deviation, log-10 MPN/100 mL: log10-transformed most probable number per 100 mL

[a] 1 household missing water sample.

[b] 10 water samples not processed for AMR *E. coli.*

Table S4. Water quality vs. binary intermittency (N=236)

	No Intermittency	Intermittency	Intermittency vs. No Intermittency			
	N=159[a]	N=77	Unadjusted		Adjusted	
Prevalence	**% (n)**	**% (n)**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**
E. coli	66.0% (105)	64.0% (48)	0.98 (0.81, 1.20)	0.869	0.96 (0.79, 1.17)	0.691
AMR *E. coli* [b]	10.5% (16)	4.2% (3)	0.39 (0.21, 0.75)	0.084	0.48 (0.17, 1.40)	0.184
Log10-MPN	**Mean (SD)**	**Mean (SD)**	**ΔLog10 (95% CI)**	**p-value**	**ΔLog10 (95% CI)**	**p-value**
E. coli	0.8 (1.1)	0.7 (1.0)	-0.11 (-0.36, 0.14)	0.386	-0.07 (-0.30, 0.16)	0.554
AMR *E. coli* [b]	-0.2 (0.3)	-0.3 (0.2)	-0.04 (-0.13, 0.05)	0.342	-0.03 (-0.09, 0.03)	0.380

AMR: Antimicrobial-resistant, MPN: Most probable number, SD: Standard deviation, PR: Prevalence ratio, CI: Confidence interval, ΔLog10: Difference in log10-transformed most probable number

[a] 1 household missing water sample.

[b] 10 water samples not processed for AMR *E. coli.*

Table S5. Water quality vs. categorical intermittency frequency (N=236)

	None	Rare	Frequent	Rare vs. No Intermittency				Frequent vs. No Intermittency			
	N=159[a]	N=36	N=41	Unadjusted		Adjusted		Unadjusted		Adjusted	
Prevalence	**% (n)**	**% (n)**	**% (n)**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**
E. coli	66.0% (105)	69.4% (25)	61.0% (25)	1.05 (0.86, 1.29)	0.634	0.88 (0.68, 1.13)	0.306	0.92 (0.70, 1.23)	0.528	1.06 (0.83, 1.36)	0.647
Log10-MPN	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**ΔLog10 (95% CI)**	**p-value**	**ΔLog10 (95% CI)**	**p-value**	**ΔLog10 (95% CI)**	**p-value**	**ΔLog10 (95% CI)**	**p-value**
E. coli	0.8 (1.1)	0.8 (0.9)	0.6 (1.0)	0.00 (-0.23, 0.24)	0.972	-0.22 (-0.53, 0.09)	0.166	-0.21 (-0.55, 0.13)	0.222	0.09 (-0.18, 0.36)	0.517

AMR: Antimicrobial-resistant, MPN: Most probable number, SD: Standard deviation, PR: Prevalence ratio, CI: Confidence interval, ΔLog10: Difference in log10-transformed most probable number

[a] 1 household missing water sample.

Table S6. Water quality vs. categorical intermittency duration (N=232[a])

	None	Short	Long	Short vs. No Intermittency				Long vs. No Intermittency			
	N=159[b]	N=36	N=37	Unadjusted		Adjusted		Unadjusted		Adjusted	
Prevalence	**% (n)**	**% (n)**	**% (n)**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**
E. coli	66.0% (105)	66.7% (24)	62.2% (23)	1.01 (0.79, 1.30)	0.941	0.99 (0.73, 1.35)	0.956	0.94 (0.73, 1.21)	0.642	1.05 (0.83, 1.33)	0.672
Log10-MPN	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**ΔLog10 (95% CI)**	**p-value**	**ΔLog10 (95% CI)**	**p-value**	**ΔLog10 (95% CI)**	**p-value**	**ΔLog10 (95% CI)**	**p-value**
E. coli	0.8 (1.1)	0.8 (1.0)	0.6 (0.9)	0.01 (-0.39, 0.40)	0.980	-0.20 (-0.56, 0.16)	0.274	-0.23 (-0.48, 0.02)	0.080	-0.02 (-0.38, 0.32)	0.871

AMR: Antimicrobial-resistant, MPN: Most probable number, SD: Standard deviation, PR: Prevalence ratio, CI: Confidence interval, ΔLog10: Difference in log10-transformed most probable number

[a] 4 households dropped from analysis because of missing data on intermittency duration.

[b] 1 household missing water sample.

