## Title
Effects of extreme weather, water treatment, and COVID-19 on water quality and child health in rural Kenya



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Effects of extreme weather, water treatment, and COVID-19
on water quality and child health in rural Kenya

By

Julie Powers

A dissertation submitted in partial satisfaction of the
requirements for the degree of
Doctor of Philosophy
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Committee in charge:
Professor Amy J. Pickering, Chair
Professor Kara Nelson
Professor John Colford Jr.

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Abstract

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In 2019, approximately 5 million children died before reaching age five, largely due to preventable or treatable causes. Water treatment could interrupt diarrheal disease transmission, and reduce child mortality, but 2 billion people still lack access to safe water at home. Both climate change and the COVID-19 pandemic may affect the ways in which infectious disease are transmitted. This dissertation examines water treatment and child health in rural Kenya and provides evidence of how climate change and the COVID-19 pandemic have affected infectious disease transmission.

**Chapter 1** presents background information on the global burden of diarrheal diseases and other diseases associated with poverty, discusses evidence for water treatment as an intervention strategy, outlines the potential implications of climate change and the COVID-19 pandemic, and describes the study areas in rural western Kenya. **Chapter 2** provides evidence for the effects of climate change on diarrheal disease transmission by quantifying the effects of extreme weather (heavy precipitation and high temperature) on bacteria levels in two key transmission pathways: drinking water and hands. We find that heavy precipitation and high temperature increase bacteria levels in drinking water but decreases bacteria levels on child hands. The relationship between heavy precipitation and bacteria in stored water holds only when households have not treated their water, suggesting that water treatment is an appropriate mitigation strategy and may be particularly important after periods of heavy precipitation or high temperature. **Chapter 3** evaluates one such water treatment intervention at drinking water kiosks in Kisumu, Kenya. The Venturi chlorine doser can be attached to any pipe outflow. We evaluate the technical feasibility and kiosk and customer demand for the device. We find that the device reliably doses water with liquid chlorine. We also find that kiosks were willing to pay to lease or lease-to-own the device, and that customers reported buying chlorinated water. The COVID-19 pandemic has disrupted daily activities world-wide and may have affected infectious disease transmission. **Chapter 4** examines the effects of the COVID-19 pandemic on child mortality and respiratory illness in the study area in rural Kenya. Finally, **Chapter 5** concludes the dissertation by summarizing my research findings and discussing overarching themes.

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# CHAPTER 1. Introduction

## 1.1 DISEASES OF POVERTY

In 2019, approximately 5 million children died before reaching age five and nearly half of these children died in their first 28 days of life. The top causes of under-5 child mortality were neonatal disorders[a] (37.3%), lower respiratory infections (13.3%), and diarrheal diseases (9.9%)[1]. Many of these deaths could have been averted with basic prevention and treatment measures including WASH interventions (water treatment, sanitation, and hygiene), immunizations, and access to healthcare with a trained provider[2]. The burden of under-5 deaths is much higher in low-income countries than in high-income countries[1]. In 2020, the under-5 child mortality rate in Kenya was 41.9 deaths per 1,000 live births, more than six times the under-5 child mortality rate in the United States (6.3 deaths per 1,000 live births)[3]. The cause-specific under-5 mortality rates for the top causes of death were also higher in Kenya than in the United States and were particularly disparate for diarrheal deaths: the rate in Kenya was 382 times the rate in the United States (Table 1-1)[1].

Table 1-1: Cause-specific under-5 child mortality in Kenya and the United States in 2019.

Data is from the 2019 Global Burden of Disease Study[1]. Rates show the number of deaths per 100,000 population of under-5 children. Only the top 3 causes of under-5 mortality globally are included: neonatal disorders, lower respiratory infections, and diarrheal diseases.

| Cause | Kenya under-5 mortality rate | United States under-5 mortality rate | Kenya Rate / US Rate |
|---|---|---|---|
| Neonatal disorders | 285 | 58 | 5 |
| Diarrheal diseases | 122 | 0.3 | 382 |
| Lower respiratory infections | 98 | 3 | 35 |

Diarrhea is usually caused by enteric pathogen infections, which may be bacterial, viral, or parasitic[4]. Enteric pathogens are transmitted via the faecal-oral route: contaminated feces from an infected human or animal spread through environmental pathways and are ingested by another person (Figure 1-1)[4–8]. In addition to mortality, diarrhea has been associated with poor health outcomes including reduced linear growth[9–12], malnutrition[9,11,13], and cognitive impairment[9,14–16], the impacts of which could last into adulthood[17,18].

[a] According to Global Burden of Disease classifications, neonatal disorders include complications due to preterm birth, birth asphyxia/trauma, sepsis and other infections, jaundice, and other neonatal disorders[1].

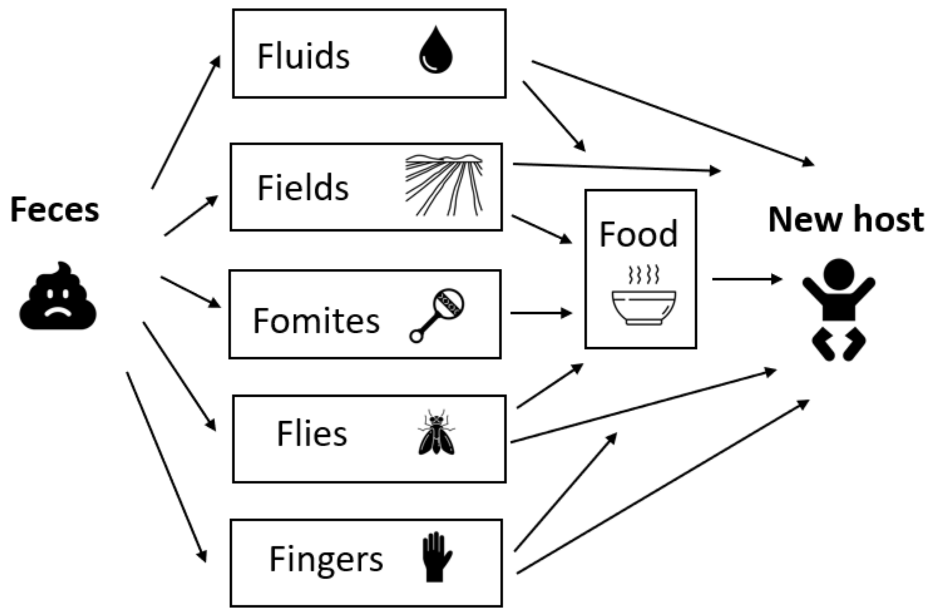


Figure 1-1 F-diagram of fecal transmission pathways[19]

Adapted from Wagner & Lanoix, 1958

## 1.2 WATER TREATMENT

### 1.2.1 Evidence of impact

Water treatment has been advocated as a solution to interrupt transmission of diarrheal diseases, particularly for the 2 billion people who still lack access to safe water at home[20]. According to recent systematic reviews of randomized controlled trial (RCT) evidence, treating water with chlorine solution leads to an estimated 23% reduction in diarrhea risk[21] and treating water (variety of methods) leads to a 30% reduction in the odds of child mortality[22]. The observed reduction in child mortality is larger than would be expected based on averting deaths due to diarrhea alone, suggesting that water treatment may also reduce deaths due to other causes.

One potential pathway is through reduced risk of respiratory infections. A few studies have found that diarrhea may increase the risk of lower respiratory infections. A time-to-event analysis in Ghana found that any diarrhea in the past two weeks increased the hazard rate of lower respiratory infection and estimated that 26% of lower respiratory cases may be due to diarrhea in the past two weeks. They also found that the effect increased approximately linearly with each additional day of diarrhea, demonstrating a strong dose-response relationship[23]. Cohort studies in India and Nepal found a similar dose-response relationship[24]. Studies in Pakistan and among Bedouin children living in Israel found that diarrhea increased risk of pneumonia, a specific type of lower respiratory infection[25,26]. Water treatment interventions that reduce diarrhea risk could also reduce the risk of respiratory infections. A recent randomized controlled trial in Rwanda also supports this hypothesis. They distributed both water filters and a clean cookstove intervention and found that the intervention reduced fecal contamination in drinking water samples but did not affect air quality. However, both diarrhea and lower respiratory infections were reduced, leading the authors to hypothesize that the reduction of diarrhea due to water treatment may have also contributed to reduced lower respiratory infections[27]. This potential synergistic effect is significant because lower respiratory infections and diarrhea are the second and third leading cause of under-5 deaths, respectively.

Despite the above evidence of impact, several recent randomized controlled trials have found that water treatment interventions are not always effective in reducing diarrhea or improving child growth[28–30]. The interventions in these trials included manual chlorine dispensers installed at water sources[30] and chlorine delivery for household water treatment[28–30]. Trial investigators have suggested that very frequent contact with participants may be necessary to achieve high adherence and reduce diarrhea: most studies that observed a reduction in diarrhea had daily to fortnightly contact with promoters[31], while promoters in these trials visited participants monthly[28,30] to six times monthly. Low adherence to existing interventions highlights the need for innovative, low-cost technologies that require drastically less behavior change.

### 1.2.2 Access to water treatment

Despite the potential benefits, lack of access to water treatment is still a major challenge. In 2020, 2 billion people (26% of the global population) did not have access to safely managed[b] drinking water. Lack of access to safely managed drinking water is even more severe in rural areas, where 40% of people lack access[20]. The United Nations Sustainable Development Goals were established in 2015, with Sustainable Development Goal 6 calling for universal and equitable access to safe water and sanitation by 2030[32]. Progress has been made toward this goal: the proportion of the global population with access to safely managed drinking water has increased from 70% in 2015 to 74% in 2020. However, the current rate of progress is insufficient to ensure universal access by 2030. A recent Joint Monitoring Report estimated that achieving universal access to safely managed drinking water by 2030 would require a quadrupling of current rates of progress[20].

## 1.3 POTENTIAL EFFECTS OF CLIMATE CHANGE

Human health is sensitive to shifts in weather patterns; it is predicted that climate change will severely impact human health including through increased risk of diarrheal diseases [33,34]. Large uncertainties are associated with projecting the severity of the impact on diarrhea due to climate change, and more empirical data is needed to better understand the relationships between climate and human health [33]. Because diarrhea is the third leading cause of death for children under 5, even small increases in risk would represent significant impacts.

[b] According to the Joint Monitoring Program, safely managed drinking water is water that is from an improved source that is accessible on premises, available when needed, and free from fecal and priority chemical contamination[20].

## 1.4 POTENTIAL EFFECTS OF THE COVID-19 PANDEMIC

On March 12, 2020, the World Health Organization declared COVID-19 a global pandemic[35]. As of December 2022, there have been more than 640 million cases and 6.6 million deaths worldwide[36]. In response to the pandemic, many governments closed schools and businesses, issued curfews and stay-at-home orders, and required masking in public places. In Kenya, schools were closed for 6 to 10 months[37,38]. The pandemic drastically changed the ways that people interacted with each other worldwide. The pandemic and associated response measures may have also affected the prevalence and transmission of infectious diseases.

## 1.5 SITE-SPECIFIC CONTEXT

The study site for Chapters 2 and 4 is in rural areas of Kakamega, Bungoma, and Vihiga counties. Chapter 3 took place in rural and peri-urban areas of Kisumu County, which is located directly south of Vihiga county (Figure 1-2).

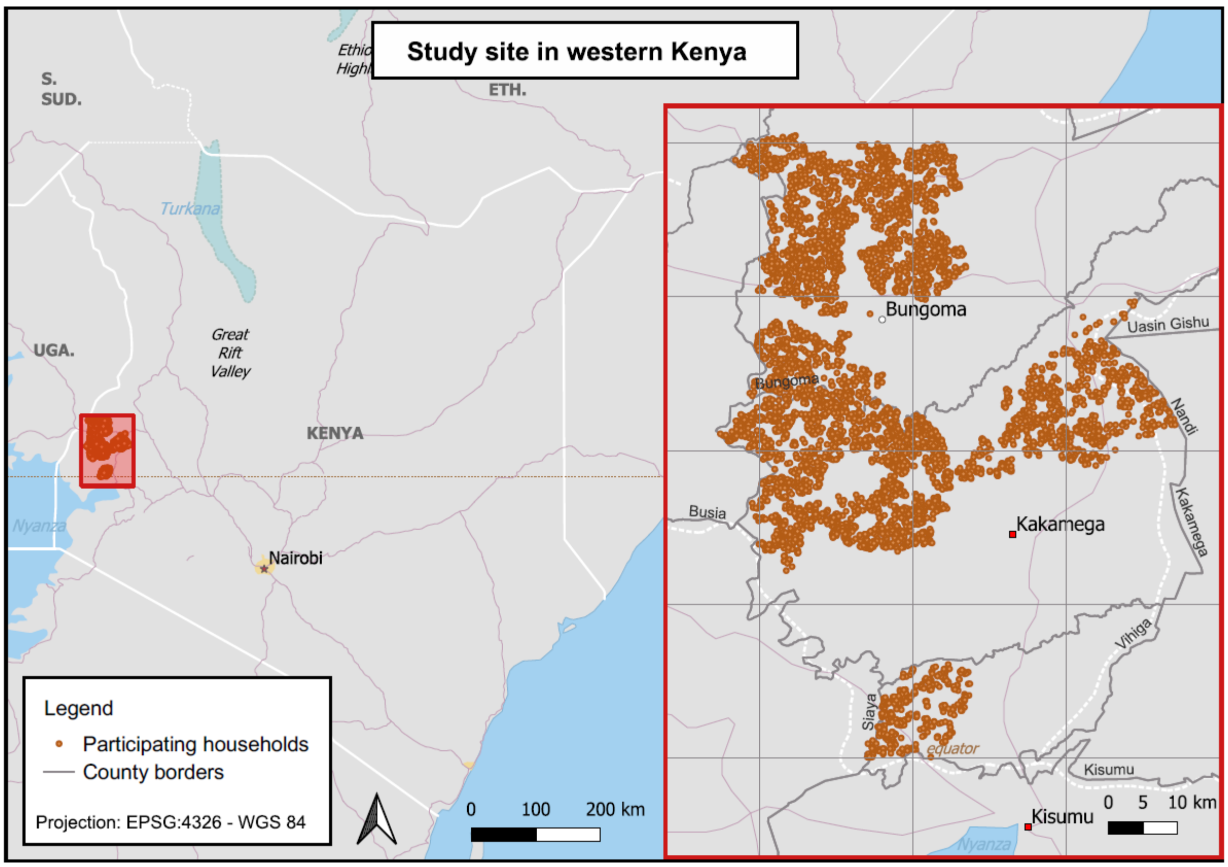


Figure 1-2 Study site in western Kenya for Chapters 2 and 4.

Households included in Chapter 2 are plotted.

### 1.5.1 A brief history of colonization and independence in Kenya

A basic understanding of the history of colonization and independence in Kenya is informative for understanding the study context and the social and political factors that have affected poverty in the region. In 1884, major European powers met in Berlin to decide how they would divide control of Africa, with Britain, France, Portugal, Germany, Italy, and Spain each laying claim to portions of the continent. No African representatives were present[39]. The Imperial British East Africa Company sent its first expedition through Kenya in 1890. In 1895, Great Britain declared a protectorate over what is now Kenya and Uganda, termed British East Africa (Figure 1-3)[39,40]. British expeditions included confiscating livestock, looting villages, and killing native Africans. Between 1895 and 1901, the British Protectorate built the Ugandan Railway from Mombasa to Lake Victoria, relying largely on Indian labor. To help make the railway profitable, the commissioner of the protectorate encouraged British and South Africans to settle there and farm cash crops.[39,40] By 1916, British farmers had claimed 5 million acres of land[39]. During World War I, British and German forces clashed in East Africa, and thousands of Africans were forced to join as soldiers and porters. In 1920, the East Africa protectorate became a British colony called Kenya[39,40].


Figure 1-3 Imperial Partitions of Eastern Africa.

Source: Kenya. Encyclopedia Britannica (2022).

Though opposition to British colonialism had always existed, pressure for political equality grew during the 1940s. Africans were not allowed the same rights as white settlers, and members of some tribes had been relocated to native reserves. Jomo Kenyatta emerged as the leader of the Kenya African Union, advocating for a peaceful transition to African majority rule[41]. Some (particularly among the Kikuyu tribe) felt that the Kenya African Union's approach had not been successful and advocated more aggressive measures, leading to the Mau Mau uprising. Counter measures were swift and aggressive. In 1952, the colonial government declared a state of emergency, arrested Jomo Kenyatta, and brought in military reinforcements[41]. During the eight years of fighting, at least 11,000 rebels were killed, with unofficial estimates as high as 25,000. In contrast, only 32 white settlers were killed[41,42]. Approximately 1 million Kikuyu were forcibly relocated and locked inside enclosed villages[43]. An estimated 80,000 – 100,000 people were detained, often for several years and under widespread torture[41–43].

In 1963, Kenya became independent after approximately 70 years of British colonial rule[40].

## 1.6 THE WASH BENEFITS KENYA TRIAL AND FOLLOW-UP

Here I provide background on the WASH Benefits Kenya trial, which is relevant to Chapters 2 and 4. The WASH Benefits Kenya trial[30,44] was a multi-armed randomized controlled trial of water treatment and other interventions which enrolled pregnant women in their second or third trimester and followed the children born from these pregnancies for their first 2 years of life. The trial took place in three counties in rural western Kenya: Bungoma, Kakamega, and Vihiga (Figure 1-2). WASH Benefits Kenya enrollment occurred between November 2012 and May 2014. The trial evaluated the effect of water treatment (W), improved sanitation (S), handwashing (H), nutritional supplementation (N), and combinations of these interventions (WSH, WSHN) on early child diarrhea and growth. In communities that were randomized to water treatment, chlorine solution dispensers were installed at public water sources and refilled as needed. The trial examined the effects of water treatment and other interventions on child diarrhea[30] and gross motor development[45] at year 1 and child diarrhea[30], linear growth[30], and communication, gross motor, and personal social development[45] at year 2. The trial also examined effects on fecal contamination in the household environment (drinking water, child hands, and toys) at years 1 and 2[46].

In Chapter 2, I leverage environmental *E. coli* contamination data collected during a three-year period of the WASH Benefits Study. In Chapter 4, I follow up on villages enrolled in the WASH Benefits study to examine the effects of the COVID-19 pandemic on child mortality and illness.

## 1.7 ORGANIZATION OF REMAINING CHAPTERS

The remaining chapters are organized as follows (Figure 1-4).

In Chapter 2, I examine the effects of 7-day high temperature (>32°C) and heavy precipitation (>90$^{th}$ percentile) on *E. coli* contamination levels in drinking water and on child hands.

In Chapter 3, I evaluate the technical performance and demand for a novel venturi chlorine doser at drinking water kiosks.

In Chapter 4, I assess the effects of the COVID-19 pandemic on child mortality and child health.

In Chapter 5, I summarize my research findings and make conclusions.

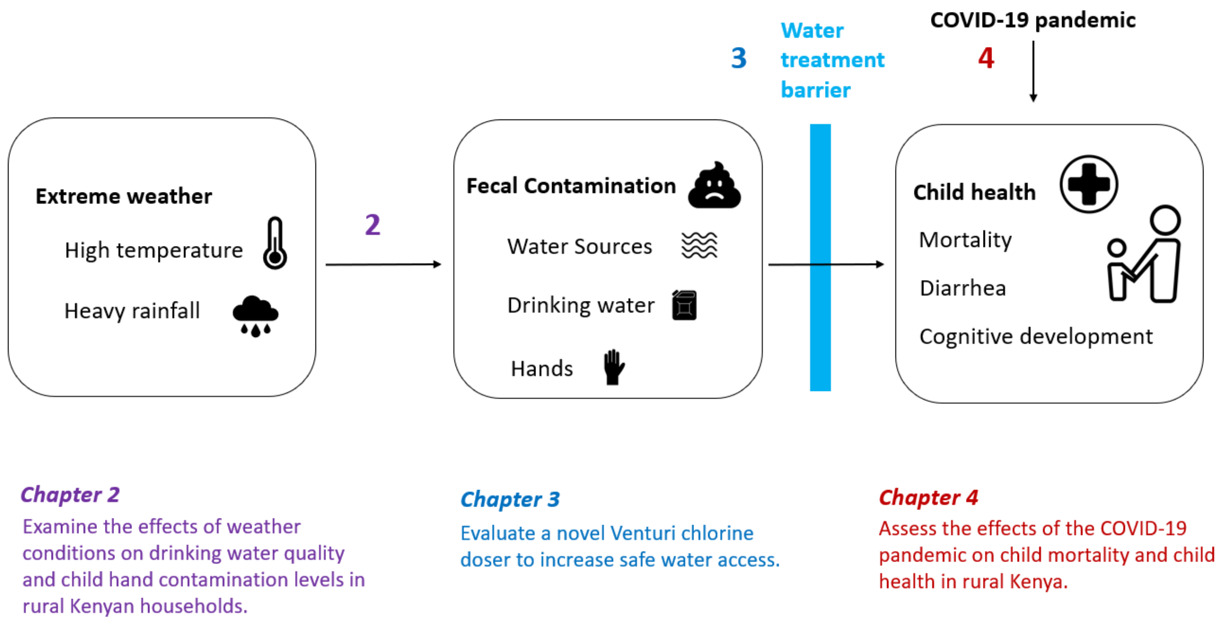


Figure 1-4 Conceptual diagram of dissertation chapters

# CHAPTER 2. Effects of weather conditions on drinking water quality and child hand contamination levels in rural Kenyan households

## 2.1 INTRODUCTION

In recent years, progress has been made in reducing the global burden of diarrhea: Among children under 5 years between 2005 and 2015, the mortality rate due to diarrhea (deaths due to diarrhea per population) decreased by 39.2% and diarrhea incidence decreased by 10.4%[47]. Diarrhea incidence has not decreased as quickly as diarrhea-associated mortality, suggesting that improved access to treatment may be largely responsible for the reductions in mortality. Extreme weather associated with climate change could threaten recent progress[33] because temperature[48–54] and heavy rainfall[51,54–56] are positively associated with diarrhea. A systematic review by Levy et al. identified 53 quantitative analyses (65%) showing a significant positive association between temperature and diarrhea and 10 quantitative analyses (71%) showing a significant positive association between heavy rainfall events and diarrhea[57]. Some studies have found that the association between rainfall and diarrhea only holds under certain conditions, such as following prolonged dry periods[55,58,59]. Notably, of the 141 studies identified by Levy et al., only 11 (< 8%) were conducted in Sub-Saharan Africa[57,60], suggesting a need for additional evidence in this geographic area.

The underlying causal mechanisms for the relationships between weather and diarrhea are not well established[34,61]. Heavy rainfall may cause surface runoff and flooding, potentially transporting feces and contaminating household environments and drinking water sources. However, heavy rainfall could also dilute the concentration of fecal matter in drinking water sources. High temperatures may influence pathogen survival in the environment, but the direction of the effect is unclear: pathogens may die off at a faster rate under high temperature conditions, but growth could also accelerate among bacterial pathogens if sufficient nutrients are present[62,63]. A few recent studies found that heavy rainfall was associated with increased *Escherichia coli* (fecal indicator bacteria) levels in drinking water sources[60,64–66] and household stored water[64,65] in locations in Bangladesh[65,66], Burkina Faso[60], Nepal[65], and Tanzania[64,65]. Higher temperatures increased *E. coli* levels in Bangladesh and Nepal, but decreased *E. coli* levels in Tanzania[65]. This variation by location suggests that the effects of weather on water quality are highly context-specific and underscores the need for evidence from additional locations.

In addition to physical and biological mechanisms, temperature and precipitation extremes could also lead to community or household-level behavioral changes that influence exposure to pathogens[65]. At the community level, agricultural activities such as application of animal feces as fertilizer may be correlated with temperature and precipitation. Planting occurs twice per year for many common crops in Kakamega and Bungoma counties (located in Food and Agriculture Organization's Upper and Lower Midland Zones), once in February to March and again in August to October[67]. February to March is typically warmer than average, and both planting periods directly precede the rainy seasons, which occur from March to May and from October to December[68]. At the household level, it is common to use multiple water sources[69,70]. Households may choose to collect rainwater after periods of heavy rainfall. If heavy rainfall or high temperatures lead to perceived changes in water quality (e.g., color or turbidity), households may react to these changes and decide to switch sources or treat their water.

Climate change is expected to shift weather patterns globally, including in Sub-Saharan Africa, where the burden of diarrhea-related mortality is already very high. On a global level, as mean surface temperature rises, extreme precipitation events are projected to become more frequent and intense, and heat waves are projected to become more frequent and longer in duration[71]. In East Africa, mean annual temperature is expected to increase 2-4 degrees Celsius by 2050[72]. Precipitation projections vary widely: some models predict a potential increase of 2-4 extreme precipitation events annually in East Africa (Kenya and Tanzania)[73] while others predict an increase in intensity and density of extreme precipitation events, but not a change in the actual number of events[74]. Kolstad & Johansson estimated that projected regional warming will increase the relative risk of diarrhea in equatorial Africa by 23% by the end of the 21st century, threatening recent progress[33]. However, large uncertainties are associated with projecting the severity of the impact on diarrhea due to climate change, and more empirical data is needed to better understand the relationships between climate and human health[33]. The goal of this work is to examine associations between weather (heavy 7-day precipitation and high 7-day temperature) and environmental *E. coli* contamination (source water, stored water, and child hands) in Kenyan households. To our knowledge, this is the first study to examine the effects of weather on hand contamination.

## 2.2 METHODS

### 2.2.1 Data Sources

We leveraged environmental *E. coli* contamination data from the WASH Benefits Study in western Kenya (Figure 2-1), a multiyear randomized controlled trial that studied the effects of water, sanitation, hygiene, and nutrition interventions on diarrhea and growth in children during their first two years of life[30,44]. Investigators designed the trial with a control arm (C) and six intervention arms: water treatment (W); sanitation (S); handwashing with soap (H); combined water, sanitation, and handwashing (WSH); nutrition (N); and combined water, sanitation, handwashing, and nutrition (WSHN) (see Supplementary Methods).

WASH Benefits visited households prior to intervention delivery (baseline, 2012-2014) and approximately one (midline) and two years (endline) after intervention delivery. Investigators assessed environmental contamination in a subset of households: Study staff collected source water samples (N=1,673) only at baseline; stored water samples from the C/N, WSH/WSHN, W, and H arms at baseline (N=5,761), midline (N=1,577), and endline (N=2,329); and child hand rinse samples from the C/N and WSH/WSHN arms at midline (N=1,026) and endline (N=1,634). Observations from the C and N arms (C/N) and observations from the WSH and WSHN arms (WSH/WSHN) were grouped because nutrition was not expected to impact environmental contamination. GPS coordinates were collected for each water source (baseline) and for each household (baseline, midline, and endline). For stored water collection, study staff asked respondents to show them what they would use if their child 0-3 years old wanted a drink of water. Study staff also sampled the water source that the household reported collecting the stored water from if it was within the same village. All water samples were collected as 150 mL samples in sterile Whirlpak bags. If the respondent reported adding chlorine to the stored water, study staff added sodium thiosulfate to neutralize chlorine residual and measured free chlorine residual using the Hach Pocket Colorimeter II. Child hand rinse samples were collected by filling a Whirlpak bag with 250 mL clean distilled water, placing the index child's hands in the bag one at a time, massaging the hand, and shaking the hand. More details on this method have been published elsewhere[75–77]. All samples were transported to the field lab on ice and processed the same day of collection. Laboratory technicians analyzed all environmental contamination samples by membrane filtration with MI media (BD, United States) to detect *E. coli* and incubated at 35 degrees Celsius for 20 hours following U.S. Environmental Protection Agency approved method 1604[78].

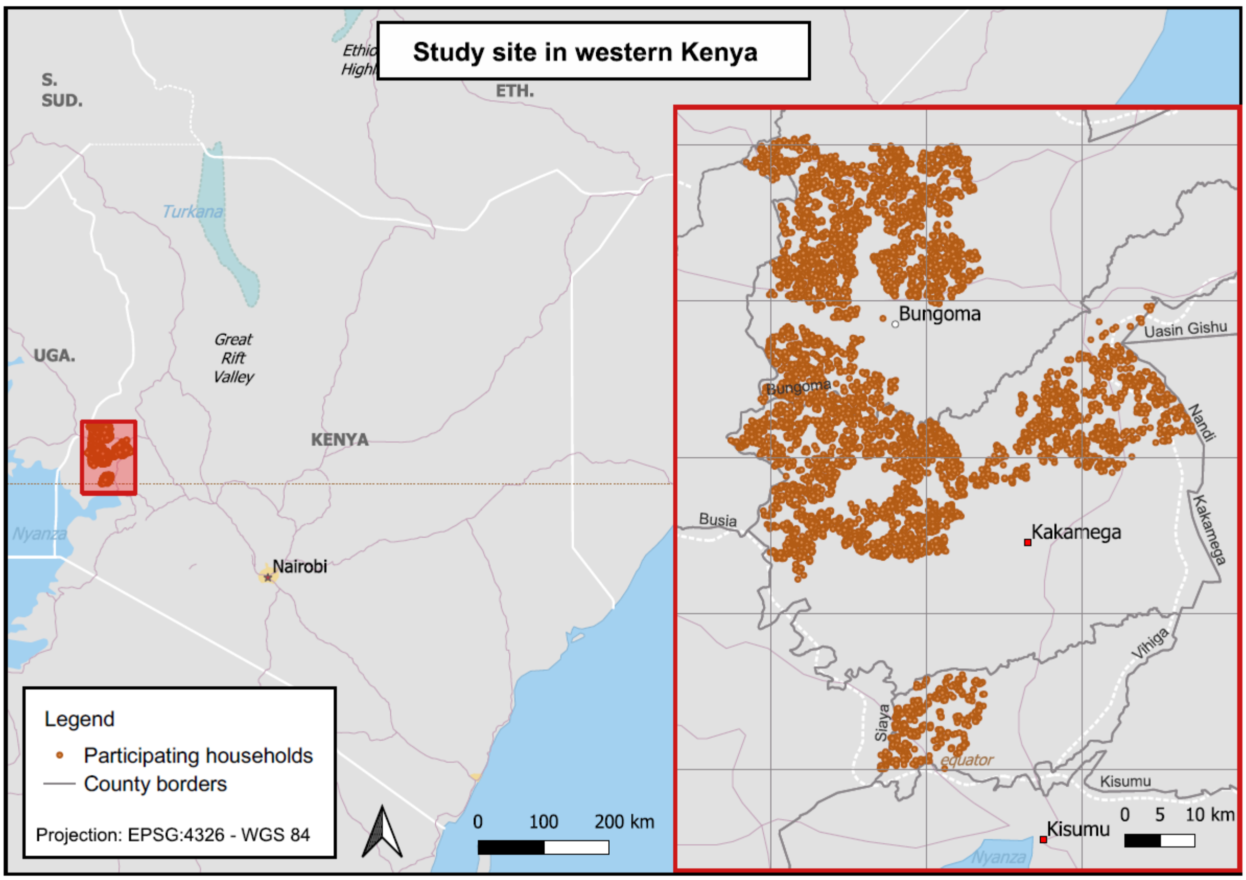


Figure 2-1 Study Site (2500 km2) in western Kenya.

Participating households (N=5,761) are plotted.

We paired gridded meteorological data with point household observations using Google Earth Engine Code Editor, a web-based integrated development environment for the Google Earth Engine JavaScript API. We extracted temperature and precipitation data from the following publicly available gridded sources using the sample collection location GPS coordinates and date of collection:

- *Precipitation:* Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a quasi-global rainfall time series dataset spanning 1981 to present. Daily precipitation is available at 0.05 degree resolution, corresponding to an area approximately 5.6 km by 5.6 km[79].
- *Temperature:* National Centers for Environmental Prediction (NCEP) Climate Forecast System (CFS) spans 1979 to present. Maximum land surface temperature is available for every 6 hours at 0.2 degree resolution, which corresponds to approximately 22.3 km by 22.3 km[80].

### 2.2.2 Data Analysis

*2.2.2.1 Primary Analysis*

We examined the effects of heavy 7-day precipitation (>90$^{th}$ percentile of our data, 72.7 mm) and high 7-day temperature (mean of daily maximums > 32 degrees C) on environmental *E. coli* levels. We chose threshold predictor variables because we were primarily interested in the effects of extreme weather and did not necessarily expect effects to be linear. This is supported by previous studies, which have observed increased diarrhea risk at heavy rainfall levels[57]. In previous diarrhea risk studies and recent water quality studies, temperature and precipitation have been examined at a variety of timescales (monthly, weekly, daily)[57,60,64,65]. We selected exposures at the weekly level for this analysis based on the assumption that *E. coli* survival would be highest at shorter time scales. We computed 7-day measures using the 7 days prior to sample collection (excluding the day of).

We performed data cleaning and analysis in Stata/MP 16.1 and RStudio version 2022.07.0. For our primary analysis, we used multivariate ordinary least squares (OLS) linear regression to examine the combined effect of heavy precipitation and high temperature on $\log_{10}$-transformed *E. coli* levels in source water, stored water, and on child hands. We controlled for WASH Benefits treatment arm in all models.

*2.2.2.2 Effect modification*

We considered 8-week precipitation as a potential effect modifier because some studies have found that the association between rainfall and diarrheal illness only holds following prolonged dry periods[55,58,59]. We calculated 8-week precipitation tertiles and repeated the analysis stratified in two subgroups: low precipitation (0$^{th}$ to 33$^{rd}$ percentile) compared to moderate or high precipitation (>33$^{rd}$ percentile). We hypothesized that water treatment may mitigate the effects of weather on water quality. For this reason, we examined self-reported water treatment (any method) and confirmed chlorine water treatment (detectable free chlorine residual) as effect modifiers. We considered improved source versus unimproved source as an effect modifier because we hypothesized that water collected from an unimproved source may be more susceptible to contamination during heavy precipitation events than water collected from an improved source. We also considered specific source type (for source types with > 100 observations) because mechanisms may differ by source type. For example, surface water sources (streams, rivers, lakes, ponds) are generally more open and may be more exposed to sunlight during hot weather (potentially inactivating bacteria) compared with other source types. In addition to conducting stratified analyses, we tested for statistical significance of effect modifiers by including an interaction term in our multivariate models.

#### *1.2.2.3 Sensitivity Analysis*

A potential weakness of this study is that the results may be sensitive to the chosen predictor variable definitions (7-day period, choice of "heavy/high" thresholds). To mitigate this, we performed several sensitivity analyses with varied specifications. We repeated the analysis using: (1) 5-day time periods rather than 7-day time periods, (2) absolute precipitation and temperature rather than thresholds, (3) the 90$^{th}$ percentile of 7-day mean max temperature (35.8 degrees C) as a threshold for "high temperature", rather than 32 degrees C, and (4) heavy 1-day precipitation (exceeds 90$^{th}$ percentile, 15.5 mm) during any 1-day period in the previous 7 days rather than total 7-day precipitation.

#### *1.2.2.4 Behavior*

Because respondents may react to changes in weather, we examined effects of heavy 7-day precipitation (>90$^{th}$ percentile of our data, 72.7 mm) and high 7-day mean maximum temperature (mean of daily maximums > 32 degrees C) on several water-related behavioral measures: whether stored water was collected from an improved source, what source type stored water was collected from, whether the respondent treated the water, what treatment methods were used, and how long the water was stored for. We used multivariate Poisson regression for binary outcomes (improved source, source type, treatment, and treatment method) and multivariate OLS regression for continuous outcomes (water storage time). We controlled for treatment status in all models.

## 2.3 RESULTS AND DISCUSSION

As previously reported[46], *E. coli* prevalence was high (>90%) among all water source types and on child hands (Table 2-1). *E. coli* levels (CFU/100 mL) were lower in household stored water (median = 29 CFU/100 mL) than in water sources (median = 69 CFU/100 mL), potentially because some households (19%) reported treating their water or because only one sample was collected per source (sources are typically used by multiple households; if more households collect from less contaminated sources, median water quality among source water that is collected may be better than source quality in general). The median *E. coli* level on child hands was 37 CFU/100 mL.

Table 2-1 Descriptive Statistics.

Sample size (N) is shown for all variables. Median, 25th percentile, and 75th percentile are shown for continuous variables. Prevalence of yes responses (number and percent) is shown for binary variables. Sample sizes are smaller for E. coli concentration variables than for E. coli presence variables because a small number of plates with E. coli colonies were uncountable.

| | | Variable | N | Median (p25, p75) or n (%) |
|---|---|---|---|---|
| Weather | | 7-day total precipitation (mm), Median (IQR) | 11,951 | 35.1 (17.0, 53.2) |
| | | 7-day mean of daily max temperature (deg C), Median (IQR) | 11,988 | 31.1 (27.4, 33.8) |
| *E. coli* | Source water | Present (yes/no), n (%) | 1,673 | 1,614 (96.5%) |
| | | Concentration (CFU/100 mL), Median (IQR) | 1,650 | 69.0 (22.0, 246.0) |
| | Stored water | Present (yes/no), n (%) | 9,667 | 8,574 (88.7%) |
| | | Concentration (CFU/100 mL), Median (IQR) | 9,627 | 29.0 (7.0, 91.0) |
| | Child hands | Present (yes/no), n (%) | 2,660 | 2,416 (90.8%) |
| | | Concentration (CFU/100 mL), Median (IQR) | 2,634 | 37.0 (5.0, 238.5) |
| Stored water behavior | | Collected from an improved source (yes/no), n (%) | 9,733 | 7,762 (80%) |
| | | Treated water, any method (yes/no), n (%) | 9,718 | 1,803 (19%) |
| | | Treated water with chlorine (detectable free chlorine residual) (yes/no), n (%) | 9,701 | 756 (7.8%) |

### 2.3.1 Primary Analysis

High temperatures and heavy total precipitation during the week before sample collection were significantly associated with environmental *E. coli* levels (Figure 2-2). In water sources, heavy precipitation (> $90^{th}$ percentile) was associated with a 0.29 increase in $\log_{10}$ CFU *E. coli* per 100 mL water ($p < 0.001$) and high temperature (mean > 32 degree C) was associated with a 0.16 increase in $\log_{10}$ CFU *E. coli* per 100 mL water ($p < 0.001$). These effects are similar in magnitude to the effect associated with improved sources (reductions of 0.33 $\log_{10}$ *E. coli* CFU per 100 mL in water sources and 0.19 $\log_{10}$ *E. coli* CFU per 100 mL in household stored water), indicating that the effects of heavy precipitation and high temperature are meaningful. In household stored water, heavy precipitation was associated with a 0.079 increase in $\log_{10}$ CFU *E. coli* per 100 mL water ($p = 0.042$), demonstrating that temperature and precipitation affect water quality at the point that it is being consumed. High temperature was not significantly ($p > 0.05$) associated with *E. coli* levels in household stored water.

Heavy precipitation was not significantly associated with *E. coli* levels on child hands. However, high temperature was significantly associated with a 0.39 decrease in $\log_{10}$ *E. coli* CFU per two hands ($p < 0.002$), potentially due to faster die-off of bacteria due to heat and sunlight (which is positively correlated with temperature). Temperature is also inversely related to relative humidity, and low relative humidity could reduce bacterial transfer from the household environment (e.g., floor, toys) to child hands. Lopez et al. (2013) found that *E. coli* and most other organisms they examined had lower transfer efficiencies from fomites to fingers at low relative humidity[81]. Temperature is unlikely to influence hand washing effectiveness[82–84] or hand rinse sample bacterial yield[85], but it could impact hand washing or bathing frequency because children and their caregivers may use water to cool down when it is hot. During direct observation in north-western Burkina Faso, Traore et al. (2016) found that children swam and mothers bathed under-five children more frequently during a hot period compared with a cold period[86]. Increased bathing or other water contact could have had co-benefits for hand hygiene. Pickering et al. (2011) found that bathing (of self or child) decreased *E. coli* levels on mothers' hands[87].

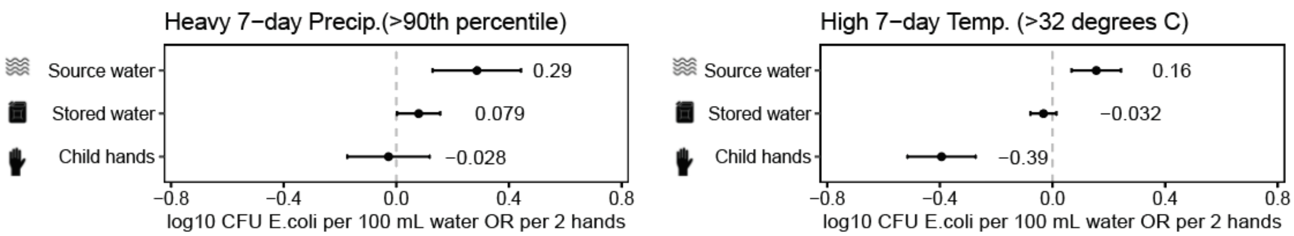


Figure 2-2 Associations between heavy 7-day precipitation (left), high 7-day temperature (right), and E. coli levels in source water, stored water, and child hands.

Point estimates are plotted and labeled. Units are $\log_{10}$ CFU E. coli per 100 mL for source water and stored water, and per 2 hands for child hands. Error bars show 95% confidence intervals.

### 2.3.2 Effect Modification: 8-Week Rainfall

Low long-term precipitation modified the effect of heavy precipitation on *E. coli* levels in water sources ($p = 0.004$ on interaction term, Supplementary Table 1), with a larger increase (0.61 $\log_{10}$ CFU *E. coli* per 100 mL) after low 8-week rainfall compared to moderate or high 8-week rainfall (Figure 2-3). Low long-term precipitation also modified the effect of high temperature on *E. coli* levels on child hands ($p = 0.045$ on interaction term, Supplementary Table 1), with a larger reduction (-0.67 $\log_{10}$ CFU *E. coli* per 100 mL) after low 8-week rainfall (Figure 2-3).

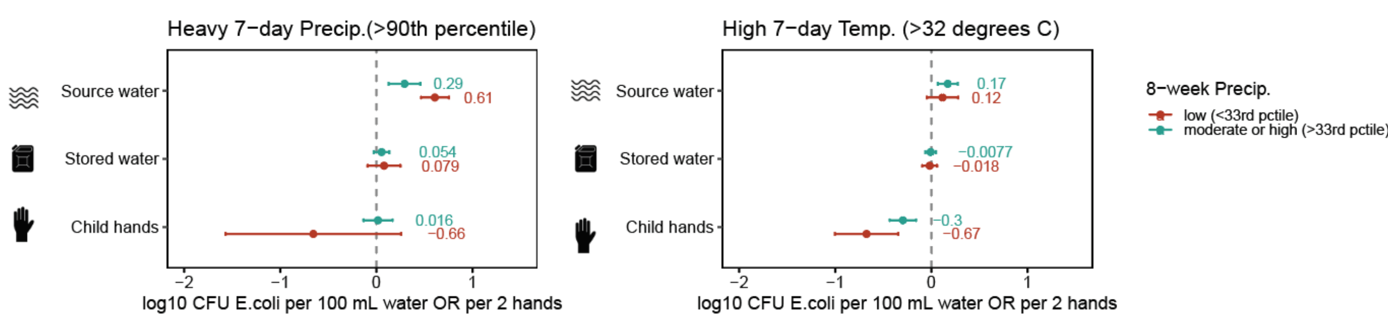


Figure 2-3 Effect modification by low long-term (8-week) precipitation.

Associations between heavy 7-day precipitation (left), high 7-day temperature (right), and E. coli levels in source water, stored water, and child hands. Results are stratified by low ($0^{th}$ to $33^{rd}$ percentile) vs. moderate or high ($>33^{rd}$

percentile) 8-week rainfall. Point estimates are plotted and labeled. Units are $log_{10}$ CFU E. coli per 100 mL for source water and stored water, and per 2 hands for child hands. Error bars show 95% confidence intervals.

### 2.3.3 Effect modification: Water treatment

Water treatment modified the effect of heavy precipitation on *E. coli* levels in stored water ($p < 0.001$ on interaction term, Supplementary Table 2). While heavy precipitation was associated with increased *E. coli* levels (0.094 $log_{10}$ CFU *E. coli* per 100 mL) in stored water from households who did not treat their water, this relationship did not hold among households who treated their water (Figure 2-4).

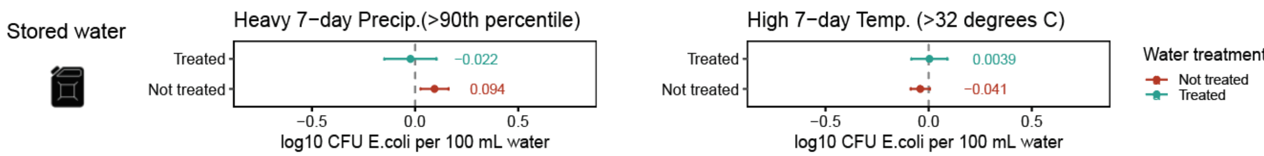


Figure 2-4 Effect modification by self-reported water treatment.

Associations between heavy 7-day precipitation (left), high 7-day temperature (right), and E. coli levels in household stored water. Results are stratified by treated vs. not treated. Point estimates are plotted and labeled. Units are $log_{10}$ CFU E. coli per 100 mL. Error bars show 95% confidence intervals.

Confirmed chlorine water treatment did not modify the effects of heavy precipitation or high temperature on *E. coli* levels in stored water (Supplementary Figure 1, Supplementary Table 3). This analysis was limited by a small number of samples with detectable free chlorine residual (N = 756).

### 2.3.4 Effect Modification: Source Type

Heavy precipitation was associated with a larger increase in *E. coli* levels in unimproved sources (0.42 $log_{10}$ CFU *E. coli* per 100 mL, $p = 0.026$ on interaction term, Figure 2-5, Table A-4) compared to water from improved sources, likely because unimproved sources are at higher risk for contamination via runoff or flooding. Heavy precipitation was associated with a larger increase in *E. coli* levels in unprotected springs (0.52 $log_{10}$ CFU *E. coli* per 100 mL, $p = 0.005$ on interaction term, Figure 2-5, Table A-5) compared with other source types. Unprotected wells versus other source types modified the effect of high temperature on *E. coli* levels in water sources ($p = 0.001$ on interaction term, Table A-5) and changed the direction of the effect: Although high temperature increased *E. coli* levels in water sources overall (Figure 2-2), high temperature reduced *E. coli* levels in unprotected wells (-0.2 $log_{10}$ CFU *E. coli* per 100 mL), potentially because unprotected wells are open and more exposed to sunlight (correlated with temperature) than other source types.

Source type also modified the effects of heavy precipitation and high temperature on *E. coli* levels in stored water. Heavy precipitation was associated with a larger effect on *E. coli* levels in stored water collected from a protected spring (0.15 $\log_{10}$ *E. coli* CFU per 100 mL, p = 0.006 on interaction term, Figure 2-5, Table A-5) compared to water collected from other source types. Collection from boreholes versus other source types modified the effect of high temperature on *E. coli* levels in stored water (p = 0.017, Table A-5) and changed the direction of the effect: Although high temperature was weakly associated (statistically insignificant, p = 0.26) with decreased *E. coli* levels in stored water overall (Figure 2-2), high temperature was associated with increased *E. coli* levels in water collected from boreholes (Figure 2-5).