Table S7. Child health outcomes vs. binary intermittency (N=292)

	No Intermittency	**Intermittency**	**Intermittency vs. No Intermittency**			
	N=202	**N=90**	**Unadjusted**		**Adjusted**	
Prevalence	**% (n)**	**% (n)**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**
Diarrhea	16.3% (33)	31.1% (28)	1.90 (1.07, 3.37)	**0.027**	**1.94 (1.11, 3.39)**	**0.021**
WHO diarrhea	13.9% (28)	22.2% (20)	1.60 (1.03, 2.83)	0.103	1.63 (0.78, 3.39)	0.190
ARI	40.6% (82)	57.8% (52)	1.42 (1.09, 1.86)	**0.010**	1.43 (0.99, 2.09)	0.059
ARI with fever	17.3% (35)	38.9% (35)	2.24 (1.40, 3.59)	**0.001**	**2.00 (1.11, 3.60)**	**0.021**
Rash	11.9% (24)	16.7% (15)	1.40 (0.75, 2.61)	0.286	1.25 (0.60, 2.62)	0.551
Used antibiotics	29.7% (60)	41.1% (36)	1.38 (0.99, 1.93)	0.057	1.19 (0.85, 1.68)	0.318
Counts	**Mean (SD)**	**Mean (SD)**	**CR (95% CI)**	**p-value**	**CR (95% CI)**	**p-value**
Times of antibiotic use	1.0 (2.6)	1.7 (3.7)	1.74 (0.99, 3.06)	0.055	1.49 (0.84, 2.13)	0.226

SD: Standard deviation, PR: Prevalence ratio, CI: Confidence interval, CR: Count ratio

Table S8. Child health outcomes vs. categorical intermittency frequency (N=292)

	None	**Rare**	**Frequent**	**Rare vs. No Intermittency**				**Frequent vs. No Intermittency**			
	N=202	**N=39**	**N=51**	**Unadjusted**		**Adjusted**		**Unadjusted**		**Adjusted**	
Prevalence	**% (n)**	**% (n)**	**% (n)**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**
Diarrhea	16.3% (33)	33.3% (13)	29.4% (15)	2.04 (0.95, 4.39)	0.068	**2.15 (1.10, 4.21)**	**0.025**	1.80 (0.93, 3.49)	0.082	1.72 (0.91, 3.26)	0.096
WHO diarrhea	13.9% (28)	25.6% (10)	19.6% (10)	1.85 (0.89, 3.84)	0.097	2.01 (0.87, 4.64)	0.102	1.41 (0.72, 2.77)	0.312	1.29 (0.60, 2.78)	0.516
ARI	40.6% (82)	48.7% (19)	64.7% (33)	1.20 (0.81, 1.78)	0.363	1.12 (0.69, 1.82)	0.654	1.59 (1.25, 2.03)	**<.0005**	**1.72 (1.19, 2.50)**	**0.004**
ARI with fever	17.3% (35)	33.3% (13)	41.1% (22)	1.92 (1.02, 3.64)	**0.045**	1.66 (0.84, 3.27)	0.145	2.49 (1.62, 3.82)	**<.0005**	**2.28 (1.23, 4.21)**	**0.009**
Rash	11.9% (24)	23.1% (9)	11.8% (6)	1.94 (1.17, 3.23)	**0.011**	1.69 (0.81, 3.51)	0.159	0.99 (0.39, 2.53)	0.984	0.78 (0.25, 2.44)	0.674
Used antibiotics	29.7% (60)	41.0% (16)	41.2% (21)	1.38 (0.89, 2.14)	0.148	1.19 (0.73, 1.92)	0.485	1.39 (0.96, 2.00)	0.083	1.19 (0.85, 1.66)	0.300
Counts	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**CR (95% CI)**	**p-value**	**CR (95% CI)**	**p-value**	**CR (95% CI)**	**p-value**	**CR (95% CI)**	**p-value**
Times of antibiotic use	1.0 (2.6)	1.6 (2.3)	1.8 (4.53)	1.62 (0.82, 3.19)	0.163	**2.02 (1.03, 3.99)**	**0.042**	1.83 (0.87, 3.84)	0.111	1.17 (0.40, 3.43)	0.780

SD: Standard deviation, PR: Prevalence ratio, CI: Confidence interval, CR: Count ratio

Table S9. Child health outcomes vs. categorical intermittency duration (N=287[a])