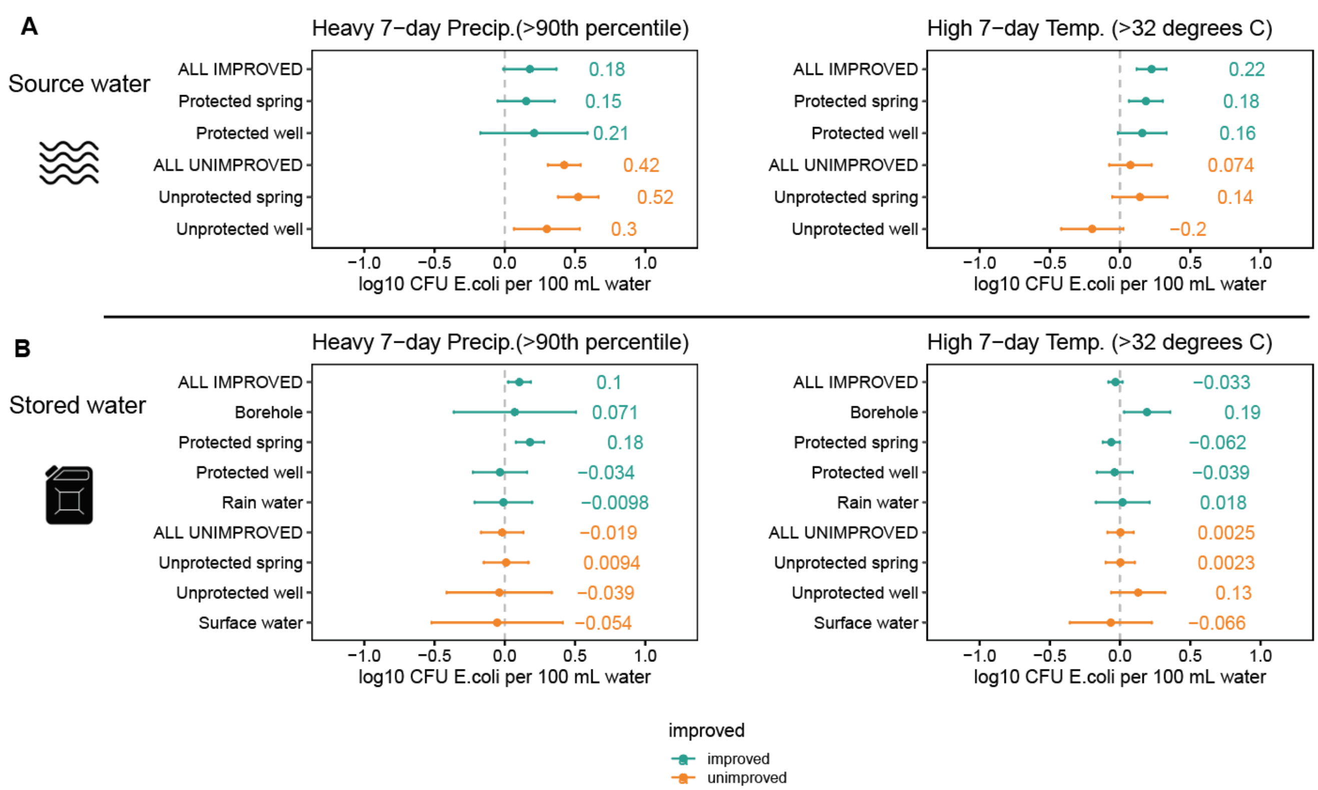


Figure 2-5 Effect modification by source type.

Associations between heavy 7-day precipitation (left), high 7-day temperature (right), and E. coli levels in source water (Figure 2-5A) and stored water (Figure 2-5B). For source water, results are stratified by observed source type. For stored water, results are stratified by the source type that the respondent reported collecting the water from. Point estimates are plotted and labeled. Units are $\log_{10}$ CFU E. coli per 100 mL. Error bars show 95% confidence intervals.

### 2.3.5 Behavior

Although high temperature was associated with increased *E. coli* levels in water sources, this did not hold true in household stored water (Figure 2-2), potentially because stored water quality is more complex and impacted by numerous household-level behavioral choices. We found evidence that households altered water-related behaviors (i.e., where to collect water, whether to treat it, how long to store it) in response to the weather. Households were more likely to collect water from an improved source after high 7-day temperature (prevalence ratio = 1.1, $p = 0.003$, Figure 2-6), driven predominantly by an increased likelihood of collection from a protected spring or protected well (improved) and decreased likelihood of collection from an unprotected spring or source water (unimproved) (Figure 2-6). This could be due to changes in availability (e.g., some sources may dry up during hot weather) or because respondents choose different water sources based on perceived changes in quality (e.g., color, turbidity, taste). Increased collection from an improved source could mitigate the effect of elevated *E. coli* levels in water sources after high 7-day temperature because collection from an improved source is associated with improved water quality (-0.19 $log_{10}$ CFU *E. coli* per 100 mL in our data). High 7-day temperature was also associated with shorter water storage time (mean difference = 3.81 hours, $p = 0.01$, Figure 2-6), perhaps because households drink[88,89] or use[90,91] more water during hot weather. Because water storage time can make water more prone to recontamination[92], shorter storage time could also mitigate the effects of high temperature.

Heavy precipitation increased *E. coli* levels in both water sources and stored water, but the effect magnitude was smaller in household stored water. Heavy precipitation was not significantly associated with the decision to treat water or collect from an improved source (Figure 2-6). However households were more likely to collect rainwater after heavy rain (prevalence ratio = 2.2, $p < 0.001$, Figure 2-6). Increased rainwater collection (improved source) could diminish the effects of elevated *E. coli* levels in water sources after heavy precipitation because the mechanisms by which heavy precipitation affects water quality in other source types (e.g., runoff) may not apply to rainwater collection (Figure 2-5). Although rainwater collection was associated with improved water quality in our data (-0.09 $log_{10}$ CFU *E. coli* per 100 mL), roof-harvested rainwater is not always free from microbial[93,94] and chemical[93,95] contamination both because contaminants from the atmosphere may be present in rainwater and because contaminants may accumulate on the roof. Respondents were more likely to collect rainwater after heavy 7-day precipitation (prevalence ratio = 2.2, $p < 0.001$) and less likely to collect rainwater after high 7-day temperature (prevalence ratio = 0.41, $p < 0.001$) (Figure 2-6).

Temperature and precipitation extremes may have also triggered other unobserved behavioral changes that mediate impacts on environmental *E. coli* levels. For example, children may play outside less (potentially reducing exposure) when it has been raining or is very hot. Children and their caregivers may also interact more with water when it is hot out[86], which could have co-benefits for hand hygiene[87].

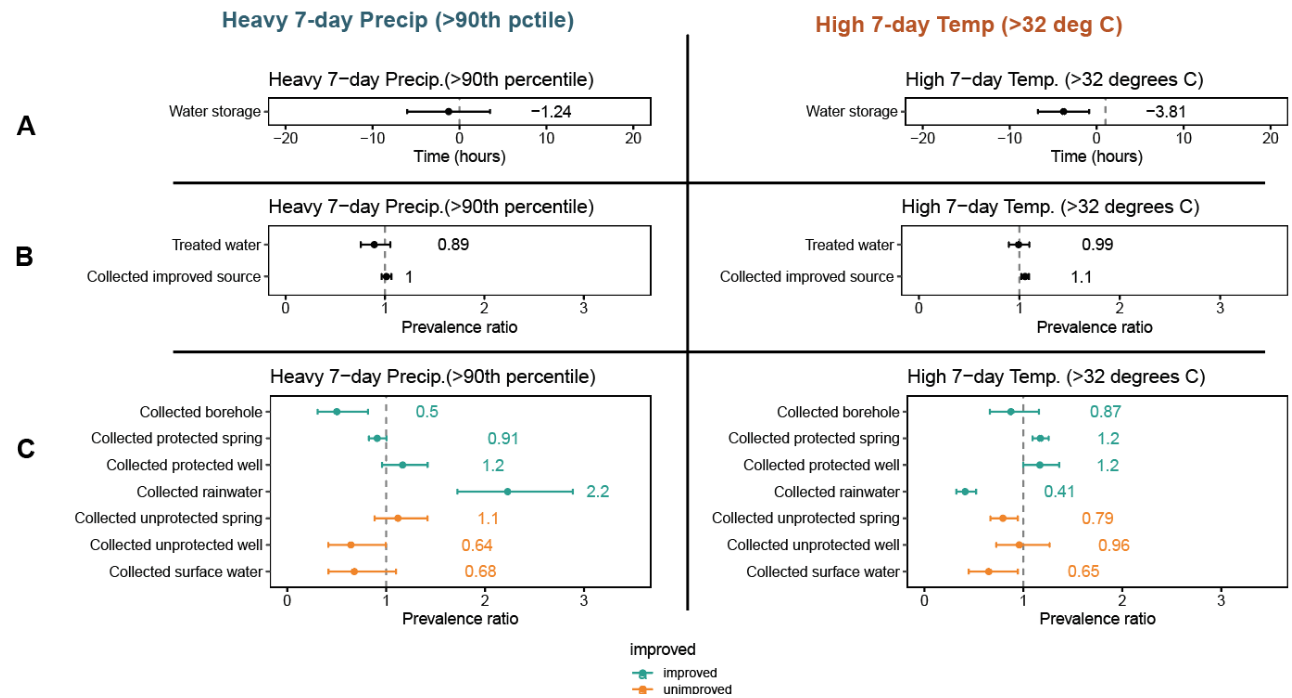


Figure 2-6 Associations between heavy 7-day precipitation (left), high 7-day temperature (right), and reported stored water behaviors: water storage time (Figure 2-6A), water treatment and collection from an improved source (Figure 2-6B), and source type that the respondent reported collecting water from (Figure 2-6C).

Water storage time in hours is plotted and labeled for Figure 2-6A. prevalence ratios are plotted and labeled for Figure 2-6B and Figure 2-6C.  Error bars in all panels show 95% confidence intervals.

A limitation of this analysis is that data was not collected uniformly over the course of each year. As a result, the available data may not be representative of typical seasonal meteorological conditions for the study area. For example, relatively few source water observations were collected at times of year that typically have low precipitation and high temperatures (January, February) and high precipitation and high temperatures (April, May). However, data collection was spread out such that at least some data was collected in every month of the year.

There are important fecal transmission pathways (e.g., fomites, fields, flies, food) that were beyond the scope of this study. Additional work examining the impact of weather on other pathways would be valuable for anticipating climate change impacts and prioritizing interventions. Because mechanisms and behaviors may vary by context, evidence from additional geographic locations would strengthen our understanding of weather impacts on fecal contamination in water and on hands. Because weather has a significant effect on environmental *E. coli* levels, inclusion of weather variables such as temperature and precipitation may improve the precision of impact evaluations on fecal contamination in the environment even when these are not the primary exposures of interest. Satellite data enables the incorporation of weather data with relative ease.

We found that heavy precipitation and high temperature had meaningful and statistically significant effects on *E. coli* levels in water sources, stored water, and child hands. These effects were consistent across multiple sensitivity analyses (Supplementary Figures 2-5), suggesting that the effects were true and not sensitive to the choice of model specification. In water sources, heavy rainfall increased *E. coli* levels, perhaps by transporting feces via increased runoff and flooding. This finding is consistent with studies in other locations[60,64,65]. The effect was larger after low 8-week rainfall, potentially because long dry periods allowed feces to accumulate in the environment. Heavy rainfall also increased *E. coli* levels in household stored water. Notably, heavy rainfall did not increase *E. coli* levels among the subset of respondents who reported treating their water, suggesting that water treatment can mitigate effects on water quality. In this first study of weather and hand contamination, high temperature decreased *E. coli* levels on child hands. There are a few potential explanations for this finding. Heat and sunlight may have increased *E. coli* die-off. Low relative humidity (inversely related to temperature) may have reduced bacterial transfer from contaminated fomites to child hands[81]. Finally, the effect may have been mediated by behavioral changes, such as increased bathing when it is hot.

Our findings demonstrate that in rural Kenya, extreme weather due to climate change will likely increase bacterial contamination in drinking water but reduce contamination on child hands. We show that individuals react to weather in ways that may mitigate effects on household stored water. Our findings provide insight on how climate change could impact environmental transmission of bacterial pathogens in Kenya. We suggest that water treatment may be especially important after periods of heavy precipitation (particularly when preceded by dry periods) and after periods of high temperatures.

# CHAPTER 3. Evaluation of a novel venturi chlorine doser to increase safe water access

## 3.1 INTRODUCTION

Despite global progress, 2.1 billion people still lack access to safe water at home[96]. Improved drinking water sources have the potential to provide safe water and include piped water, boreholes or tubewells, protected dug wells, protected springs, and packaged or delivered water.[96] While 89 percent of the global population uses at least a basic drinking water service (round trip to collect water from an improved source takes 30 minutes or less), only 71 percent of the global population uses a source that meets the Sustainable Development Goal (SDG) criteria for safely managed (accessible on premises, water available when needed, free from fecal and priority chemical contamination)[96]. In many places, universal access to safe water is out of reach due to the high cost and lack of available financing to create and support necessary water treatment and distribution infrastructure. In some settings that have centralized treatment, leaking pipes, low water pressure, and intermittent supply contribute to recontamination during distribution[97–100]. Intermittent supply has been associated with increased diarrhea[101,102] and typhoid fever[103]. Piped and other improved sources do not always deliver water free from contamination[96–100,104–106]; an estimated 1.4 billion people use contaminated water from improved sources[96].

Point-of-use (POU) treatment has been advocated as an interim solution and has been shown to improve water quality[107] and reduce diarrheal disease[21,107]. Treatment with chlorine products is very affordable (0.05 USD per 1,000 liters of water treated with chlorine solution when purchased in bulk in Kenya (Paul Byatta, Evidence Action, personal communication), and it has the advantage of providing residual protection[108,109]. However, sustained uptake and scale up of POU technologies remain low[110–112] in part because POU places the burden of treatment on individual households, requiring sustained behavior change. This is especially problematic because POU treatment requires high and consistent compliance in order for potential health benefits to be realized—even small declines in compliance result in large reductions of potential health benefits[113,114].

Water treatment at community collection points, or point-of-collection (POC) treatment, could lessen the household-level burden of behavior change when centralized treatment and distribution is not feasible. Since 26% of the global population relies on water collection off-premises[96], adding treatment devices at the POC may improve access to water free from contamination without large infrastructure improvements. POC chlorine treatment may be manual or automatic; recent studies have evaluated the efficacy and uptake of both in development and emergency contexts[115,116,30,117–120]. Manual chlorine dispensers add a set volume of diluted chlorine to collection containers (20 L) with the turn of a knob[30,115,117]. When installed at shared water points, the dispensers have the potential to increase adoption through social pressure because the decision to use the dispenser is public[115]. However, manual chlorine dispensers still require some behavior change by individual users, and uptake rates can be variable. [30,115,117]

An advantage of automatic (in-line) chlorinators over manual chlorine dispensers is that individuals seeking drinking water do not have to know how to use the device and do not have to change the way they collect water. In-line chlorinators allow users to collect any volume of chlorinated water; manual chlorine dispensers are designed to treat 20 L at one time. Currently most available electricity-independent in-line chlorinators use solid chlorine tablets[121,122]. In settings where solid chlorine tablets are not widely available, tablet supply can be a significant barrier to sustained chlorinator use[116]. For this reason, members of our team designed a low-cost, electricity independent liquid chlorine (e.g. dilute bleach) doser, drawing on our experiences from two previous pilot studies of liquid chlorine dosers[118,119]. A small randomized controlled trial we conducted in urban Bangladesh compared installation of an early prototype of the device tested in this study at shared handpumps to distribution of chlorine tablets (Aquatabs®). Drinking water chlorination levels were higher in chlorine doser compounds at the POC compared to the Aquatabs group, suggesting in-line chlorination requires less intensive promotion for sustainable uptake[118]. Another study in Bangladesh tested the ZIMBA[123], an automated batch chlorinator that attaches to handpumps or taps and requires a storage tank for mixing after the chorine dose is added. The ZIMBA dosed consistently at handpumps, but users reported that the device caused longer, inconvenient wait times during water collection[119].

In this study, we designed a novel in-line chlorine doser, the Stanford-MSR Venturi (Figure 3-1). We field-tested the doser at water kiosks in Kisumu, Kenya from August 2017 to May 2018. A potential drawback of POC treatment is that it relies on organized operation and maintenance at the community level; if this fails, the entire community is left without safe water[116]. For this reason, we piloted a business service model and evaluated effective demand (willingness and ability to pay) for the Venturi among kiosk operators and for the resulting treated water among customers. Many other studies of chlorine dispensers and automatic chlorinators have provided the intervention free of charge[30,115,117–119], or rarely collected fees in practice due to resistance to paying for water[116]. Our objectives were to assess: 1) the technical performance of the device, 2) customer demand for chlorinated water, and 3) kiosk owner willingness and ability to pay a monthly fee for the device. The study design provided a unique opportunity to assess customer demand for chlorinated versus unchlorinated water as each kiosk offered customers the choice of purchasing from chlorinated or unchlorinated water taps; previous automatic chlorinator studies have not offered or measured this choice[116,118,119,124].

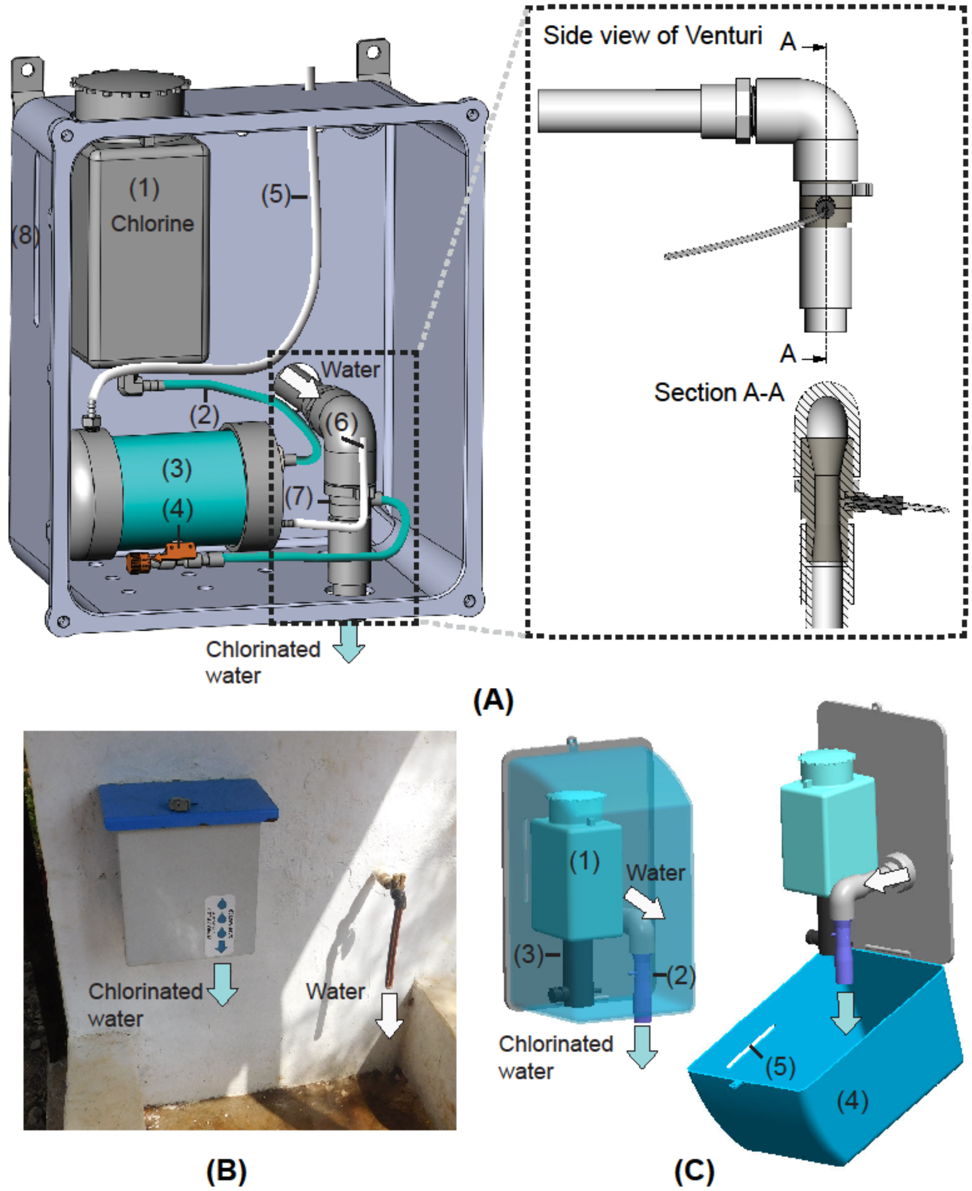


Figure 3-1 A Schematic cross-section of Venturi.

The device consists of (1) 1-L chlorine storage tank; (2) source pinch valve; (3) float tank; (4) needle valve for dose adjustment; (5) vent pinch valve; (6) sight tube; and (7) Venturi. Chlorine flows from the chlorine tank (1) into the float tank (3) when the source pinch valve (2) is open. A float valve maintains the level of chlorine in the float tank. The sight tube (6) may be used to adjust the float tank level to just below the chlorine injection height. The needle valve (4) determines a precise amount of chlorine flowing toward the Venturi (7) and may be adjusted. Differential pressure caused by the flow of water through the Venturi (7) pulls chlorine into the water stream. A window (8) allows operators to easily see the level of chlorine available in the chlorine storage tank. B Venturi installed at water kiosk in Kisumu, Kenya. Left tap provides water chlorinated with the Venturi and right tap provides unchlorinated water. C Concept for future molded Venturi. The device would consist of (1) 1-L chlorine storage tank; (2) molded Venturi; (3) float valve and needle valve assembly; (4) outer cover; and (5) window to see the level of chlorine available. The estimated manufacturing cost of the molded Venturi is 34 USD.

## 3.2 METHODS

### 3.2.1 Technology

The novel Stanford-MSR Venturi (Figure 3-1**)** is an automatic (in-line) chlorinator that can be attached directly to the outlet of piped water taps and is compatible with flow rates of 6 to 60 liters per minute. Stanford University researchers and students invented the initial Venturi prototype through a field-based user-centered design process, and the company MSR Global Health refined the design to improve dosing precision and manufacturability. The main challenge of the design process was consistently achieving accurate (±0.5 mg/L) dosing over a wide range of flow rates with low backpressure and minimal maintenance. Using a test stand in the lab, we optimized the Venturi geometry. Key design parameters of the Venturi are the throat diameter (Ø 12.7 mm, controls the backpressure and range of flow rates the Venturi can accurately dose), the height of the outlet relative to the injection point (63.5 mm, increases dosing at low flow rates), and the height of the float tank relative to the injection point (2.0 mm, can cause a dosing delay if too low and affects overall concentration). Since the device operates on very low pressure, a float (constant head) tank is required to prevent the liquid level from affecting the dosing. We selected a needle valve flow restrictor because it dosed more consistently over a range of flow rates and had a wider adjustability range than other flow regulators.
We conducted field tests of early prototypes of the Venturi with user input, which revealed dosing consistency issues that we addressed in the final design. We observed non-dosing at flow rates less than 10 L/min, caused by channel flow. We mitigated this by making the flow area above the Venturi consistent and minimizing the vertical drop to the injection point. After implementing these changes, we achieved a minimum functional flow rate of below 6 L/min. Bubbles also formed in the chlorine supply tubing, which was problematic because it could airlock the needle valve or fittings and prevent dosing. We addressed this issue by positioning the needle valve directly on the bottom of the float tank, using compression fittings instead of hose barbs, switching from PVC to fluorocarbon tubing, and eliminating service loops in the tubing. Based on user feedback, we added a security cover to the enclosure to prevent theft of chlorine.