	None	**Short**	**Long**	**Short vs. No Intermittency**				**Long vs. No Intermittency**			
	N=202	**N=45**	**N=40**	**Unadjusted**		**Adjusted**		**Unadjusted**		**Adjusted**	
Prevalence	**% (n)**	**% (n)**	**% (n)**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**
Diarrhea	16.3% (33)	37.8% (17)	25.0% (10)	2.31 (1.10, 4.86)	**0.027**	**2.21 (1.05, 4.65)**	**0.036**	1.53 (0.84, 2.79)	0.166	1.58 (0.79, 3.17)	0.193
WHO diarrhea	13.9% (28)	24.4% (11)	20.0% (8)	1.76 (0.91, 3.42)	0.094	1.76 (0.93, 3.33)	0.084	1.44 (0.69, 3.03)	0.323	1.48 (0.51, 4.26)	0.472
ARI	40.6% (82)	53.3% (24)	65.0% (26)	1.31 (0.95, 1.81)	0.096	1.31 (0.90, 1.90)	0.159	1.60 (1.18, 2.17)	**0.003**	**1.61 (1.02, 2.55)**	**0.042**
ARI with fever	17.3% (35)	33.3% (15)	47.5% (19)	1.92 (1.14, 3.25)	**0.015**	1.51 (0.78, 2.91)	0.222	2.74 (1.74, 4.31)	**<.0005**	**2.58 (1.53, 4.34)**	**<.0005**
Rash	11.9% (24)	20.0% (9)	12.5% (5)	1.68 (0.90, 3.15)	0.103	1.49 (0.65, 3.39)	0.344	1.05 (0.44, 2.51)	0.909	1.09 (0.42, 2.88)	0.857
Used antibiotics	29.7% (60)	42.2% (19)	42.5% (17)	1.42 (0.94, 2.14)	0.094	1.34 (0.91, 1.97)	0.137	1.43 (0.84, 2.44)	0.188	1.13 (0.64, 2.00)	0.662
Counts	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**CR (95% CI)**	**p-value**	**CR (95% CI)**	**p-value**	**CR (95% CI)**	**p-value**	**CR (95% CI)**	**p-value**
Times of antibiotic use	1.0 (2.6)	1.2 (1.9)	2.4 (5.2)	1.24 (0.66, 2.34)	0.500	1.79 (0.94, 3.44)	0.079	2.46 (1.17, 5.17)	**0.018**	1.68 (0.47, 5.99)	0.426

SD: Standard deviation, PR: Prevalence ratio, CI: Confidence interval, CR: Count ratio

[a] 5 children dropped from analysis because of missing data on intermittency duration.

Table S10. Caregiver stress vs. binary intermittency (N=237)

	No Intermittency	**Intermittency**	**Intermittency vs. No Intermittency**			
	N=160	**N=77**	**Unadjusted**		**Adjusted**	
Stress score	**Mean (SD)**	**Mean (SD)**	**ΔPSS (95% CI)**	**p-value**	**ΔPSS (95% CI)**	**p-value**
PSS composite score[a]	18.8 (6.3)	21.6 (6.8)	**2.85 (1.36, 4.34)**	**<.0005**	1.17 (-0.46, 2.80)	0.160
Prevalence	**% (n)**	**% (n)**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**
High stress*	9.4% (15)	22.4% (17)	**2.39 (1.26, 4.53)**	**0.008**	1.65 (0.81, 3.33)	0.167
Upset by unexpected events	13.1% (21)	23.4% (18)	**1.78 (1.07, 2.96)**	**0.026**	1.47 (0.90, 2.42)	0.128
Unable to control things[a]	12.5% (20)	31.6% (24)	**2.53 (1.40, 4.56)**	**0.002**	1.73 (0.99, 3.00)	0.053
Nervous or stressed	18.8% (30)	31.2% (24)	1.66 (1.00, 2.77)	0.051	1.44 (0.84, 2.48)	0.186
Not confident to solve problems	11.9% (19)	18.2% (14)	1.53 (0.83, 2.82)	0.170	1.99 (0.86, 4.59)	0.106
Not feeling things go their way	20.6% (33)	15.6% (12)	0.76 (0.44, 1.31)	0.316	0.96 (0.52, 1.77)	0.896
Unable to cope	15.6% (25)	26.0% (20)	**1.66 (1.01, 2.73)**	**0.045**	1.16 (0.67, 2.00)	0.596
Unable to control irritations	18.1% (29)	7.8% (6)	**0.43 (0.2, 0.94)**	**0.035**	**0.36 (0.19, 0.71)**	**0.003**
Not on top of things	18.8% (30)	13.0% (10)	0.69 (0.40, 1.20)	0.191	0.82 (0.47, 1.42)	0.472
Angry	11.3% (18)	27.3% (21)	**2.42 (1.23, 4.79)**	**0.011**	1.74 (0.96, 3.17)	0.069
Difficulties pile up	20.6% (33)	32.5% (25)	**1.57 (1.02, 2.42)**	**0.039**	1.17 (0.77, 1.78)	0.464