The Venturi can be adjusted to varying doses by twisting a needle valve. Needle valve settings correspond to the rotation of the needle valve from closed to open and range from zero to ten, with zero representing fully closed and ten representing fully open. We calibrated the dosing for each Venturi in the lab over a range of flow rates and needle valve settings prior to field installation. We filled each chlorine tank with 1.2% chlorine solution and allowed dechlorinated water to flow through the Venturi for 30-60 seconds before collecting a sample of chlorinated water. We measured flow rate using a Dwyer Instruments VFC II and immediately measured free chlorine residual using a Hach Pocket Colorimeter II. For each Venturi, we selected a needle valve setting for installation that resulted in 0.5 mg/L to 1.5 mg/L free chlorine residual over flow rates of 6 L/min to 38 L/min.

The device doses WaterGuard or an equivalent liquid chlorine (1.2% sodium hypochlorite) solution, which are readily available in Kenyan markets. Operators may monitor the current level of liquid chlorine in the device through a window on the side of the device (Figure 3-1**).** To refill the device, operators open the cover, remove the cap from the chlorine storage tank, and pour bottles of WaterGuard (or other chlorine solution) directly into the tank. To improve consumer acceptance, we targeted dosing in the field to be between 0.2 mg/L and 1.2 mg/L to avoid high doses that could result in user taste complaints,[125] while still meeting the minimum WHO recommended free chlorine residual[126].

### 3.2.2 Study recruitment

This study was conducted in rural and peri-urban areas of Kisumu, Kenya. In Kenya, water kiosks are common [127] and typically include multiple taps where customers may collect water for a fee per 20-L jerry can. SWAP performed the field activities in this study. SWAP acted as a distributor of the device in some ways (performing sales pitches, installations, and collecting payments). SWAP also performed additional tasks specific to the research study (weekly monitoring and follow-up survey collection). Kiosks were invited to participate in this study if they met the following eligibility criteria: (1) they were located within Kisumu County; (2) they reported operating daily; (3) the water provided was not currently chlorinated (kiosks served by Kisumu Water & Sewerage Company (KIWASCO) were excluded because the water was reported to be chlorinated); and (4) the kiosk taps were high enough to allow 20 L jerrycans to pass underneath the outlet fitted with the Venturi ( ≥ approximately 65 cm).

### 3.2.3 Ethics

SWAP field staff obtained written informed consent from kiosk owners and operators prior to enrollment in the study. Field staff read consent forms aloud to respondents in Luo, Swahili or English based on respondent preference. The Ethics Review Committee at Maseno University, Kenya, and the Institutional Review Board at Stanford University (protocol 40689) approved the study protocol.

### 3.2.4 Baseline

SWAP field staff conducted baseline surveys with kiosk managers and operators to obtain information on water sales and management practices. Kiosk operators were responsible for the daily operation of the kiosk (collecting customer payments and operating the faucets), while kiosk managers were responsible for funds management and financial decisions. Typically, field staff conducted surveys with one kiosk manager and one kiosk operator per kiosk. If one person managed multiple kiosks, field staff surveyed the kiosk manager and all relevant kiosk operators. In cases where one person both managed and operated the kiosk, field staff administered only one survey. Field staff used SurveyCTO software installed on tablet computers to administer these surveys and for all other field data collection.

### 3.2.5 Intervention delivery

Following the baseline survey, kiosk owners received a sales pitch and a choice of four service packages (Table 3-1). All service packages included installation of the chlorine doser and basic maintenance support for up to six months. Kiosk owners could decide whether to lease the device or lease-to-own the device and whether to have chlorine refills delivered. Kiosks that chose to lease the device had the option to purchase the device for a lump sum at the end of the

6-month study period. At the time of the study, MSR estimated the target sale price of the device to be 150 USD. We therefore developed the service package prices (6-month totals, including the lump sum to purchase, ranged from USD 252-270) in consultation with project partners in an effort to cover the target sale price of the device, as well as the estimated cost of maintenance and chlorine deliveries.

Field staff presented sales pitches using marketing flipbooks and sales brochures. The marketing flipbooks described challenges to accessing safe water, health benefits of treating water, and how the Venturi may be used to meet this need. The sales brochure outlined the specific service package options and prices. Kiosk owners opting to commit to a sales package signed a contract describing the chosen package, payment schedule, and terms that would warrant termination. This contract stipulated that any payments late by more than six days following the due date would be assessed a late fee of 1 USD and that if payment was late by 30 days or more, the device would be uninstalled, and contract cancelled.

Since a limited number of Venturi devices (eight) were available for sale, field staff recruited kiosks for sales pitches on an ongoing basis. Kiosk owners made payments via M-PESA, a mobile phone-based money transfer service. Field staff installed the device within seven days of first payment and provided padlocks to the kiosk operator for securing the device. To install the Venturi, SWAP field staff mounted the rectangular enclosure to the kiosk so that the device fit onto the water supply tap. If necessary, field staff adjusted the diameter of the water supply pipe inlet to connect to the Venturi.

#### 3.2.6 Follow up

SWAP field staff made weekly visits to each kiosk. During each visit, field staff conducted a short interview with the kiosk operator to record chlorinated and unchlorinated water sales information for each day of the previous week (usually obtained from a logbook), chlorinated and unchlorinated water sale prices, satisfaction with the device, and any maintenance issues. The volume of sales was self-reported by operators (not verified by meter). Upon arrival, field staff collected three water samples from the Venturi outlet in 250-mL breakers and immediately measured free chlorine residual from each sample using a Hach Pocket Colorimeter™ II [128]. If free chlorine residual was outside of or close to the limits of our target dose (0.2 mg/L to 1.2 mg/L), field staff repeated sample collection and free chlorine residual measurements. Staff adjusted the dosing dial at their discretion, generally if free chlorine residual was outside or close to the limits of our target dose (0.2 mg/L to 1.2 mg/L) after repeat testing. If staff adjusted the dosing dial or performed other maintenance, they recorded these changes and collected three additional water samples and free chlorine measurements. Field staff also reminded kiosk operators and managers of upcoming payment due dates and any late payments.

Field staff conducted post-intervention customer surveys between 3 and 6 months after installation, including questions about water purchase behavior, perceptions, and preferences. Field staff surveyed at least 10 customers per kiosk over 2 to 6 days. For the post-intervention customer surveys, we instructed field staff to interview every fifth customer. In practice, field staff interviewed approximately every fifth customer when kiosks were busy (a line of customers waiting or a steady flow of customers arriving); when kiosks were not busy field staff waited for customers to come and surveyed customers at a smaller interval (i.e., every 1-2 customers) over a longer period. Field staff conducted post-intervention kiosk operator and manager surveys between 2 and 5 months after installation, including questions about sales, device perceptions and feedback, and payments. An operator and a manager at each kiosk participated in the kiosk operator and manager surveys apart from kiosk E, where the manager also worked as the operator most of the time.

### 3.2.7 Data analysis

We used the mean of the first three free chlorine residual measurements for each visit in our analysis. We considered a detectable level of chlorine residual to be greater than 0.05 mg/L (based on a colorimeter detection range of 0.02 mg/L to 2.00 mg/L and incremental steps of 0.01 [35]). Since kiosks opted in on different dates, we aggregated and analyzed dosing and sales data by months since installation, not calendar months. Although operating daily was used in selection criteria, in practice kiosks frequently closed for a variety of reasons such as heavy rain, problems with kiosk management, and political violence related to elections. Because kiosks may have closed in anticipation of low sales, we considered all reported sales and did not adjust based on whether the kiosk had closed (i.e., sales that were missing or the kiosk was closed were counted as zero). We performed data analysis in Stata/SE 14 and created figures in R.

## 3.3 RESULTS

### 3.3.1 Service package enrollment

Seven of the 26 kiosk owners (27%) who heard the sales pitch committed to purchasing a service package (Table 3-1), and field staff installed seven Venturi devices. The four service package options were each chosen by one or two kiosks (Table 3-2). The water source for Kiosk E was a spring; all other kiosk sources were boreholes. Kiosks were urban, peri-urban, and rural (Table 3-2

Table 3-1 Price elements by service package type (in USD)

| **Service package type** | **Monthly payment** | **Lump-sum price for purchase**[a] | **Total price for purchase (6 monthly payments + lump-sum price)** |
|---|---|---|---|
| Lease | 15 | 170 | 260 |
| Lease + chlorine delivery[b] | 18 | 170 | 278 |
| Lease-to-own | 42 | | 252 |
| Lease-to-own + chlorine delivery[b] | 46 | | 276 |

a) Kiosks that chose to lease the device could purchase the device for a lump sum at the end of the 6-month study period.
b) Chlorine delivery prices assumed that kiosks used 10 bottles of WaterGuard per month (0.30 USD per 150-mL bottle of WaterGuard). Price was adjusted based on actual WaterGuard use.

### 3.3.2 Follow up: free chlorine residual

All samples collected from the Venturi devices in the lab (N = 71) had detectable free chlorine residual. Free chlorine residual ranged from a minimum of 0.5 mg/L to a maximum of 3.0 mg/L across needle valve settings (Figure B-1). At the settings selected, free chlorine residual was between 0.91 mg/L and 1.48 mg/L across flow rates of 6 L/min to 38 L/min (Figure 3-2).

Table 3-2 Kiosk characteristics and payments

| Kiosk | Location | Service package | Payment as % of average monthly revenue | Unique sales approaches | Completed monthly payments? | Device purchased? |
|---|---|---|---|---|---|---|
| A | Rural | Lease | 14.2% | Sales of chlorinated water restricted (daily cap per customer). | Yes | Yes |
| B | Rural | Lease | 41.5% | - | Yes | No |
| C | Rural | Lease-to-own | 139.8% | Chlorinated water used on-site for visitors and children in addition to sales. | Yes | Yes |
| D | Peri-urban | Lease + chorine delivery | 424.3% | Problems with kiosk management. Kiosk often opened late or remained closed. | No, device removed due to payment default. | No |
| E | Peri-urban | Lease-to-own | 68.7% | Adapted device to be mobile; required customers to buy some chlorinated water before purchasing unchlorinated water. | Yes | Yes |
| F | Urban | Lease + chorine delivery | 6.4% | - | Yes | Yes |
| G | Rural | Lease-to-own + chlorine delivery | 93.6% | - | Yes | Yes |

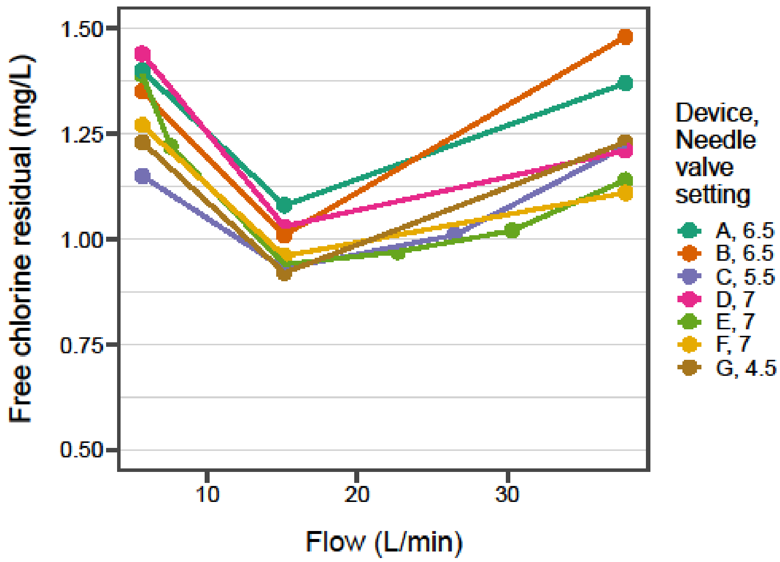


Figure 3-2 Free chlorine residual (mg/L) in water collected from the Venturis in the lab by flow rate (L/min).

The needle valve determines a precise amount of chlorine flowing toward the Venturi and may be adjusted. Needle valve settings correspond to the rotation of the needle valve from closed to open. The settings range from 0 to 10, with 0 representing fully closed and 10 representing fully open. The settings are marked on the needle valve. The needle valve settings shown were selected in the lab and used at installation in the field.

Of 167 water samples collected from kiosk taps fitted with the Venturi, 163 (97.6%) had detectable free chlorine residual (>0.05 mg/L). Free chlorine residual ranged from undetected to a maximum of 1.59 mg/L. 144 samples (88.0%) had free chlorine residual ≥ 0.2 mg/L, the WHO recommended minimum [126]. 164 samples (98.2%) had free chlorine residual ≤ 1.2 mg/L, our maximum threshold based on taste acceptability [125]. The device dosed within a precise range: 144 (86.2%) samples had free chlorine residual ≥ 0.2 mg/L and ≤ 1.2 mg/L. Mean free chlorine residual was 0.55 mg/L (standard deviation: 0.29). The mean free chlorine residual by month since installation remained between 0.37 mg/L and 0.74 mg/L (Figure 3-3). Field staff adjusted the dosing dial on five of 167 visits (3.0%). The device functioned with observed flow rates between 2.2 L/min and 63.2 L/min.

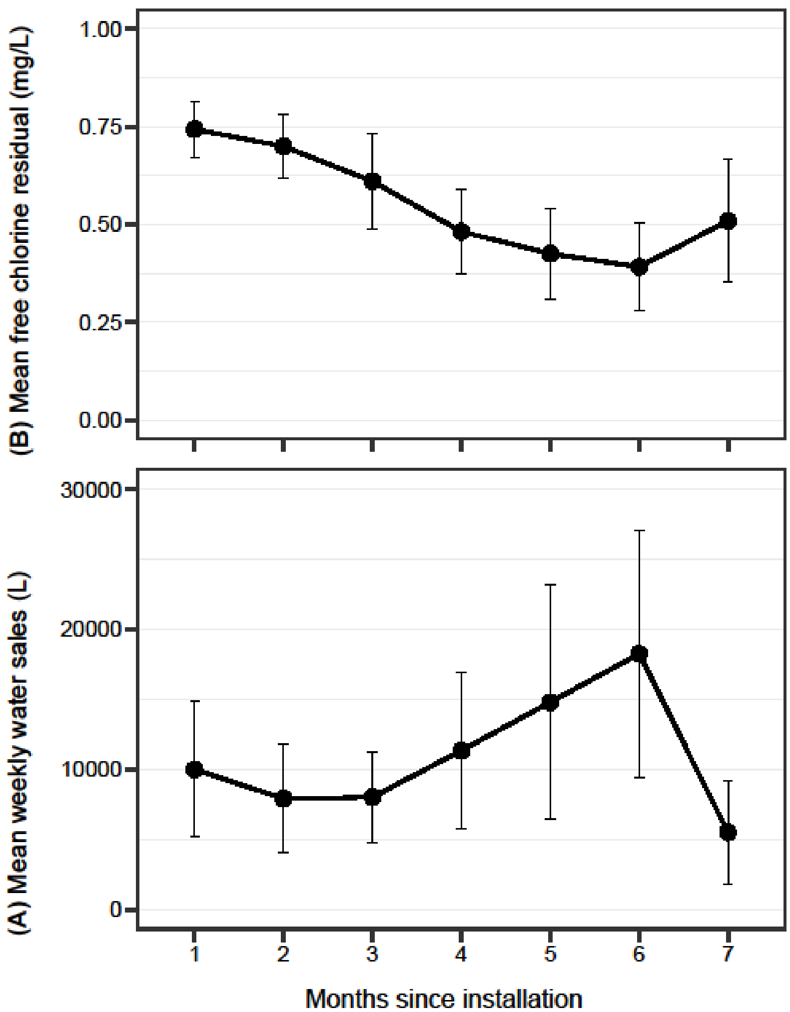


Figure 3-3 Water sales (L) and free chlorine residual (mg/L) at all kiosks by month since installation.

**A** Mean weekly water sales (L) at all kiosks by month since installation of the device. **B** Mean free chlorine residual (mg/L) in water collected from Venturi at all kiosks by month since installation of the device. Error bars show 95% confidence intervals. The non-dosing problem at Kiosk F began occurring after 3 months of installation and a new device was installed 6 months after the original installation. Data are aggregated by months since original installation.

Dosing performance varied by kiosk (Table B-1). Three of the four observations with no detectable free chlorine residual were collected at Kiosk F (Table B-1**)**. The device at Kiosk F performed well during the first three months of installation: all observations were within the desired 0.2-1.2 mg/L range. However, persistent non-dosing began after month 3. Field staff examined the device, observed reddish brown sediment deposits clogging the device, and concluded that these deposits were likely caused by iron in the source water. Field staff attempted to clean/unclog the device on multiple visits. Six months after the original installation, field staff uninstalled the device and installed a new device to resolve this problem. Dosing performance improved after the new device was installed (Figure 3-3**,** Figure B-2).

### 3.3.3 Follow-up: kiosk payments

Six of the seven kiosks fulfilled all payments of their service package. All three of the kiosks that selected lease-to-own options (kiosks C, E, and G) paid in full and became owners of the device upon completing the final payments. Three of the four kiosks that selected lease options (A, B, and F) paid in full during the study period; and of these, two decided to also purchase the device after six months of use (A and F). Kiosk D missed three payments and field staff uninstalled the device on January 24, 2018, four months after installation. In summary, five of the seven kiosks that had a device installed successfully purchased the device. Payments were frequently late: kiosks only made 60% of possible payments on time. Four of the five kiosks that successfully purchased a device took slightly longer than six months to do so; on average kiosks took 7.5 months to complete payments.

### 3.3.4 Follow-up: sales

Overall, chlorinated water sales made up 19.1% of total water sales at the enrolled kiosks. Only one kiosk collected more average monthly revenue from chlorinated water sales than they spent on monthly service package payments (Table B-2); however, five of seven kiosks collected more average monthly revenue from combined chlorinated and unchlorinated water sales than they spent on monthly service package payments (Table 3-2, Table B-2). Monthly payments were higher than average monthly revenue at Kiosk D, where the device was uninstalled due to payment default. Total water sales fluctuated during the study period and increased during the period 3 to 6 months after installation (Figure 3-3). Based on a median installation date of September 15, this roughly corresponds with Kenya's hot dry season. Only 69.2% of weekly observations with available data recorded kiosks opening for all days in the week and 30.8% reported closing at least one day. Total sales, the percentage of sales that were chlorinated, and chlorinated and unchlorinated water prices varied by kiosk (Figure 3-4). Three kiosks sold chlorinated and unchlorinated water for approximately the same price, and four kiosks charged more for chlorinated water (Figure 3-4).

### 3.3.5 Follow-up: customer surveys

Customers reported purchasing a mean of 142 L from the kiosks per day (median: 100 L). 94.4% of customers reported purchasing water from the kiosk at least 2 days per week (43.7% of customers reported purchasing water from the kiosk every day, while 50.7% reported purchasing water 2 to 6 days per week and 5.6% reported purchasing water one day per week or less). Average customer-reported one-way walk time from home to the kiosk was 9.4 minutes (median: 7 minutes). Most (91.6%) customers reported using additional water sources other than the given kiosk, but they collected the majority of their water from the kiosk (66.2% reported that >60% of their household water supply came from the kiosk). Rainwater catchment was the most frequently reported alternative water source: 53.5 % of customers reported practicing rainwater catchment. The high reported use of rainwater is consistent with observed seasonal fluctuation in total kiosk sales (Figure 3-3).

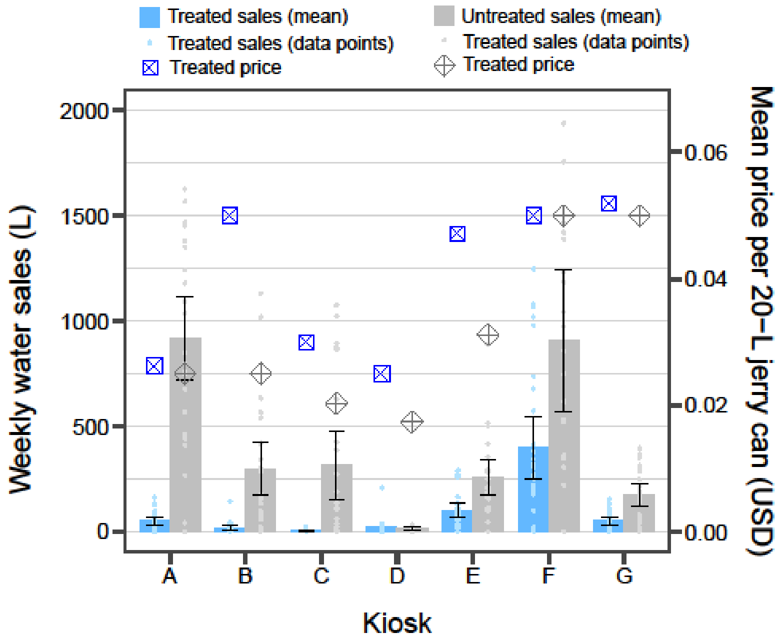


Figure 3-4 Weekly water sales (L) and prices (USD) by kiosk.

Error bars show 95% confidence intervals. For weekly water sales data points, outliers >2000 L are not shown.

Most (90.1%) customers reported being very or somewhat satisfied with the quality of water from the kiosks. 52.0% of customers reported purchasing both unchlorinated water and water chlorinated with the Venturi, while 14.1% reported purchasing only water chlorinated with the Venturi and 33.8% reported purchasing only unchlorinated water. Water use differed between chlorinated and unchlorinated water: 89.4% of customers who collected chlorinated water reported using it for drinking, while only 24.6% of customers who collected unchlorinated water reported using it for drinking. Water safety perceptions also differed between chlorinated and unchlorinated water: 83% of customers who purchased chlorinated water considered it to be very safe, while only 18% of customers who purchased unchlorinated water considered it to be very safe. On average, customers reported paying 4.2 KSH (0.042 USD) per 20-L jerry can of chlorinated water and 3.0 KSH (0.03 USD) per 20-L jerry can of unchlorinated water. When asked to list what they liked about the Venturi, attractive/high quality appearance was the characteristic most frequently mentioned (64.8% of customers). When asked to list what they disliked, 76.1% of customers reported that they did not dislike anything about the doser.

### 3.3.6 Follow-up: operator and manager surveys

All kiosk operators and managers reported satisfaction with the performance of the Venturi and with the quality of water produced by the Venturi. When asked to list what they liked about the Venturi, convenience of use was most frequently mentioned (84.6% of kiosk operators and managers). When asked for suggestions for how the doser could be improved, the most frequently mentioned suggestion was that the spout should be longer or include an extension pipe (30.8% of operators and managers). Other suggested improvements included lower price, longer payment periods, ability to serve multiple taps with a single device, improved security, and changes to the appearance. Profits from water sales was most frequently listed as a source of payment for the Venturi (87.5% of kiosk managers). Other sources of payment included community contributions and donations from partner organizations. Most (75%) kiosk managers reported that it was somewhat or very difficult for them to make monthly lease payments.

## 3.4 DISCUSSION

The Venturi consistently chlorinated drinking water at kiosks for six months (97.6% of all samples had detectable free chlorine residual, with most non-detects from the device with iron deposits) and within a precise range (86.2% of samples had free chlorine residual ≥ 0.2 mg/L and ≤ 1.2 mg/L). The Venturi performed well in comparison with field trials of other in-line chlorinators, which have reported detectable free chlorine residuals ranging from 77% to 100% [118,119,124] of samples at the POC. Five of the seven devices functioned for six months with minimal technical support; one device had to be uninstalled early due to payment default (not technical problems); and one device was replaced after six months due to clogging by iron deposits. Overall, the low frequency of technical adjustments to the device (<5% of weekly visits) suggests that the device is likely to continue consistent dosing without regular monitoring at kiosks. Notably, our results suggest the device is not suitable for water sources with high levels of iron without a prefilter. Exact iron levels were not measured as part of this study; future work should include measurements of iron concentration in order to determine if water points should be screened for a threshold concentration of iron prior to installation.

The kiosks' overall success in completing service package payments and in purchasing the devices suggest this technology and the associated service/lease options is a financially viable strategy for kiosks to provide safe water in similar communities. Five of the seven kiosks who committed to a sales package decided to purchase the device after six months of device usage experience, suggesting that the device functions well and is desirable to kiosk managers and operators. Effective demand (defined as the ability and willingness to pay) suggested the service package pricing was acceptable. However, only 27% of kiosks who heard sales pitches committed to a sales package, indicating that kiosks may have self-selected based on ability to pay. Some kiosks reported funding payments solely through water sales, while others subsidized leasing the device through grants and other funding mechanisms. The Venturi may have the potential to scale in the private sector or through subsidies from community organizations, non-governmental organizations (NGOs), and government funding mechanisms. The health benefits of drinking chlorinated water [21,107,124,129,130] may be viewed as justification for these subsidies, which could enable community access to safe water when effective demand is inadequate for full cost recovery.

Late payments were problematic throughout the study and most kiosks took slightly longer than six months to complete purchase payments (7.5 months on average). Several managers of kiosks selecting lease-only expressed a desire to continue making monthly payments rather than a lump sum payment to complete the purchase process. Allowing kiosks to switch from lease to lease-to-own plans or offering only lease-to-own plans with longer payment periods (and lower monthly payments) could enable more kiosks to purchase the device. For example, kiosks could be offered the choice of 6, 12, 18, and 24-month lease-to-own payment periods. A payment plan that allows flexibility by season (higher rate during dry season and lower rate during wet season) could also improve payment compliance rates.

Kiosk managers had varying priorities (in addition to maximizing chlorinated water sales), which likely motivated their choice of strategies and contributed to differential sales success between kiosks. Kiosk A typically sold chlorinated and unchlorinated water at the same price, but restricted sales of chlorinated water for drinking use only (using a daily cap per customer) in order to save money on chlorine refills. Chlorinated water sales at kiosk A were low (4.4% of total sales), but this may be due in part to the limit per customer. Since restricting a product can sometimes make it seem more valuable and increase customers' likelihood of purchase [131], a purchasing limit per customer could lead to a higher proportion of customers purchasing chlorinated water. Keeping the price of chlorinated water similar to unchlorinated water could enable more customers to purchase at least some chlorinated water for drinking purposes. Kiosk B adopted a very different strategy, selling chlorinated water at double the price of unchlorinated water, which resulted in a low volume of chlorinated water sales (5.5% of total sales) but at a higher price. Comprehensive customer-level sales data (how many customers purchased chlorinated water versus unchlorinated water each week and how much they purchased) was outside of the scope of this study but would be necessary to test if a higher proportion of customers were purchasing chlorinated water at kiosk A compared to kiosk B. Sales at kiosk C were similarly low (4.2% of total sales). However, kiosk C also provided chlorinated water on-site to visitors and children attending feeding programs at the community organization. Thus, the sales data may not fully capture the reach of chlorinated water at kiosk C.

Among kiosks with a higher proportion of chlorinated water sales, some kiosks sold chlorinated and unchlorinated water for the same price or utilized other unique strategies to facilitate the sale of chlorinated water. Kiosk E adapted the device to be mobile and moved it between three different sales sites, responding to demand. Kiosk E also required customers to buy some chlorinated water before purchasing unchlorinated water. As a result, chlorinated water sales made up a large portion of total water sales (27.4%) despite its higher price. Kiosks F and G both sold chlorinated and unchlorinated water at approximately the same price and actively promoted the use of chlorinated water for all purposes, and chlorinated water sales made up a large portion of total water sales (31.7% and 20.0%, respectively). Chlorinated water sales at kiosk D represented a large portion of total water sales (52.5%), but the overall water sale volume was very low. The kiosk often closed, citing competition from nearby KIWASCO water and problems with kiosk management as the reasons for closures.

Since kiosks frequently closed and sometimes forgot to record sales, these results may slightly underestimate total kiosk sale potential if kiosks were open every day. The six-month study period is also a limitation, which did not allow us to fully capture the seasonal effect on water sales throughout an entire calendar year. It is unknown how the device performs long term (beyond six months) and without free technical support. It is possible that problems with iron deposits will occur at other kiosks after a longer period of use. Microbial water quality measurements and health outcomes were not included in the study; however, substantial reductions in *E. coli*[118,124] and child diarrhea[124] have been demonstrated by in-line chlorination at similar dosing levels in Bangladesh. Future work examining the effect of in-line chlorination on diarrhea, enteric infections, and under-five child mortality in Sub-Saharan Africa would be valuable for catalyzing investment in scaling up this technology. We were not able to evaluate whether this business model would be profitable for the service provider since Safe Water and Aids Project (SWAP), a local NGO, was providing the service as well as performing research evaluation activities. In practice, the service provider would not need to visit kiosks on a weekly basis, which would significantly reduce staffing and transportation costs. Future work should evaluate whether this model is profitable for a real-world distributor.

The Venturi has several advantages over existing technologies. The estimated manufacturing cost of the molded Venturi (Figure 3-1) is 34 USD with a projected lifespan of five years. The device can dose within a precise and acceptable range.  Independence from electricity is advantageous, allowing the device to reliably dose during power cuts. The device uses WaterGuard (distributed by Population Services International in over 20 countries) or dilute bleach, which are widely available in low-resource settings. Using liquid chlorine is an advantage over solid tablet dosers with cartridges, which require waiting for an empty cartridge and possible non-dosing before replacement. Liquid chlorine has the potential to be more affordable than solid chlorine tablets if produced locally, such as with electrochlorinators[121]. Unlike other product options[119,123], the Venturi does not affect water collection time. The technical performance of the Venturi, advantages over existing technologies, and effective demand from kiosks suggest that the Venturi has the potential to increase safe water access in low-income communities.

# CHAPTER 4. Effects of COVID-19 pandemic on child mortality and child health in rural Kenya

## 4.1 INTRODUCTION

COVID-19 related lockdown measures and disruptions have affected life in Kenya and throughout the world. Kenya reported its first confirmed case of COVID-19 on March 13, 2020[132] and announced nationwide school closures on March 15, 2020[133]. Infection with COVID-19 could have directly contributed to excess mortality[134] and other adverse health outcomes[135]. Indirect effects (e.g. job losses and behavioral changes) may have also affected child health. Measures requiring individuals to stay home or limit travel have increased poverty and food insecurity in Kenya and other low- and middle-income countries[136–138] and may have reduced ability to pay for healthcare and food. In a nationally representative survey of Kenyan adults with mobile phones between May 14 and July 3, 2020, 42% reported missed or reduced meals, 25% reported a drop in income, and 37% reported a drop in employment compared with pre-pandemic levels[138].

Some behavioral changes associated with the COVID-19 pandemic may have had positive effects on child health. A study in informal settlements in Nairobi (Kenya) measured social contacts during the pandemic and suggested that they were reduced based on comparisons with other studies, but did not have baseline data for the same study population from before the pandemic[139]. Although intended to prevent the spread of COVID-19, widespread social distancing[140], masking[141], and increased handwashing[142,143] have the potential to reduce transmission of other illnesses. Reductions of respiratory illnesses such as influenza and RSV have been observed during the pandemic in many countries including Argentina, Australia, Bangladesh, Bolivia, Canada, Chile, Madagascar, Mexico, Paraguay, South Africa, and the United States[144–147], but we are not aware of evidence from Sub-Saharan Africa.

The pandemic may have affected access to maternal and neonatal healthcare. Expectant mothers (and others) may have avoided seeking care at clinics and hospitals due to fear of contracting or being tested for COVID-19 and forced to quarantine[148,149], or have been unable to travel to give birth in a healthcare facility because of nightly curfews[150]. In twelve qualitative surveys in Kilifi County, Kenya, expectant mothers and mothers who recently gave birth reported that they feared visiting hospitals for maternal care due to the risk of contracting COVID-19. Traditional midwives also reported increased demand for their services[149]. Giving birth at home or with traditional midwives rather than in a health facility could have contributed to increased neonatal mortality: in a hospital-based study in Nepal, the number of institutional births was reduced by >50% and the risk of preterm birth, stillbirth, and neonatal mortality increased[151]. The authors noted that women with high risk pregnancies may have been more likely to give birth in hospital even during the pandemic, while women with lower risk may have been more likely to stay home[151]. Community-based (rather than institutional) evidence is critical for determining whether these trends hold in Kenya and for women who gave birth outside of institutions.

School closures in Kenya (6 to 10 months) [38,152] may have affected learning, school enrollment, and attendance even after schools reopened. The government introduced remote television, radio, and online lessons during school closures[153]. However, according to a May 2020 survey report by Usawa Agenda and Uwezo, access was low and inequitable: only 22.2% of all school going children accessed any remote learning materials, and children in public schools were half as likely to have access compared to those in private schools[154]. A recent longitudinal survey among secondary school girls in Kenya found three times the risk of school dropout during the pandemic compared to pre-pandemic[155]. We are not aware of any studies that have investigated the effects of the pandemic on school enrollment among young (pre-primary and primary) children in Kenya. However, in many U.S. States, school enrollment declined sharply in 2020, particularly among preschoolers and kindergartners[156,157]. School enrollment in Kenya following COVID-19 related closures could have been similarly affected.

## 4.2 METHODS

### 4.2.1 Study design

As the severity of the COVID-19 pandemic became clear, we identified an opportunity to leverage an existing study design to better understand the impacts of the pandemic in rural Kenya. We enrolled villages that were located in Bungoma, Kakamega, or Vihiga counties and were previously enrolled in select arms of the WASH Benefits Kenya trial (water; water, sanitation, and handwashing; water, sanitation, handwashing, and nutrition; active control; or passive control)[30]. Respondents were eligible if they were women 50 years of age or younger at the time of enrollment, had a child after January 1, 2008, and lived in an eligible village. Respondents were visited in person by our team for a separate study investigating the impact of a water treatment intervention on child survival, between July 26, 2019 and March 14, 2020 (Figure 4-1), when data collection was halted due to the COVID-19 pandemic. During this time, we censused 575 out of 816 eligible villages, and enrolled and surveyed 34,052 eligible women. Once we were able to safely resume in-person data collection, we censused the remaining 241 villages and enrolled and surveyed 12,068 remaining eligible women between January 12, 2021 and May 26, 2021.

During in-person interviews, we measured diarrhea, fever, and cough (yesterday and in the past 7 days) among eligible mothers and their under-5 children. We recorded birth dates, death dates, and age at death for all births since January 1, 2008. We conducted WHO Verbal Autopsies to ascertain the cause of death for all under-5 deaths. In addition to standard neonatal (<28 days), infant (<1 year), and child (<5 years) mortality, we included <4 month mortality because we wanted to be able to compare children who were born after the pandemic began to those with no exposure, and we had limited follow-up time after the pandemic began. We also measured child school enrollment and attendance (number of days attended in the last full week).

We followed up with a subset of enrolled women by phone between June 25, 2020 and December 22, 2020 (Figure 4-1) while we were unable to conduct in-person surveys. We divided the respondents who provided a phone number (N = 29,301) into seven random survey rounds of equal size. Each survey round had the same proportion of respondents from each geographic block. The final sample size (N = 10,503) was not predetermined because the trajectory of the pandemic was unclear and we planned to conduct phone surveys until we were able to safely resume in-person data collection. We attempted to contact each respondent five times. We attempted to contact all respondents in survey rounds 1, 2, and 3, and partially completed survey round 4. We stopped conducting phone surveys because we were able to resume in-person data collection. Our response rate (number of surveys completed/number of respondents we attempted to contact) was 68%.

During phone surveys, we measured COVID-19 perceptions and behaviors (including knowledge of symptoms, vaccine and test willingness, masking, travel, and social distancing); child and mother health outcomes (diarrhea, bloody stool, fever, cough, difficulty breathing, headache, sore throat, loss of smell or taste, chills, repeated shaking with chills, unusual muscle pains, unusual pain or pressure in the chest, unusual fatigue, congestion or runny nose, nausea or vomiting, loss of appetite new confusion, inability to wake or stay awake, skin rash); household economic outcomes (changes to work hours and income, coping mechanisms); and household food security (assessed using household hunger scale (HHS)).

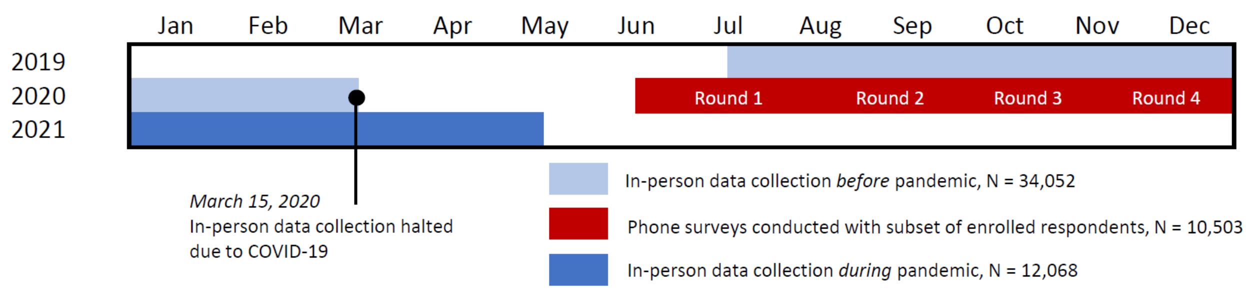


Figure 4-1 Data collection timeline

### 4.2.2 Statistical Analysis

Our pre-specified statistical analysis plan is available on Open Science Framework (https://osf.io/f7mrp/). Data cleaning was performed using StataMP 16 and R (v 4.2.1, R Core Team 2022). Statistical analyses were performed using R including the *survival* (v 3.3-1, Thernau 2022 ) and *lmtest* (v 0.9-40, Zeileis & Hothorn 2002) packages. We used modified Poisson regression for binary outcomes (mother and child health, school enrollment), and ordinary least squares linear regression for linear outcomes (school attendance). We used the Cox proportional hazards model with time-varying exposure for mortality outcomes. We screened additional covariates for inclusion in adjusted models using likelihood ratio tests (included if $p<0.2$). We performed stratified analysis for potential effect modifiers and tested for statistical significance using likelihood ratio tests. We considered results with p-values less than 0.05 statistically significant.

We considered mother and child health, school enrollment, and school attendance to be instantaneous outcomes measured at the time of the survey. Mothers and children were considered not exposed if surveyed before March 14, 2020 and exposed if surveyed on or after March 14, 2020. To account for potential seasonality effects, we performed subgroup analyses for instantaneous outcomes, including only data that was collected on dates at the same time of year before and after the start of the pandemic (January 12, 2020 to March 14, 2020 and January 12, 2020 to March 14, 2021, see Figure 1). We adjusted for the month of year in this analysis. For school attendance and enrollment outcomes, we excluded data collected during official school vacations plus a 2 day buffer on either side of the break to account for vacation schedule differences.

We used time-varying exposure to analyze child mortality because we had limited data on children who were fully exposed to the pandemic (i.e. only very young children were born after the pandemic began). We also expected that even partial exposure to the pandemic could affect child survival. Children were always considered unexposed if they were surveyed, reached 28 days (or other threshold age), or died on or before March 14, 2020. Children were always considered exposed if they were born after March 14, 2020. Children were partially exposed if they were alive but had not reached 28 days (or other threshold age) by March 14, 2020. They contributed unexposed child-time for the period between their birth date and March 14, 2020, and exposed child-time for the period between March 15, 2020 and the date that they were surveyed, turned 28 days, or died. We performed a sensitivity analysis excluding children who were partially exposed. Because we expected that mortality may have changed over time independent of the pandemic, we also conducted a secondary analysis excluding children born before January 1, 2018.

## 4.3 RESULTS

### 4.3.1. Prevalence of diarrhea, fever, and cough during vs. before COVID-19 pandemic

Caregiver reported prevalence of diarrhea, fever, and cough among respondents and their under-5 children decreased substantially during the COVID-19 pandemic (Table 4-1, Figure 4-2). Among under-5 children, diarrhea prevalence decreased from 11.5% in the pre-pandemic period to 5.9% during the pandemic (adjusted PR: 0.53, 95% CI: 0.48, 0.59), fever prevalence decreased from 8.6% to 7.1% (adjusted PR: 0.82, 95% CI: 0.72, 0.94), and cough prevalence decreased from 20.4% to 16.3% (adjusted PR: 0.8, 95% CI: 0.73, 0.89). Among respondents, diarrhea prevalence decreased from 2.8% in the pre-pandemic period to 2.2% during the pandemic (adjusted PR: 0.79, 95% CI: 0.67, 0.93), fever prevalence decreased from 11.5% to 9.3% (adjusted PR: 0.81, 95% CI: 0.73, 0.89), and cough prevalence decreased from 13.7% to 10.8% (adjusted PR: 0.79, 95% CI: 0.72, 0.87).

### 4.3.2 School enrollment and attendance during vs. before COVID-19 pandemic

School enrollment decreased slightly during the pandemic, from 86.7% to 86.1% (adjusted PR: 0.93, 95% CI: 0.92, 0.94) (Table 4-1, Figure 4-2). In subgroup analyses by child age, this effect was largest for young children (adjusted PR (95% CI): 0.62 (0.53, 0.73) for age 3, 0.82 (0.76, 0.87) for age 4, and 0.94 (0.92, 0.97) for age 5). This effect did not hold for children 6 years or older (Figure C-1).

Table 4-1 Prevalence of diarrhea, fever, cough, and school enrollment before pandemic, during pandemic, and prevalence ratios.

| | Before pandemic | | During pandemic | | Prevalence ratio (95% CI) | |
|---|---|---|---|---|---|---|
| | Prevalence (%) | N | Prevalence (%) | N | Unadjusted | Adjusted |
| Respondent[s] | | | | | | |
| 7-day diarrhea | 2.8 | 20,512 | 2.2 | 12,065 | 0.78 (0.66, 0.92) | 0.79 (0.67, 0.93) |
| 7-day fever | 11.5 | 12,395 | 9.3 | 12,067 | 0.8 (0.73, 0.89) | 0.81 (0.73, 0.89) |
| 7-day cough | 13.7 | 12,395 | 10.8 | 12,064 | 0.78 (0.71, 0.86) | 0.79 (0.72, 0.87) |
| Under-5 child[b] | | | | | | |
| 7-day diarrhea | 11.5 | 77,428 | 5.9 | 29,067 | 0.53 (0.47, 0.59) | 0.53 (0.48, 0.59) |
| 7-day fever | 8.6 | 77,428 | 7.1 | 29,067 | 0.82 (0.72, 0.94) | 0.82 (0.72, 0.94) |
| 7-day cough | 20.4 | 77,428 | 16.3 | 29,067 | 0.8 (0.73, 0.88) | 0.8 (0.73, 0.89) |
| 3-12 year old child[b] | | | | | | |
| School enrollment | 86.7 | 46,245 | 86.1 | 18,089 | 0.93 (0.91, 0.96) | 0.93 (0.92, 0.94) |

a) For respondent health outcomes, we screened the following covariates for inclusion in adjusted models: mother completed primary education and number of people living in the households.

b) For child outcomes, we included child age in months in both unadjusted and adjusted models. We also screened the following covariates for inclusion in adjusted models: mother completed primary education, mother age in years, and number of people living in the household.

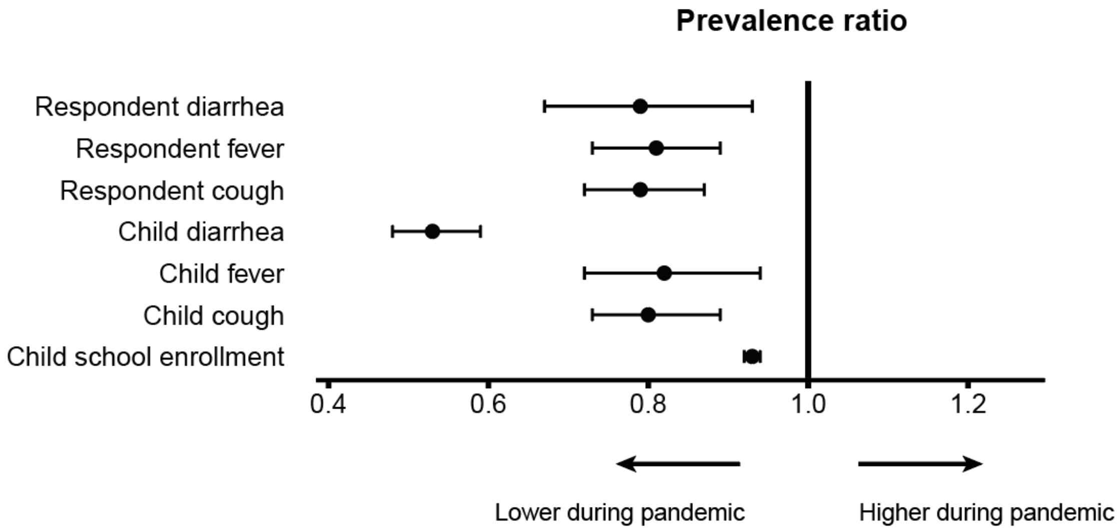


Figure 4-2 Prevalence ratio of diarrhea, fever, cough, and school enrollment comparing period during COVID-19 pandemic began in Kenya vs. before pandemic.

Error bars show 95% confidence intervals.

### 4.3.3 Mortality hazard associated with COVID-19 pandemic

Exposure to the COVID-19 pandemic period was associated with increased neonatal mortality HR: 1.29, 95% CI: 1.02, 1.64) in an unadjusted model and weakly associated with increased neonatal mortality (HR: 1.21, 95% CI: 0.96, 1.53) in an adjusted model (Table 4-2, Figure 4-3). Under-4 month, under-1 year, and under-5 year mortality were not significantly different during the pandemic compared with the pre-pandemic period.

Analysis of cause-specific mortality was limited by small sample sizes and resulting insufficient statistical power (Table 2). However, trends suggest that there may have been a decrease in infectious-disease mortality during the pandemic (under-5 adjusted HR: 0.71, 95% CI: 0.49, 1.02), consistent with the reductions we observed in prevalence of diarrhea, fever, and cough. Deaths due to prematurity significantly increased during the pandemic (adjusted HR: 3.36, 95% CI: 1.4, 8.03). Deaths due to birth asphyxia may have also increased, though effects were not statistically significant (adjusted HR: 1.18, 95% CI: 0.82, 1.7).