PSS: Perceived stress scale, SD: Standard deviation, ΔPSS: Difference in PSS composite score, CI: Confidence interval, PR: Prevalence ratio

[a] PSS composite score could not be calculated for 1 household that had a missing response to one question in the 10-question scale.

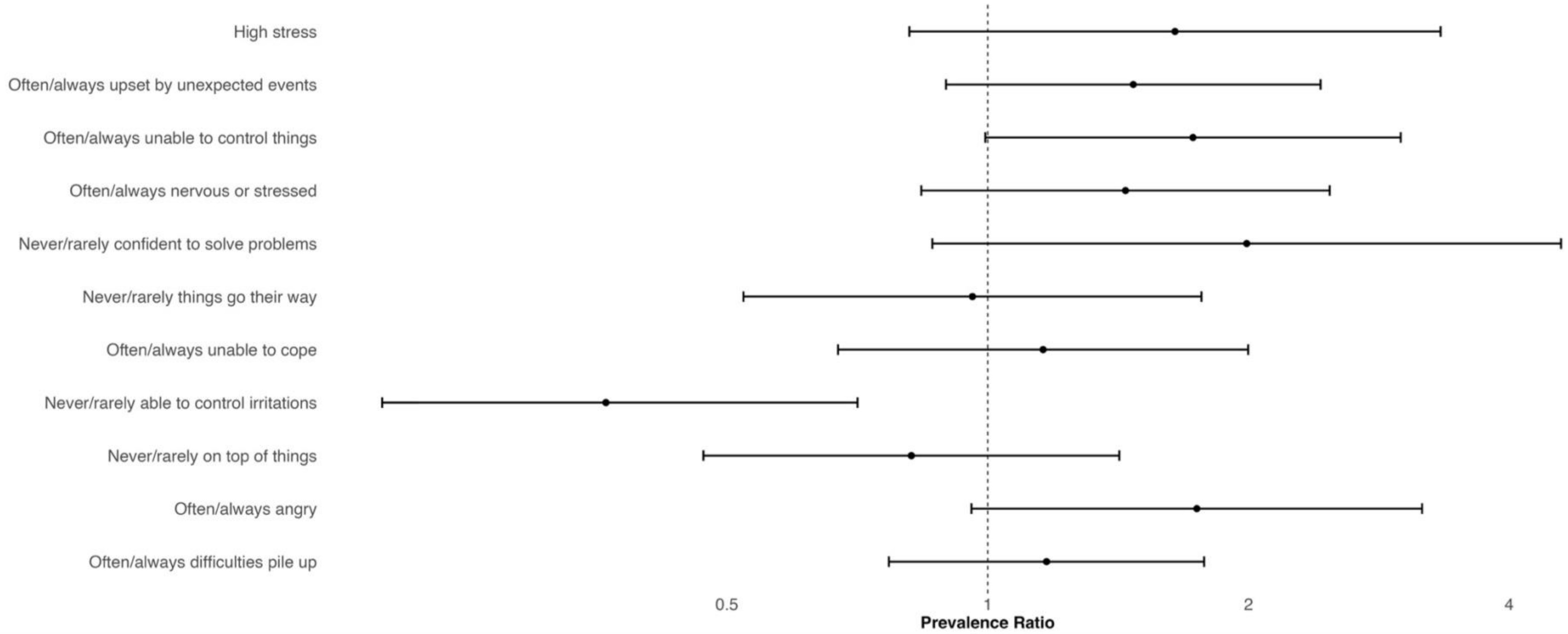


Figure S2. Forest plot of associations between water intermittency and self-reported caregiver stress. The circles denote point estimates for prevalence ratios and the horizontal lines denote the 95% confidence intervals. Models controlled for age of the respondent, age of the target child, total number of individuals living in household, respondent's highest level of education, highest level of education level for anyone in household, asset-based household wealth quintile, average weekly expenditures by household, household food insecurity score, whether household used piped water for their primary water source, whether household's designated handwashing station had soap, whether household had an improved latrine (as defined by the WHO), flooring material inside household, total number of animals in compound, and respondent's report of the last time it rained.

Table S11. Caregiver stress vs. categorical intermittency frequency (N=237)

	None	**Rare**	**Frequent**	**Rare vs. No Intermittency**				**Frequent vs. No Intermittency**			
	N=160	**N=36**	**N=41**	**Unadjusted**		**Adjusted**		**Unadjusted**		**Adjusted**	
Stress score	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**ΔPSS (95% CI)**	**p-value**	**ΔPSS (95% CI)**	**p-value**	**ΔPSS (95% CI)**	**p-value**	**ΔPSS (95% CI)**	**p-value**
PSS composite score[a]	18.8 (6.3)	19.9 (6.28)	23.2 (6.73)	1.08 (-0.78, 2.94)	0.256	0.19 (-1.90, 2.28)	0.860	4.44 (2.39, 6.50)	**<.0005**	2.15 (0.24, 4.06)	**0.028**
Prevalence	**% (n)**	**% (n)**	**% (n)**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**
High stress*	9.4% (15)	11.1% (4)	32.5% (13)	1.19 (0.36, 3.85)	0.778	0.98 (0.33, 2.92)	0.976	3.47 (1.77, 6.81)	**<.0005**	2.05 (0.99, 4.25)	0.052
Upset by unexpected events	13.1% (21)	16.7% (6)	29.3% (12)	1.27 (0.59, 2.71)	0.538	0.61 (0.62, 2.24)	0.614	2.23 (1.20, 4.14)	**0.011**	1.67 (0.99, 2.84)	0.056
Unable to control things[a]	12.5% (20)	25.0% (9)	37.5% (15)	2.00 (0.93, 4.29)	0.075	1.48 (0.72, 3.06)	0.286	3.00 (1.48, 6.07)	**0.002**	1.97 (0.89, 4.38)	0.094
Nervous or stressed	18.8% (30)	27.8% (10)	34.2% (14)	1.48 (0.79, 2.76)	0.217	1.36 (0.66, 2.84)	0.406	1.82 (0.99, 3.34)	**0.053**	1.51 (0.75, 3.06)	0.250
Not confident to solve problems	11.9% (19)	25.0% (9)	12.2% (5)	2.11 (1.06, 4.20)	**0.034**	2.56 (0.95, 6.95)	0.064	1.03 (0.43, 2.46)	0.952	1.25 (0.48, 3.21)	0.650
Not feeling things go their way	20.6% (33)	25.0% (9)	7.3% (3)	1.21 (0.67, 2.19)	0.523	1.38 (0.66, 2.87)	0.387	0.36 (0.14, 0.91)	**0.031**	0.43 (0.66, 2.87)	0.062
Unable to cope	15.6% (25)	19.4% (7)	31.7% (13)	1.24 (0.57, 2.71)	0.582	1.01 (0.43, 2.39)	0.979	2.03 (1.13, 3.64)	**0.018**	1.28 (0.67, 2.45)	0.458
Unable to control irritations	18.1% (29)	5.6% (2)	9.8% (4)	0.31 (0.11, 0.89)	**0.029**	**0.30 (0.09, 0.94)**	**0.039**	0.54 (0.17, 1.68)	0.286	0.42 (0.17, 1.01)	0.053
Not on top of things	18.8% (30)	22.2% (8)	4.9% (2)	1.19 (0.68, 2.06)	0.548	1.20 (0.59, 2.45)	0.608	0.26 (0.08, 0.89)	**0.031**	0.36 (0.10, 1.26)	0.110
Angry	11.3% (18)	27.8% (10)	26.8% (11)	2.47 (1.21, 5.04)	**0.013**	**2.21 (1.06, 4.61)**	**0.034**	2.38 (1.03, 5.54)	**0.044**	1.43 (0.73, 2.79)	0.292
Difficulties pile up	20.6% (33)	33.3% (12)	31.7% (13)	1.62 (1.06, 2.45)	**0.024**	1.22 (0.68, 2.17)	0.509	1.54 (0.86, 2.75)	0.148	1.13 (0.71, 1.81)	0.601

PSS: Perceived stress scale, SD: Standard deviation, ΔPSS: Difference in PSS composite score, CI: Confidence interval, PR: Prevalence ratio

[a] PSS composite score could not be calculated for 1 household that had a missing response to one question in the 10-question scale.