Table 4-2 All-cause deaths and deaths due to infectious disease, diarrhea, birth asphyxia, and prematurity during unexposed and exposed periods.

| | Unexposed | | Exposed | | Hazard Ratio (95% CI) | |
|---|---|---|---|---|---|---|
| Age threshold | Child-years | Deaths | Child-years | Deaths | Unadjusted | Adjusted |
| Under 28 days | 7,817 | | 192 | | | |
| All-cause | | 1,757 | | 56 | 1.29 (1.02, 1.64) | 1.21 (0.96, 1.53) |
| Infectious | | 3 | | 1 | 13.67 (1.42, 131.3) | 13.67 (1.42, 131.3) |
| Diarrheal | | 0 | | 0 | .. | .. |
| Birth asphyxia | | 904 | | 28 | 1.26 (0.87, 1.81) | 1.18 (0.82, 1.7) |
| Prematurity | | 68 | | 6 | 3.58 (1.55, 8.28) | 3.36 (1.4, 8.03) |
| Under 4 months | 33,515 | | 820 | | | |
| All-cause | | 2,130 | | 62 | 1.18 (0.94, 1.49) | 1.14 (0.9, 1.43) |
| Infectious | | 200 | | 4 | 0.82 (0.31, 2.17) | 0.79 (0.3, 2.09) |
| Diarrheal | | 28 | | 0 | .. | .. |
| Under 1 year | 96,766 | | 2,335 | | | |
| All-cause | | 2,759 | | 70 | 1.04 (0.83, 1.29) | 1.00 (0.8, 1.25) |
| Infectious | | 566 | | 8 | 0.59 (0.3, 1.14) | 0.58 (0.3, 1.13) |
| Diarrheal | | 144 | | 0 | .. | .. |
| Under 5 years | 395,716 | | 10,456 | | | |
| All-cause | | 3,968 | | 101 | 1.02 (0.85, 1.23) | 0.99 (0.82, 1.19) |
| Infectious | | 1,420 | | 26 | 0.72 (0.5, 1.05) | 0.71 (0.49, 1.02) |
| Diarrheal | | 218 | | 1 | 0.19 (0.03, 1.33) | 0.19 (0.03, 1.32) |

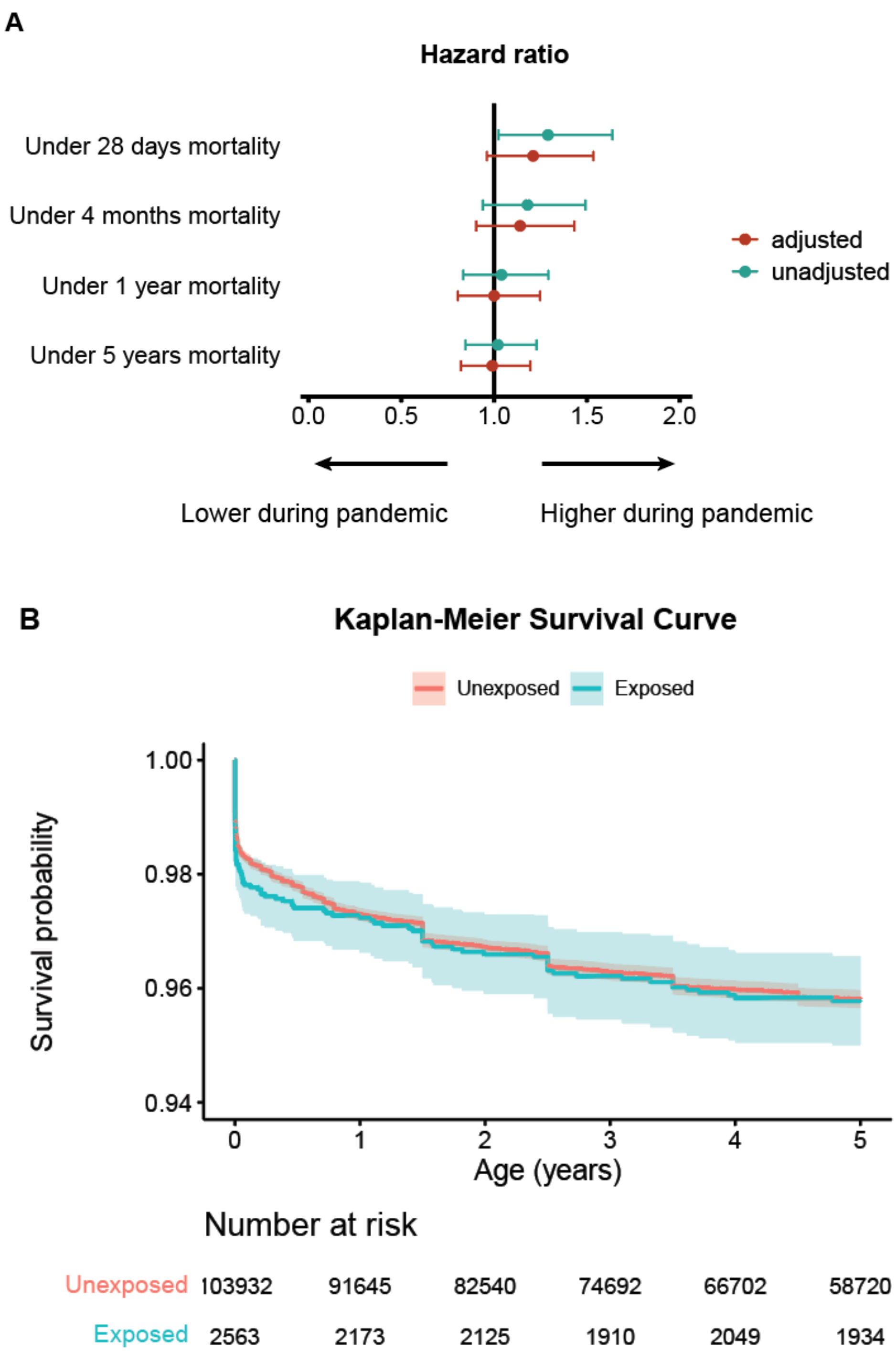


Figure 4-3 A. Hazard ratio of child mortality (under-28 day, under-4 month, under-1 year, under-5 year) comparing exposed child-time to unexposed child-time. Error bars show 95% confidence intervals. B. Kaplan-Meier Survival Curve stratified by exposure status.

Shading shows 95% confidence intervals.

### 4.3.4 Repeated cross-sectional phone surveys during COVID-19 pandemic

*Prevalence of diarrhea, fever, and cough*

Among both respondents and their under-5 children, prevalence of most symptoms was highest in round 1 (June 21, 2020 to August 12, 2020) and decreased in subsequent rounds (Table C-1, Table C-2). Some symptoms (headache, fever, and fatigue among respondents; congestion, cough, fever, and diarrhea among under-5 children) initially decreased, but rebounded by round 4.

*COVID-19 perceptions and behaviors*

When asked to identify the symptoms of COVID-19 (without prompting), most respondents listed cough (72.8%) and fever (68.4%) (Figure C-2). Very few people identified diarrhea (2.5%, 95% CI:  2.2%, 2.8%), sore throat (2.4%, 95% CI: 2.1%, 2.7%), or loss of smell/taste (0.5%, 95% CI: 0.4%, 0.7%).

When asked what measures (if any) they had taken to reduce their risk of contracting COVID-19 in the past 7 days, the vast majority of respondents mentioned handwashing (96.6%, 95% CI: 96.3%, 97.0%) and wearing a mask or face covering (91.3%, 95% CI: 90.7%, 91.8%) (Figure C-4). All other measures were mentioned by <50% of respondents.

*Economic effects*

Reporting of negative work changes was highest in round 1 and decreased over time (Figure 6). In round 1, 25.0% (95% CI: 18.8%, 31.2%) of respondents experienced a temporary layoff and this decreased to 13.8% (95% CI: 8.1%, 19.5%) in round 4. The proportion of respondents who experienced delayed wages also decreased from 18.6% (95% CI: 13.0%, 24.2%) in round 1 to 0.7% (-0.7%, 2.1%) in round 4.

In round 1, 77.4% of respondents reported that their monthly household income was currently lower than it was before the pandemic (Figure C-4). The proportion of respondents who reported a lower household income decreased in subsequent study rounds, to 61.7% in round 4.

*Food security effects*

Household food insecurity was high in round 1, with 77.0% (95% CI: 75.5, 78.6) of respondents reporting that they worried they would not have enough food and 47.2% (95% CI: 45.4, 49.0) reporting that they ran out of food in the past month (Figure C-5). Food security improved during the study period but remained high: by round 4, 64.5% (95% CI: 62.4%, 66.0%) of respondents reported worrying about having enough food and 31.7% (95% CI: 29.5, 33.9) reported running out of food. We compared food security responses to data collected in the same study area during the WASH Benefits Kenya study. We found that food insecurity was more severe in 2020 than in 2013 (Figure 4-4). However, levels of food insecurity were similar by December.

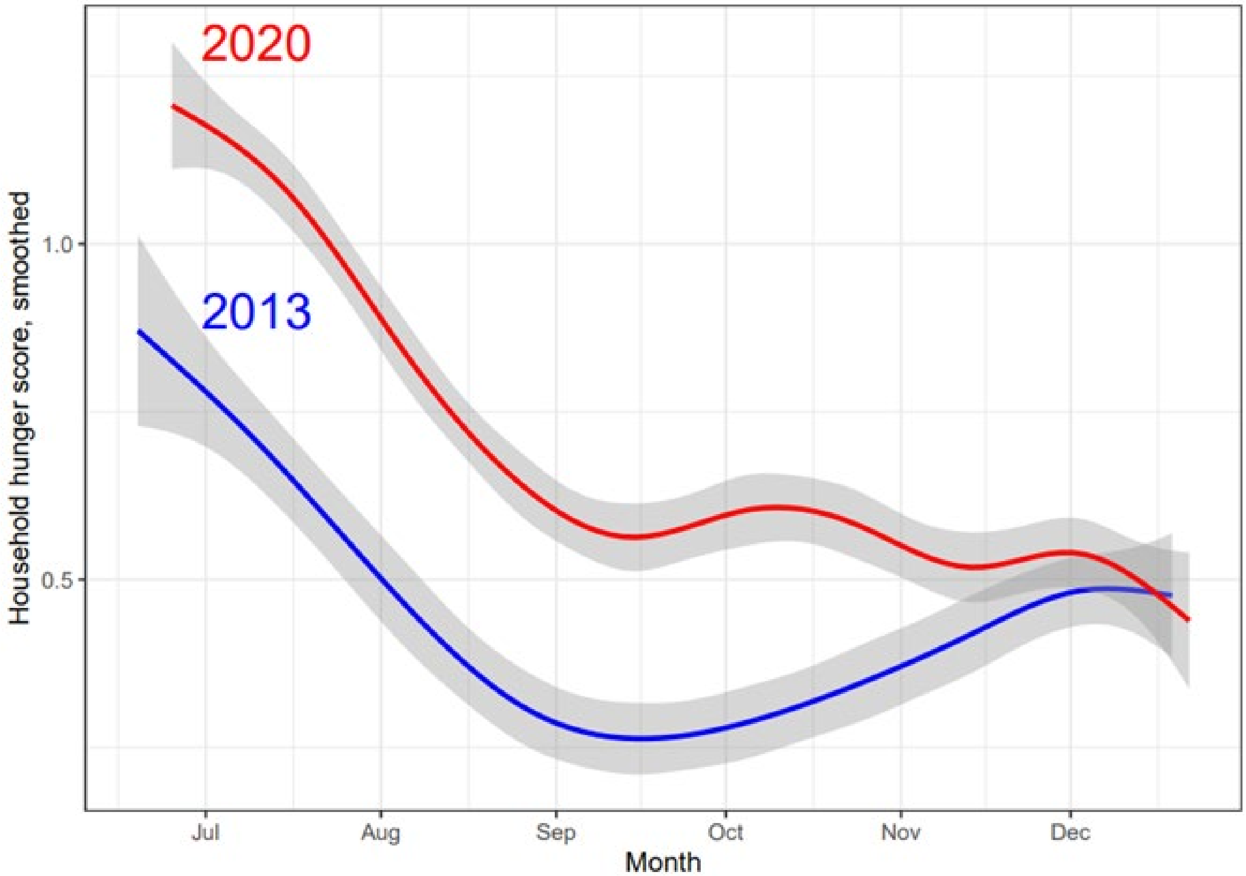


Figure 4-4 Household hunger score by month of year in 2020 vs. 2013.

## 4.4 DISCUSSION

We observed a large increase in neonatal mortality due to prematurity and potential increases in all-cause neonatal mortality and neonatal mortality due to birth asphyxia during the COVID-19 pandemic. We hypothesize that healthcare facilities may have been overwhelmed by COVID-19 cases and precautions, potentially resulting in poorer neonatal health care. In particular, the COVID-19 pandemic drove a severe oxygen shortage in Kenya (and much of Africa) during 2021, causing oxygen to be prohibitively expensive or unavailable[158,159]. Healthcare providers reported anecdotally that patients were dying because they were unable to afford oxygen[160]. Oxygen shortages may have contributed to neonatal mortality, particularly deaths due to prematurity and birth asphyxia when early resuscitation intervention is critical to infant survival[161]. The increase in neonatal mortality in our study area is unlikely to be due to mothers giving birth at home rather than in healthcare facilities because a larger proportion of mothers reported giving birth in healthcare facilities during the pandemic (93.2%, 95% CI: 92.2, 94.1) compared with before the pandemic (87.3%, 95% CI: 86.6, 88.1).

We also found a likely decline in infectious disease related mortality among under-1 and under-5 children. This is consistent with the reductions in under-5 diarrhea (nearly 50% reduction) and respiratory illness (~20% reduction in both fever and cough) that we observed. Infectious disease transmission may have been interrupted by actions taken to reduce COVID-19 risk such as wearing a mask, washing hands more frequently, or reduced contact with others (e.g. not attending school). We observed high prevalence of masking (>90%), handwashing (>95%), and staying at home more frequently (~40%), which supports this hypothesis.

The reductions in respiratory illness that we observe could be biased because respondents may have been less willing to report fever or cough due to stigma associated with COVID-19. Others have reported a stigma associated with COVID-19 infection in western Kenya[162], and some fear being forced to quarantine[148]. More than two-thirds of respondents knew that fever and cough were symptoms of COVID-19. However, the reductions in respiratory illness that we observe are consistent with the reductions in infectious disease related deaths, which may be less susceptible to bias. The reductions are also consistent with respiratory illness reductions that have been observed in other countries during the pandemic[144–147]. Kim *et al.* examined changes to the influenza-positive proportion in seven countries in the Southern hemisphere during the pandemic and found reductions in all seven countries, ranging from 3% in Argentina to 31% in Madagascar[147]. We also observe a large (~50%) reduction in child diarrhea. Because so few (2.5%) respondents associate diarrhea (2.5%) with COVID-19, we do not expect diarrhea estimates to be biased.

We are unable to say with certainty to what extent effects can be attributed to the pandemic versus independent changes over time. However, mortality rates have been declining over the past several decades. According to the UN Inter-agency Group for Child Mortality Estimation, neonatal mortality in Kenya decreased from 24.2 deaths per 1,000 live births in 2010 to 21.0 deaths per live births in 2019. Under-5 mortality rate in Kenya also decreased from 57.4 deaths per 1,000 live births in 2010 to 43.0 deaths per 1,000 live births in 2019, an average reduction of 3.2% per year[3]. If the pandemic did not affect mortality, we would have expected to see a reduction in mortality rates.

After schools reopened, school enrollment was lower among 3 to 5-year-old children compared with pre-pandemic levels. The Kenyan Ministry of Education guidelines state that children should start pre-primary 1 at age 4, continue to pre-primary 2 at age 5, and begin primary school at age 6[163]. A decline in school enrollment among 4 to 5-year-olds suggests that children who should be enrolling in school for the first time are doing so at a lower level than they were before the pandemic. Similar reductions in early school enrollment (kindergarten, preschool, or first-grade) have been observed in the United States[156,157] and South Africa[164].

Our results suggest that the COVID-19 pandemic may have contributed to increased neonatal mortality and decreased transmission of respiratory illness and diarrhea in rural Kenya. To our knowledge, this is the first study to examine effects of the pandemic on child mortality, respiratory illness, or diarrhea in Sub-Saharan. These results may inform decisions about preparing for future waves of COVID-19 and other future pandemics. Tools that were used for COVID-19 prevention (masking, staying at home) may be effective in preventing other infectious diseases. However, we suggest that pandemic response measures and resource diversion can negatively affect other health issues, particularly those that rely on hospital-based care. Pandemic preparedness should focus not only on prevention of the disease at-hand, but also on measures to ensure continuation of other essential healthcare services including maternal and neonatal care.

# CHAPTER 5. Conclusion

## 5.1 RESEARCH SUMMARY

### 5.1.1 Effects of weather conditions on drinking water quality and child hand contamination levels in rural Kenyan households

The study objective was to examine the relationship between weather and bacteria levels in drinking water and on child hands in order to better understand how climate change may affect transmission of diarrheal diseases. We linked measurements of *Escherichia coli* in source water (n=1,673), stored drinking water (n=8,924), and hand rinses from children <2 years old (n=2,660) with publicly available gridded temperature and precipitation data (at ≤0.2 degree spatial resolution and daily temporal resolution) by the GPS coordinates and date of sample collection. Measurements were collected over a 3-year period across a 2500 $km^2$ area in rural Kenya. In drinking water sources, high 7-day temperature was associated with a 0.16 increase in $\log_{10}$ *E. coli* levels ($p<0.001$), while heavy 7-day total precipitation was associated with a 0.29 increase in $\log_{10}$ *E. coli* levels ($p<0.001$). In household stored drinking water, heavy 7-day precipitation was associated with a 0.079 increase in $\log_{10}$ *E. coli* levels ($p=0.042$). On child hands, high 7-day temperature was associated with a 0.39 decrease in $\log_{10}$ *E. coli* levels ($p<0.001$). In subgroup analyses, heavy 7-day precipitation but had no effect on *E. coli* levels in drinking water from households who treated their water. Climate change may increase transmission of bacterial pathogens in water but reduce transmission on hands. Water treatment may mitigate the effects of extreme weather on transmission of bacterial pathogens.

### 5.1.2 Evaluation of a novel venturi chlorine doser to increase safe water access

The study objective was to evaluate the technical performance and demand for a novel in-line chlorine doser. The doser employs the Venturi principle to automatically add liquid chlorine at the point of water collection (tap outflows). The Venturi does not require electricity or moving parts, and users do not have to change the way they typically collect water. We field-tested the Venturi and assessed its technical performance and sales viability at water kiosks in Kisumu County, Kenya. We offered kiosk owners 6-month service packages to lease or lease-to-own the device; 27% of kiosks given a sales pitch committed to a service package. All but one kiosk paid in full during the 6-month service period and more than two-thirds purchased the device with payments totaling >$250 USD per kiosk. Kiosk customers could choose to purchase chlorinated or unchlorinated water from separate taps; 66% reported buying chlorinated water. Kiosk taps fitted with the Venturi had detectable free chlorine residual 97.6% of the time. The technical performance of the Venturi and effective demand from kiosks indicate high potential for the Venturi to increase safe water access in low-income communities.

### 5.1.3 Effects of COVID-19 pandemic on child mortality and child health in rural Kenya

The COVID-19 pandemic has disrupted normal activities world-wide and affected healthcare, the economy, and individual behaviors. We aimed to assess the effects of the COVID-19 pandemic on child mortality, illness, and schooling in rural Kenya. We enrolled respondents if they were women 50 years of age or younger, had a child after January 1, 2008, and lived in a village that was included in the WASH Benefits Kenya trial. We leveraged data collected in-person before the pandemic (July 26, 2019 to March 14, 2020) and after we were able to resume in-person interviews (January 2021 to May 26, 2021) to examine effects on child mortality, diarrhea, fever, and cough. We also conducted repeated cross-sectional phone interviews with a subset of respondents between June 25, 2020 and December 22, 2020 to assess COVID-19 perceptions, behaviors, economic status, and food security during pandemic-associated lockdowns. We enrolled 46,120 mothers and observed 406,172 under-5 child-years (395,716 before the pandemic and 10,456 during the pandemic). We found that the COVID-19 pandemic was associated with increased neonatal mortality due to prematurity (adjusted HR: 3.36, 95% CI: 1.4, 8.03) and was weakly associated with increased all-cause neonatal mortality (adjusted HR: 1.21, 95% CI: 0.96, 1.53) and increased neonatal mortality due to birth asphyxia (adjusted HR: 1.18, 95% CI: 0.82, 1.7). We also found a possible decline in infectious-disease related mortality among under-1 and under-5 children (adjusted under-5 HR: 0.72, 95% CI: 0.49, 1.02). Prevalence of child diarrhea, (PR: 0.53, 95% CI: 0.48, 0.59), fever (PR: 0.82, 95% CI: 0.72, 0.94), and cough (PR: 0.8, 95% CI: 0.73, 0.89) declined substantially during the pandemic. Mothers reported high rates of masking, handwashing, and staying at home during phone interviews conducted during the lockdown. Pandemic response measures such as masking, handwashing, and not attending school may have interrupted transmission of diarrhea and respiratory illness. We suggest that pandemic preparedness should focus not only on prevention of the disease at-hand, but also on measures to ensure continuation of other essential healthcare services including maternal and neonatal care.

## 5.2 GENERAL CONCLUSIONS AND THEMES

Millions of children still die each year from diseases that are preventable and treatable with technologies that have been available for decades. Climate change may worsen or hinder progress in reducing child mortality through increased transmission of infectious diseases, food insecurity, poor air quality, injuries due to extreme weather, heat stroke, increased conflict and migration, and disruptions to essential services (e.g. water, sanitation, healthcare). Climate change may also increase the likelihood of future pandemics: as humans and animals are forced to migrate to escape rising sea levels and extreme weather, they will interact with each other in new ways, creating new opportunities for pathogens to move from animals to people[165,166]. The COVID-19 pandemic has affected health and livelihood in ways far beyond direct infection, demonstrated the cascading effects that a global emergency can have. Climate-related emergencies are likely to similarly affect global health in expected and unexpected ways.

This dissertation demonstrates that extreme weather due to climate change affects transmission of bacterial pathogens, potentially increasing transmission via water and decreasing transmission via hands (Figure 5-1). We demonstrate that water treatment mitigates these effects. We present a passive chlorination technology that may increase global access to water treatment by shifting the burden of water treatment away from individual users and toward community-level organizations. Finally, we document the effects of the COVID-19 pandemic on illness and mortality in rural Kenya. We show that neonatal mortality increased, potentially because of healthcare systems becoming overwhelmed. We also show that diarrhea and fever prevalence decreased during the pandemic.

This dissertation contributes evidence to characterize infectious disease transmission and evaluate potential technical solutions. We suggest that passive chlorination is a powerful tool to interrupt infectious disease transmission and mitigate the effects of climate change. Solving these problems will require technology coupled with systemic changes that consider the social and political roots of diseases of poverty.