Table S12. Caregiver stress vs. categorical intermittency duration (N=233[a])

	None	**Short**	**Long**	**Short vs. No Intermittency**				**Long vs. No Intermittency**			
	N=160	**N=36**	**N=37**	**Unadjusted**		**Adjusted**		**Unadjusted**		**Adjusted**	
Stress score	**Mean (SD)**	**Mean (SD)**	**Mean (SD)**	**ΔPSS (95% CI)**	**p-value**	**ΔPSS (95% CI)**	**p-value**	**ΔPSS (95% CI)**	**p-value**	**ΔPSS (95% CI)**	**p-value**
PSS composite score[b]	18.8 (6.3)	22.2 (7.2)	21.4 (6.5)	3.39 (1.09, 5.68)	**0.004**	**1.74 (0.08, 3.40)**	**0.039**	2.58 (0.58, 4.58)	**0.012**	0.42 (-1.69, 2.53)	0.696
Prevalence	**% (n)**	**% (n)**	**% (n)**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**	**PR (95% CI)**	**p-value**
High stress*	9.4% (15)	27.8% (10)	19.4% (7)	2.96 (1.39, 6.30)	**0.005**	1.77 (0.77, 4.05)	0.177	2.07 (0.96, 4.47)	0.062	1.60 (0.75, 3.42)	0.224
Upset by unexpected events	13.1% (21)	25.0% (9)	21.6% (8)	1.90 (1.07, 3.40)	**0.029**	1.64 (0.95, 2.86)	0.077	1.65 (0.77, 3.54)	0.201	1.25 (0.66, 2.38)	0.489
Unable to control things[b]	12.5% (20)	36.1% (13)	27.8% (10)	2.89 (1.50, 5.55)	**0.001**	**1.95 (1.09, 3.50)**	**0.025**	2.22 (1.05, 4.68)	**0.036**	1.48 (0.76, 2.86)	0.248
Nervous or stressed	18.8% (30)	61.1% (22)	24.3% (9)	2.07 (1.28, 3.35)	**0.003**	**2.12 (1.09, 4.13)**	**0.028**	1.30 (0.58, 2.89)	0.524	0.95 (0.54, 1.66)	0.848
Not confident to solve problems	11.9% (19)	25.0% (9)	13.5% (5)	2.11 (1.06, 4.20)	**0.034**	**3.39 (1.30, 8.81)**	**0.012**	1.14 (0.51, 2.55)	0.753	1.54 (0.48, 5.00)	0.469
Not feeling things go their way	20.6% (33)	16.7% (6)	13.5% (5)	0.81 (0.38, 1.74)	0.586	1.17 (0.55, 2.48)	0.690	0.66 (0.32, 1.35)	0.253	0.82 (0.36, 1.87)	0.632
Unable to cope	15.6% (25)	27.8% (10)	21.6% (8)	1.78 (0.76, 4.16)	0.184	1.31 (0.57, 3.00)	0.529	1.38 (0.77, 2.50)	0.281	0.86 (0.41, 1.83)	0.703
Unable to control irritations	18.1% (29)	8.3% (3)	8.1% (3)	0.46 (0.19, 1.10)	0.082	0.49 (0.21, 1.13)	0.093	0.45 (0.11, 1.77)	0.251	**0.34 (0.13, 0.88)**	**0.026**
Not on top of things	18.8% (30)	13.9% (5)	10.8% (4)	0.74 (0.32, 1.70)	0.478	0.92 (0.41, 2.07)	0.844	0.58 (0.24, 1.39)	0.220	0.71 (0.28, 1.80)	0.464
Angry	11.3% (18)	30.6% (11)	24.3% (9)	2.72 (1.25, 5.92)	**0.012**	**2.18 (1.07, 4.43)**	**0.031**	2.16 (0.98, 4.75)	**0.055**	1.34 (0.70, 2.58)	0.378
Difficulties pile up	20.6% (33)	30.6% (11)	35.1% (13)	1.48 (0.83, 2.63)	0.180	1.08 (0.62, 1.87)	0.792	1.70 (1.07, 2.72)	**0.025**	1.29 (0.75, 2.19)	0.355

PSS: Perceived stress scale, SD: Standard deviation, ΔPSS: Difference in PSS composite score, CI: Confidence interval, PR: Prevalence ratio

[a] 4 households dropped from analysis because of missing data on intermittency duration.

[b] PSS composite score could not be calculated for 1 household that had a missing response to one question in the 10-question scale.