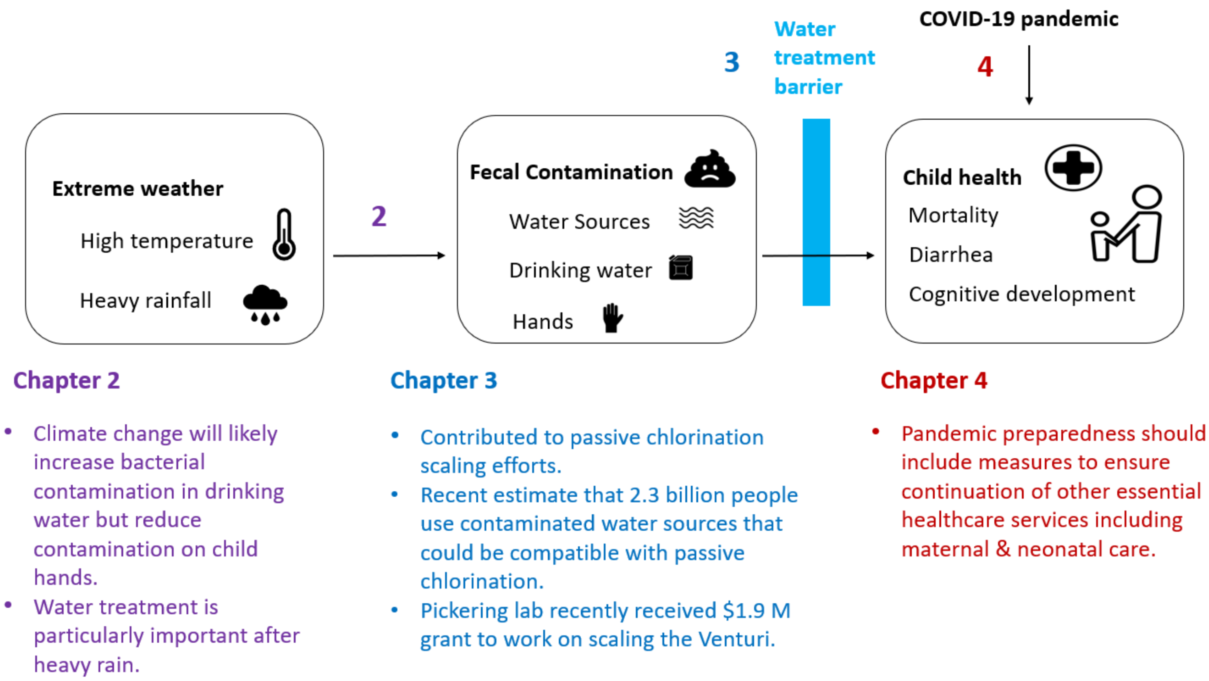


Figure 5-1 Conceptual diagram of dissertation conclusions

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# Appendix A Chapter 2 supplement

## A.1 SUPPLEMENTARY METHODS

### A.1.1 Treatment arms

In arms assigned to water treatment intervention, study staff installed chlorine dispensers at public water sources and distributed bottled chlorine to enrolled households. In sanitation arms, study staff installed or upgraded pit latrines with a plastic slab and hole cover, distributed child potties, and distributed scoops for removal of child and animal feces. In handwashing arms, study staff installed two dual dispenser tippy-tap devices per household, one near the latrine and one near the kitchen area. The devices dispensed soapy water (soap was provided) and rinse water via separate pedals. In nutrition arms, study staff distributed lipid-based nutrient supplements. In all intervention groups, promoters visited households at least once every two months.

### A.1.2 Data Cleaning and Verification

Household GPS coordinates were cleaned by comparing the coordinates collected at baseline, midline, and end line. The baseline latitude was replaced with the average of the midline and end line latitudes if baseline latitude was more than 0.05 degrees different than the midline and end line latitudes, midline and end line latitudes were not missing, and the household had not temporarily or permanently moved at midline or end line. The baseline longitude was replaced with the average of the midline and end line longitudes if baseline longitude was more than 0.05 degrees different than the midline and end line longitudes, midline and end line longitudes were not missing, and the household had not temporarily or permanently moved at midline or end line.

The midline coordinates were set equal to the baseline coordinates unless the household temporarily or permanently moved at midline. The end line coordinates were set equal to the baseline coordinates unless the household permanently moved at midline or temporarily or permanently moved at end line. The coordinates were plotted in ArcMap and visually inspected. Points that were obviously wrong (very far from other points, wrong geographic area) were replaced with the median of the coordinates from households in the same village.

Source water GPS coordinates were cleaned by comparing with the finalized household baseline coordinates. Source coordinates that differed from household coordinates by a total distance of more than 0.07 degrees were replaced with the household coordinate. Source water GPS coordinates were plotted in QGIS and visually examined. No clearly wrong points were identified.

Dates were validated through comparison between the dates recorded in the survey and the date that the samples were reported to be collected. If these dates differed by more than three days, the observations were dropped due to concerns that a failed match could have occurred while merging survey and sample data, and that the date may not be reliable.

Only one sample was considered per water source, even if multiple households reported using this source. Duplicates by sample ID were examined manually. They all appeared to be true duplicates because *E. coli* and enumerator data was identical between observations with the same sample ID. There were differences in the GPS coordinates and household ID, which could be due to the same source being recorded multiple times for different households. Duplicates were dropped.

Study child twins were dropped to avoid duplicates since environmental contamination was observed at the household level, which would be the same for twins.

## A.2 SUPPLEMENTARY RESULTS

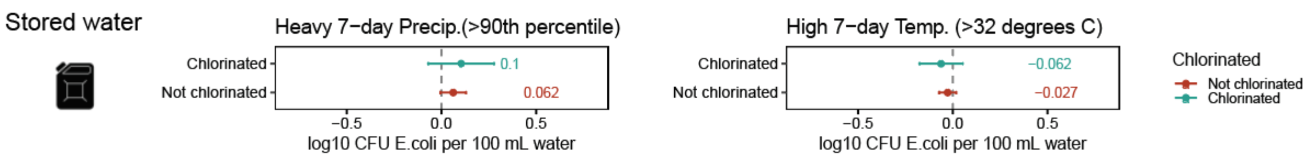


Figure A-1 Effect modification by confirmed chlorine water treatment (detectable chlorine residual).

Associations between heavy 7-day precipitation (left), high 7-day temperature (right), and E. coli levels in household stored water. Results are stratified by chlorinated vs. not chlorinated. Point estimates are plotted and labeled. Units are $\log_{10}$ CFU E. coli per 100 mL. Error bars show 95% confidence intervals.

Table A-1 Statistical significance testing for effect modification by low (0th to 33rd percentile) vs. moderate or high (>33rd percentile) 8-week precipitation

| Interaction term | Sample type | Coefficient on interaction term ($log_{10}$ CFU E. coli per 100 mL or 2 hands) | Standard error | P-value | Lower 95% CI | Upper 95% CI | N |
|---|---|---|---|---|---|---|---|
| 7-day high temp and low 8-week precipitation | stored | -0.076 | 0.052 | 0.147 | -0.178 | 0.027 | 9261 |
| 7-day heavy precipitation and low 8-week precipitation | stored | -0.039 | 0.118 | 0.743 | -0.271 | 0.194 | 9261 |
| 7-day high temp and low 8-week precipitation | source | -0.055 | 0.096 | 0.567 | -0.245 | 0.134 | 1613 |
| 7-day heavy precipitation and low 8-week precipitation | source | 0.316 | 0.111 | 0.004 | 0.099 | 0.534 | 1613 |
| 7-day high temp and low 8-week precipitation | hands | -0.359 | 0.178 | 0.045 | -0.711 | -0.007 | 2408 |
| 7-day heavy precipitation and low 8-week precipitation | hands | -0.673 | 0.511 | 0.190 | -1.681 | 0.335 | 2408 |

Table A-2 Statistical significance testing for effect modification by water treatment vs. no water treatment

| Interaction term | Sample type | Coefficient on interaction term (log10 CFU E. coli per 100 mL or 2 hands) | Standard error | P-value | Lower 95% CI | Upper 95% CI | N |
|---|---|---|---|---|---|---|---|
| 7-day high temp and water treatment | stored | 0.007 | 0.071 | 0.924 | -0.133 | 0.147 | 9193 |
| 7-day heavy precipitation and water treatment | stored | -0.324 | 0.090 | <0.001 | -0.501 | -0.148 | 9193 |

Table A-3 Statistical significance testing for effect modification by detectable free chlorine residual vs. no detectable free chlorine residual

| Interaction term | Sample type | Coefficient on interaction term (log10 CFU E. coli per 100 mL or 2 hands) | Standard error | P-value | Lower 95% CI | Upper 95% CI | N |
|---|---|---|---|---|---|---|---|
| 7-day high temp and detectable free chlorine residual | stored | -0.060 | 0.080 | 0.449 | -0.216 | 0.096 | 9176 |
| 7-day heavy precipitation and detectable free chlorine residual | stored | -0.073 | 0.105 | 0.487 | -0.279 | 0.133 | 9176 |

Table A-4 Effect modification by improved vs. unimproved source

| Interaction term | Sample type | Coefficient (log10 CFU E. coli per 100 mL or 2 hands) | Standard error | P-value | Lower 95% CI | Upper 95% CI | N |
|---|---|---|---|---|---|---|---|
| 7-day high temperature and improved source | stored | -0.036 | 0.056 | 0.522 | -0.145 | 0.074 | 9207 |
| 7-day heavy precipitation and improved source | stored | 0.11 | 0.089 | 0.217 | -0.065 | 0.284 | 9207 |
| 7-day high temperature and improved source | source | 0.151 | 0.091 | 0.098 | -0.028 | 0.329 | 1613 |
| 7-day heavy precipitation and improved source | source | -0.244 | 0.109 | 0.026 | -0.458 | -0.03 | 1613 |

Table A-5 Statistical significance testing for effect modification by source type (each source type vs. all others). Coefficient unit is $log_{10}$ CFU E. coli per 100 mL or 2 hands.

| Interaction term | Sample type | Coefficient on interaction term | Standard error | P-value | Lower 95% CI | Upper 95% CI | N |
|---|---|---|---|---|---|---|---|
| Heavy precip & protected spring | source | -0.223 | 0.134 | 0.096 | -0.485 | 0.040 | 1613 |
| Heavy precip & protected well | source | -0.101 | 0.208 | 0.627 | -0.511 | 0.308 | 1613 |
| Heavy precip & unprotected spring | source | 0.338 | 0.122 | 0.006 | 0.098 | 0.578 | 1613 |
| Heavy precip & unprotected well | source | 0.024 | 0.143 | 0.870 | -0.258 | 0.305 | 1613 |
| High temp & protected spring | source | 0.044 | 0.079 | 0.575 | -0.111 | 0.199 | 1613 |
| High temp & protected well | source | 0.020 | 0.097 | 0.837 | -0.170 | 0.210 | 1613 |
| High temp & unprotected spring | source | -0.030 | 0.107 | 0.780 | -0.241 | 0.181 | 1613 |
| High temp & unprotected well | source | -0.384 | 0.117 | 0.001 | -0.614 | -0.154 | 1613 |
| Heavy precip & borehole | stored | -0.174 | 0.221 | 0.430 | -0.607 | 0.259 | 9210 |
| Heavy precip & piped | stored | 0.082 | 0.278 | 0.769 | -0.463 | 0.627 | 9210 |
| Heavy precip & protected spring | stored | 0.195 | 0.071 | 0.006 | 0.056 | 0.335 | 9210 |
| Heavy precip & protected well | stored | -0.131 | 0.106 | 0.216 | -0.338 | 0.076 | 9210 |
| Heavy precip & rain | stored | -0.112 | 0.118 | 0.342 | -0.343 | 0.119 | 9210 |
| Heavy precip & surface water | stored | -0.107 | 0.262 | 0.682 | -0.621 | 0.406 | 9210 |
| Heavy precip & unprotected spring | stored | -0.086 | 0.097 | 0.375 | -0.275 | 0.104 | 9210 |
| Heavy precip & unprotected well | stored | -0.131 | 0.186 | 0.481 | -0.497 | 0.234 | 9210 |
| High temp & borehole | stored | 0.211 | 0.088 | 0.017 | 0.038 | 0.384 | 9210 |
| High temp & piped | stored | -0.035 | 0.207 | 0.865 | -0.441 | 0.370 | 9210 |
| High temp & protected spring | stored | -0.059 | 0.048 | 0.219 | -0.153 | 0.035 | 9210 |
| High temp & protected well | stored | -0.027 | 0.072 | 0.714 | -0.169 | 0.116 | 9210 |
| High temp & rain | stored | 0.093 | 0.098 | 0.340 | -0.099 | 0.285 | 9210 |
| High temp & surface water | stored | 0.007 | 0.161 | 0.964 | -0.309 | 0.323 | 9210 |
| High temp & unprotected spring | stored | 0.025 | 0.062 | 0.681 | -0.096 | 0.147 | 9210 |
| High temp & unprotected well | stored | 0.143 | 0.102 | 0.162 | -0.058 | 0.343 | 9210 |

Results were largely consistent across choices of model specification.

The effects of 5-day weather were similar to that of 7-day weather (Figure A-2). As with 7-day time periods, heavy 5-day precipitation (>90$^{th}$ percentile) and high 5-day temperature (>32 degrees C) were associated with increased *E. coli* levels in source water. Although 7-day heavy precipitation was significantly associated with *E. coli* levels in household stored water, 5-day heavy precipitation was not significantly associated with *E. coli* levels in household stored water (Figure A-2). However, the direction of the effect was consistent. Effects on child hands were consistent: high temperature was associated with decreased log10 *E. coli* levels and heavy precipitation was not significantly associated with *E. coli* levels.

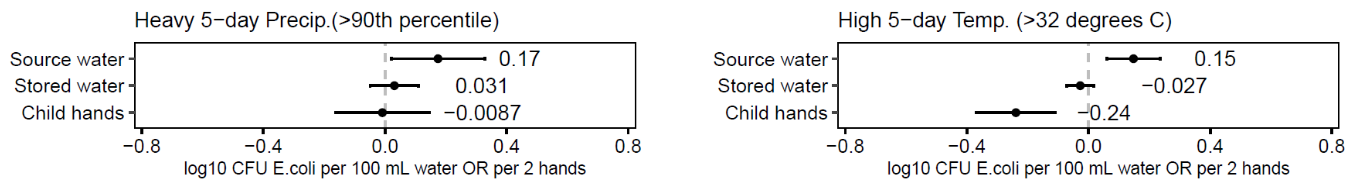


Figure A-2 Sensitivity analysis using 5-day periods rather than 7-day periods.

Associations between heavy 7-day precipitation (left), high 7-day temperature (right), and E. coli levels in source water, stored water, and child hands. Point estimates are plotted and labeled. Units are log10 CFU E. coli per 100 mL for source water and stored water, and 2 hands for child hands. Error bars show 95% confidence intervals.

The use of absolute temperature and precipitation rather than thresholds yielded consistent results across all source types (Figure 6-2, Supplementary Figure 6-3).

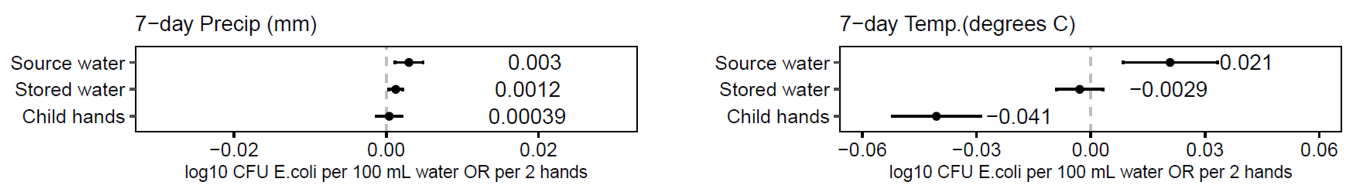


Figure A-3 Sensitivity analysis using absolute precipitation and temperature rather than thresholds.

Associations between heavy 7-day precipitation (left), high 7-day temperature (right), and E. coli levels in source water, stored water, and child hands. Point estimates are plotted and labeled. Units are log10 CFU E. coli per 100 mL for source water and stored water, and 2 hands for child hands. Error bars show 95% confidence intervals.

Defining high 7-day mean max temperature using the 90$^{th}$ percentile (35.8 degrees C) rather than 32 degrees C yielded consistent results across all source types (Figure A-4).

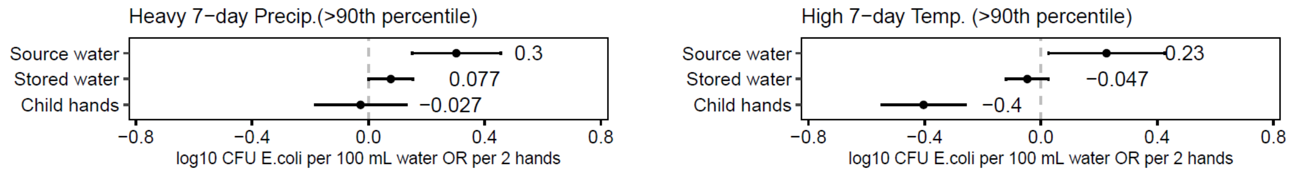


Figure A-4 Sensitivity analysis using the 90th percentile 7-day mean maximum temperature (35.8 deg C) rather than 32 deg C.

Associations between heavy 7-day precipitation (left), high 7-day temperature (right), and E. coli levels in source water, stored water, and child hands. Point estimates are plotted and labeled. Units are log10 CFU E. coli per 100 mL for source water and stored water, and 2 hands for child hands. Error bars show 95% confidence intervals.

Considering heavy rainfall events (1 or more days exceeds the 90th percentile in any of the previous 7 days) rather than 7-day total rainfall yielded slightly different results: effects on source water were no longer statistically significant (Figure A-5). However, effects on stored water were consistent and the direction of both effects were consistent.

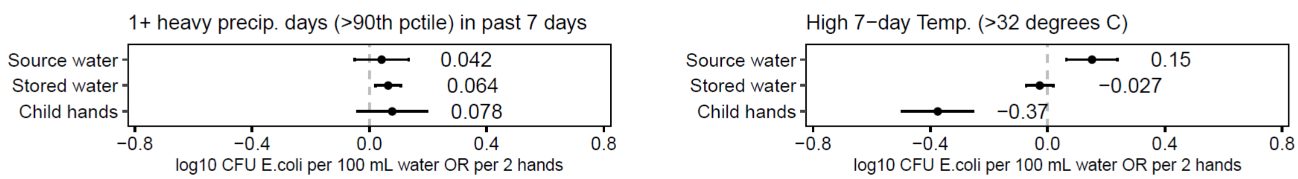


Figure A-5 Sensitivity analysis using heavy rainfall events (1 or more days exceeds the 90th percentile in any of the previous 7 days) rather than 7-day total rainfall.

Associations between heavy 7-day precipitation (left), high 7-day temperature (right), and E. coli levels in source water, stored water, and child hands. Point estimates are plotted and labeled. Units are log10 CFU E. coli per 100 mL for source water and stored water, and 2 hands for child hands. Error bars show 95% confidence intervals.

# Appendix B Chapter 3 Supplement

## B.1 SUPPLEMENTARY RESULTS

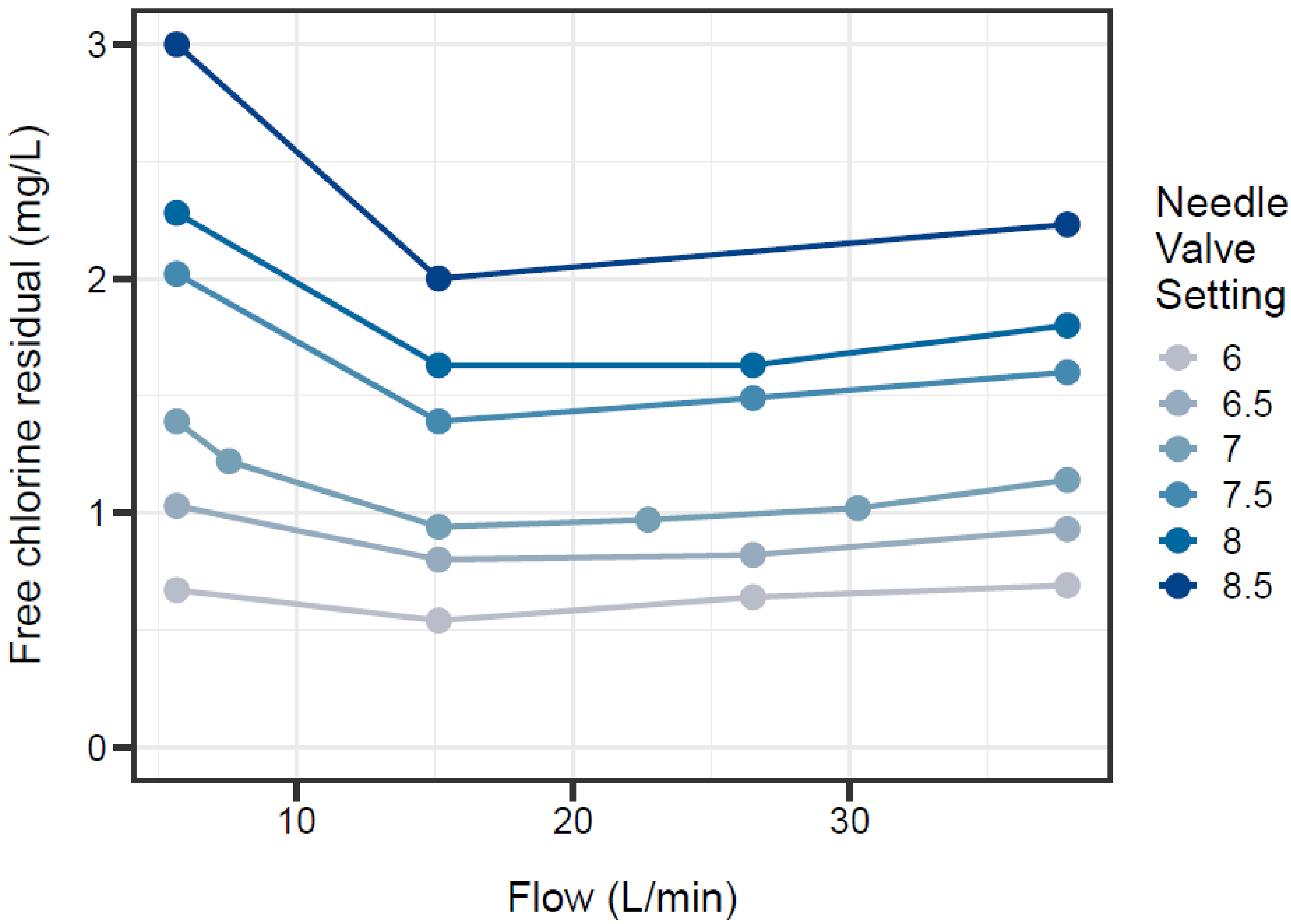


Figure B-1 Free chlorine residual (mg/L) in water collected at varying flowrates and needle valve settings from one Venturi device in the lab.

This device was installed at Kiosk E. The dose may be adjusted by twisting the needle valve.

Table B-1 Free chlorine residual (mg/L) in water collected from Venturi by kiosk

| *Kiosk ID* | *Samples with detectable free chlorine residual (>0.05 mg/L), n (%)* | *Samples dosing within range (0.2-1.2 mg/L), n (%)* | *Mean free chlorine residual (mg/L)* |
|---|---|---|---|
| *A* | 24 (96.0%) | 23 (92.0%) | 0.66 |
| *B* | 24 (100%) | 22 (91.7%) | 0.41 |
| *C* | 22 (100%) | 21 (95.5%) | 0.70 |
| *D* | 14 (100%) | 14 (100%) | 0.59 |
| *E* | 23 (100%) | 20 (87.0%) | 0.71 |
| *F* | 27 (90.0%)[a] | 20 (66.7%) | 0.41 |
| *G* | 29 (100%) | 24 (82.8%) | 0.42 |

a) At Kiosk F: From installation on 9/22/2017 to 12/12/2017, 11 out of 11 observations (100%) had detectable free chlorine residual and 11 out of 11 (100%) were in the desired 0.2-1.2 mg/L range (Mean: 0.639 mg/L). After this point, several observations had no or low detectable free chlorine residual. Field staff examined the device, concluded that iron deposits from the water were clogging the device, and attempted to clean/unclog the device on multiple visits. During this period from 1/9/2018 to 4/4/2018, 12 out of 15 observations (80.0%) had detectable chlorine residual and 5 out of 15 (33.3%) were in the desired 0.2-1.2 mg/L range (Mean: 0.194 ppm). On 4/4/2018, the device was removed and a new device was installed to resolve this problem. After the new device was installed, 4 out of 4 observations (100%) had detectable chlorine residual and 4 out of 4 (100%) were in the desired 0.2-1.2 mg/L range (Mean: 0.622 ppm).

Table B-2 Average monthly revenue by kiosk

| *Kiosk ID* | *Average recorded monthly revenue (USD)*** | *Average monthly revenue calculated from treated sales (USD)*** | *Average monthly revenue calculated from untreated sales (USD)*** |
|---|---|---|---|
| *A* | 105.60 | 5.57 | 103.02 |
| *B* | 36.14 | 3.80 | 32.10 |
| *C* | 30.03 | 0.67 | 30.24 |
| *D* | 4.24 | 2.69 | 0.92 |
| *E* | 61.18 | 20.73 | 38.46 |
| *F* | 283.45 | 85.53 | 194.79 |
| *G* | 48.06 | 11.61 | 40.07 |

**Kiosk operators were asked to record daily treated and untreated water sales, daily total revenue, and weekly treated and untreated water prices. In some cases, the total revenue recorded did not match the total revenue calculated based on reported sales and prices. As a result, average monthly treated and untreated revenue do not sum exactly to average monthly recorded revenue.

Treated water sales by month since installation remained between 10% and 25% of total water sales **(Figure 6-2)**. The percentage of observations with detectable free chlorine residual (>0.05 mg/L) by month since installation was >92% throughout the study period **(Figure 6-2**).

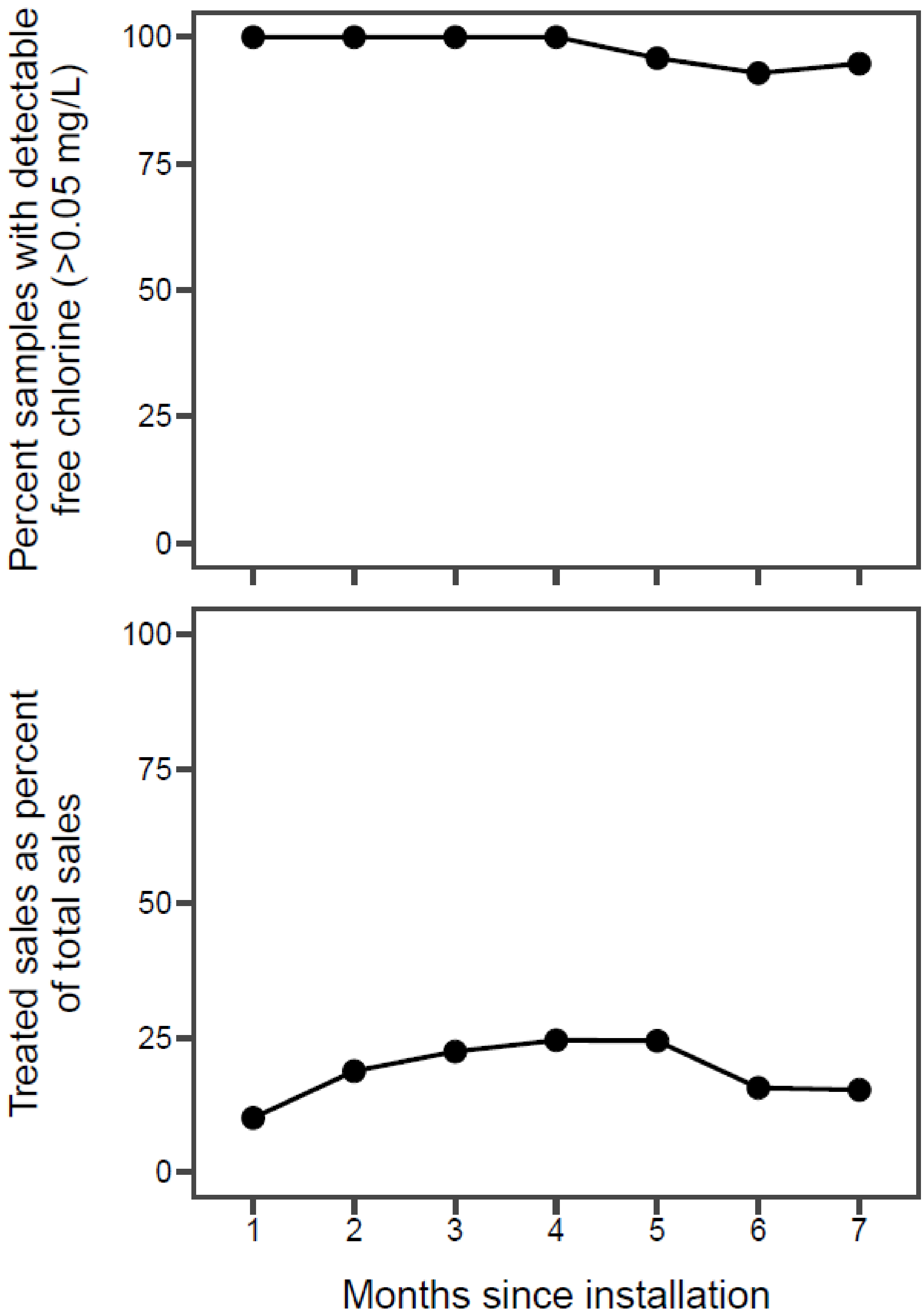


Figure B-2 Percent of samples with detectable free chlorine residual (>0.05 mg/L) (top) and treated water sales as percent of total water sales by month since installation of the device (bottom).

Data is aggregated by months since original installation.

# Appendix C Chapter 4 Supplement

## C.1 SUPPLEMENTARY RESULTS

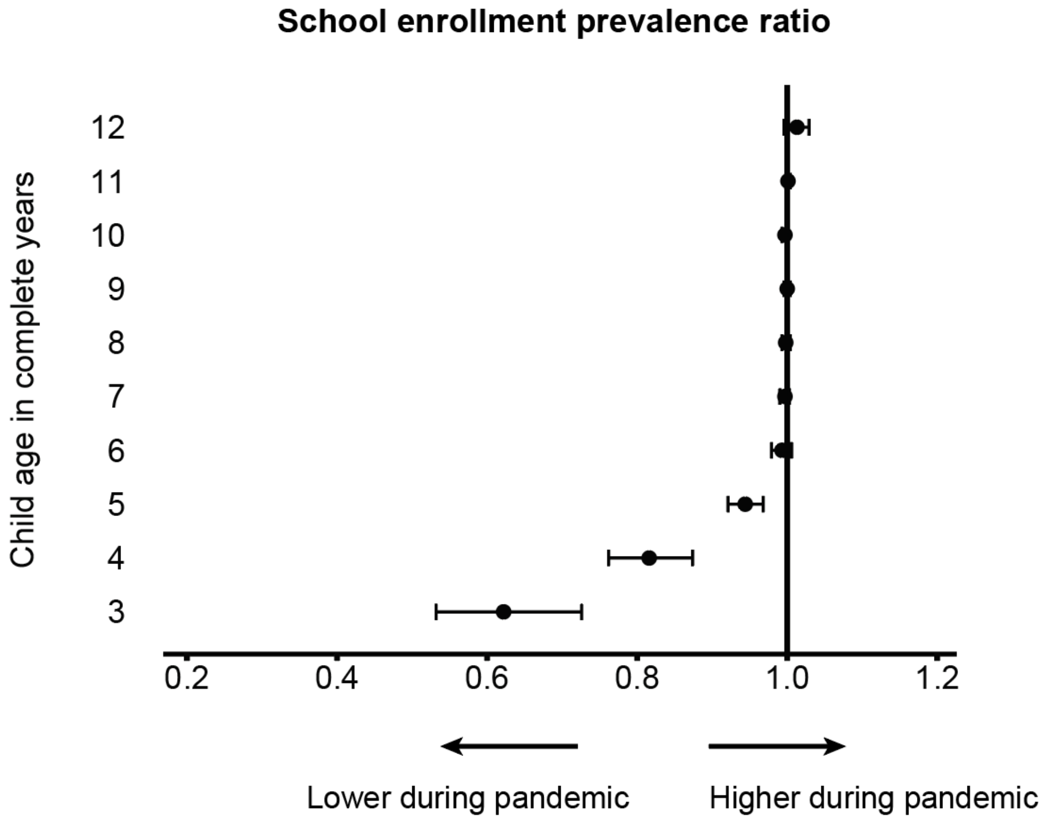


Figure C-1 Prevalence ratio of school enrollment stratified by child age comparing period during COVID-10 pandemic vs. before pandemic began.

Table C-1 7-day prevalence (95% CI) of mother health symptoms reported during phone surveys

| Symptom | Round 1 | Round 2 | Round 3 | Round 4 |
|---|---|---|---|---|
| Headache | 17.2 (15.9, 18.6) | 12.6 (11.4, 13.9) | 10.3 (9.1, 11.4) | 11.8 (10.3, 13.3) |
| Congestion | 6.8 (5.9, 7.7) | 4.4 (3.6, 5.1) | 4.9 (4.1, 5.7) | 4.3 (3.3, 5.2) |
| Cough | 5.5 (4.6, 6.3) | 3.4 (2.7, 4.1) | 3.4 (2.7, 4) | 3.1 (2.3, 3.9) |
| Fever | 5.3 (4.5, 6.1) | 2.8 (2.2, 3.4) | 2.5 (1.9, 3) | 3.1 (2.3, 3.9) |
| Unusual fatigue | 4.9 (4.1, 5.7) | 2.4 (1.8, 2.9) | 2 (1.5, 2.5) | 2.7 (2, 3.5) |
| Unusual muscle pains | 4.6 (3.8, 5.3) | 2.8 (2.2, 3.4) | 2.6 (2, 3.1) | 1.8 (1.1, 2.4) |
| Chills | 4.7 (3.9, 5.4) | 3.4 (2.7, 4.1) | 2.3 (1.8, 2.9) | 1.7 (1.1, 2.3) |
| Unusual pain or pressure in chest | 2.6 (2.1, 3.2) | 1.8 (1.3, 2.3) | 1.7 (1.2, 2.2) | 1 (0.6, 1.5) |
| New confusion | NA | NA | 0 (0, 0) | 1 (0.5, 1.4) |
| Loss of appetite | 3.9 (2.9, 5) | 1.7 (1.2, 2.2) | 1.2 (0.8, 1.6) | 1 (0.6, 1.5) |
| Diarrhea | 1.3 (0.9, 1.7) | 1.1 (0.7, 1.4) | 1.1 (0.7, 1.4) | 0.8 (0.4, 1.2) |
| Loss of smell/taste | 1.9 (1.4, 2.4) | 0.9 (0.5, 1.2) | 0.9 (0.5, 1.2) | 0.7 (0.3, 1.1) |
| Sore throat | 1.1 (0.7, 1.5) | 0.6 (0.3, 0.9) | 0.4 (0.2, 0.7) | 0.7 (0.3, 1.1) |
| Inability to wake or stay awake | NA | NA | 1.2 (-0.2, 2.7) | 0.3 (0.1, 0.6) |
| Nausea or vomiting | 1.5 (1, 1.9) | 0.8 (0.5, 1.1) | 0.7 (0.4, 1) | 0.3 (0, 0.5) |
| Skin rash | 0.7 (0.2, 1.1) | 0.6 (0.3, 0.9) | 0.2 (0.1, 0.4) | 0.3 (0, 0.5) |
| Repeated shaking with chills | 3.5 (2.8, 4.2) | 1.5 (1, 1.9) | 1 (0.6, 1.4) | 0.3 (0.1, 0.6) |
| Difficulty breathing | 1 (0.7, 1.4) | 0.4 (0.2, 0.7) | 0.4 (0.2, 0.7) | 0.2 (0, 0.4) |
| Blood in stool | 0.3 (0.1, 0.5) | 0.1 (0, 0.2) | 0.4 (0.1, 0.6) | 0.1 (-0.1, 0.2) |
| Unexplained bruising | 0.1 (-0.1, 0.4) | 0.1 (0, 0.3) | 0 (0, 0.1) | 0.1 (0, 0.3) |

Table C-2 7-day prevalence % (95% CI) of under-5 child health symptoms reported during phone surveys

| **Symptom** | **Round 1** | **Round 2** | **Round 3** | **Round 4** |
|---|---|---|---|---|
| Congestion | 10.6 (9.5, 11.7) | 10.2 (9.1, 11.3) | 11.9 (10.6, 13.1) | 11.6 (10, 13.2) |
| Cough | 7 (6.1, 7.9) | 5.9 (5, 6.8) | 5.6 (4.8, 6.5) | 5.9 (4.7, 7.1) |
| Fever | 6.5 (5.6, 7.4) | 5.5 (4.6, 6.3) | 4.8 (4, 5.7) | 5.8 (4.7, 7) |
| Diarrhea | 4.7 (3.9, 5.5) | 4.2 (3.5, 5) | 3.2 (2.5, 3.9) | 4 (3, 5) |
| Headache | 5.8 (5, 6.7) | 3.9 (3.2, 4.7) | 3.1 (2.4, 3.8) | 2.1 (1.4, 2.8) |
| Nausea | 2.1 (1.6, 2.6) | 1.9 (1.4, 2.4) | 1.1 (0.7, 1.5) | 1.6 (1, 2.3) |
| Loss of appetite | 4.2 (3.1, 5.3) | 3.3 (2.7, 4) | 2 (1.5, 2.5) | 1.4 (0.8, 2) |
| Skin rash | 2.7 (1.8, 3.5) | 2.5 (1.9, 3.1) | 2.1 (1.5, 2.6) | 1.3 (0.8, 1.9) |
| Chills | 2.1 (1.5, 2.6) | 1.8 (1.3, 2.3) | 1.4 (1, 1.9) | 1 (0.5, 1.4) |
| Loss of smell/taste | 0.7 (0.4, 1) | 0.9 (0.5, 1.2) | 0.7 (0.4, 1) | 1 (0.5, 1.4) |
| Repeated shaking with chills | 2.6 (2, 3.1) | 0.8 (0.5, 1.1) | 0.8 (0.4, 1.1) | 0.7 (0.3, 1.1) |
| Blood in stool | 0.6 (0.3, 0.9) | 0.2 (0, 0.4) | 0.3 (0.1, 0.5) | 0.4 (0.1, 0.8) |
| Unexplained bruising | 0.6 (0.2, 1) | 0.8 (0.4, 1.1) | 0.1 (0, 0.3) | 0.3 (0, 0.5) |
| Unusual fatigue | 1.2 (0.8, 1.6) | 0.9 (0.6, 1.3) | 0.3 (0.1, 0.5) | 0.3 (0, 0.5) |
| Unusual muscle pains | 1.9 (1.4, 2.3) | 0.8 (0.5, 1.1) | 0.4 (0.2, 0.7) | 0.3 (0, 0.6) |
| Difficulty breathing | 1 (0.6, 1.3) | 0.4 (0.2, 0.6) | 0.4 (0.1, 0.6) | 0.2 (0, 0.4) |
| Inability to wake or stay awake | NA | NA | 0 (0, 0) | 0.1 (-0.1, 0.2) |
| Unusual pain or pressure in chest | 0.4 (0.2, 0.6) | 0.3 (0.1, 0.4) | 0.3 (0.1, 0.5) | 0 (0, 0) |
| New confusion | NA | NA | 0 (0, 0) | 0 (0, 0) |
| Sore throat | 0.7 (0.4, 1) | 0.4 (0.1, 0.6) | 0 (0, 0.1) | 0 (0, 0) |

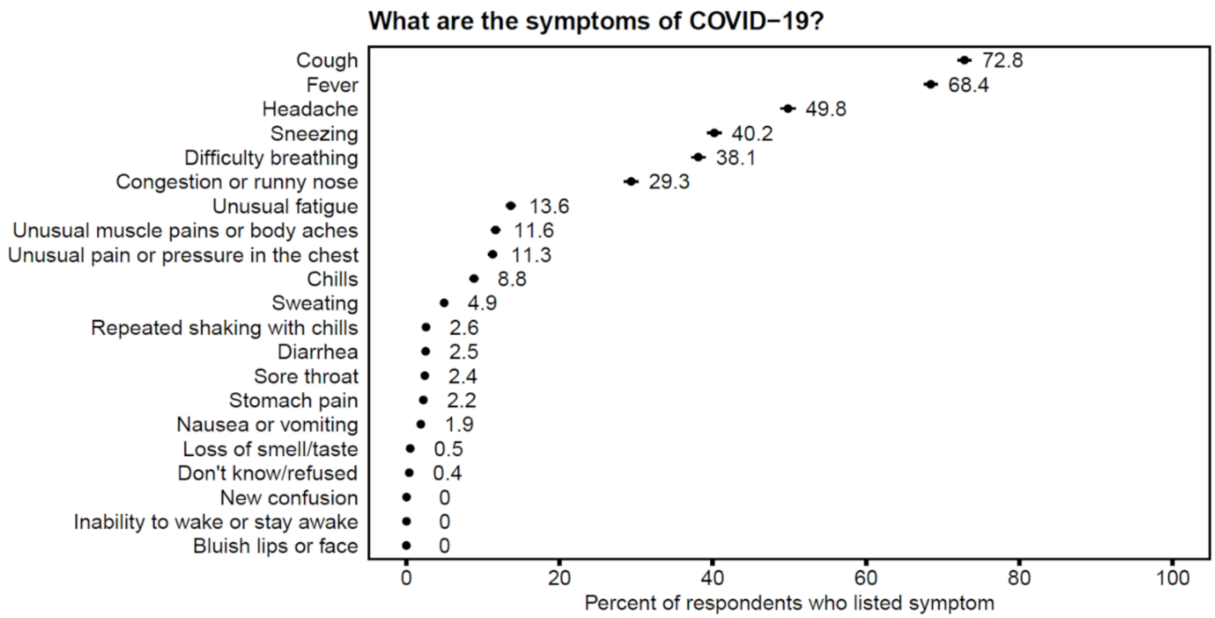


Figure C-2 Respondent beliefs about symptoms of COVID-19 reported during phone surveys

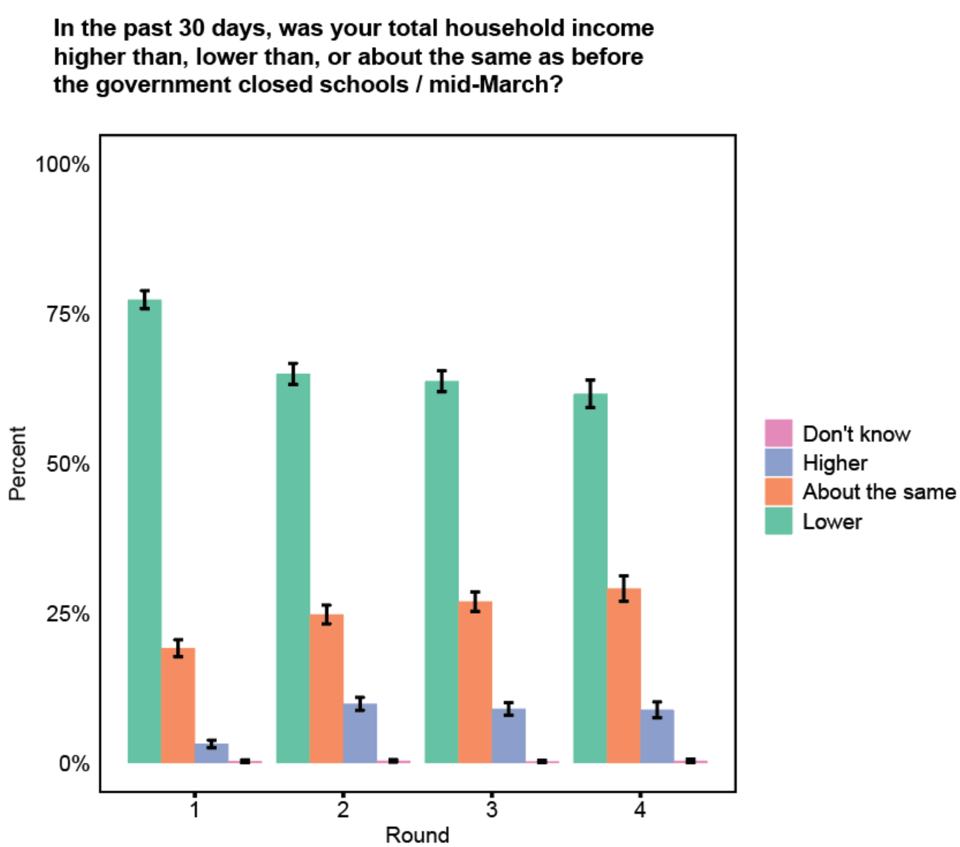


Figure C-3 Household income reported during phone surveys

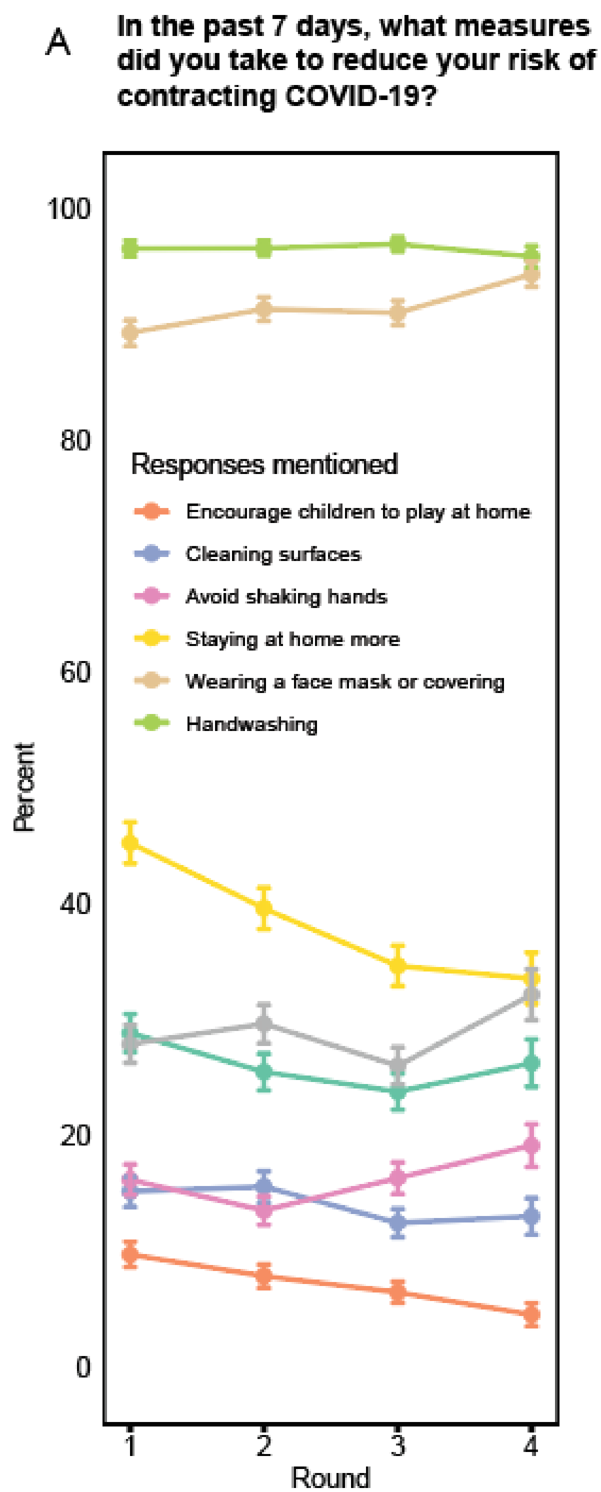


Figure C-4 COVID-19 risk mitigation behaviors by survey round

Error bars show 95% confidence intervals.

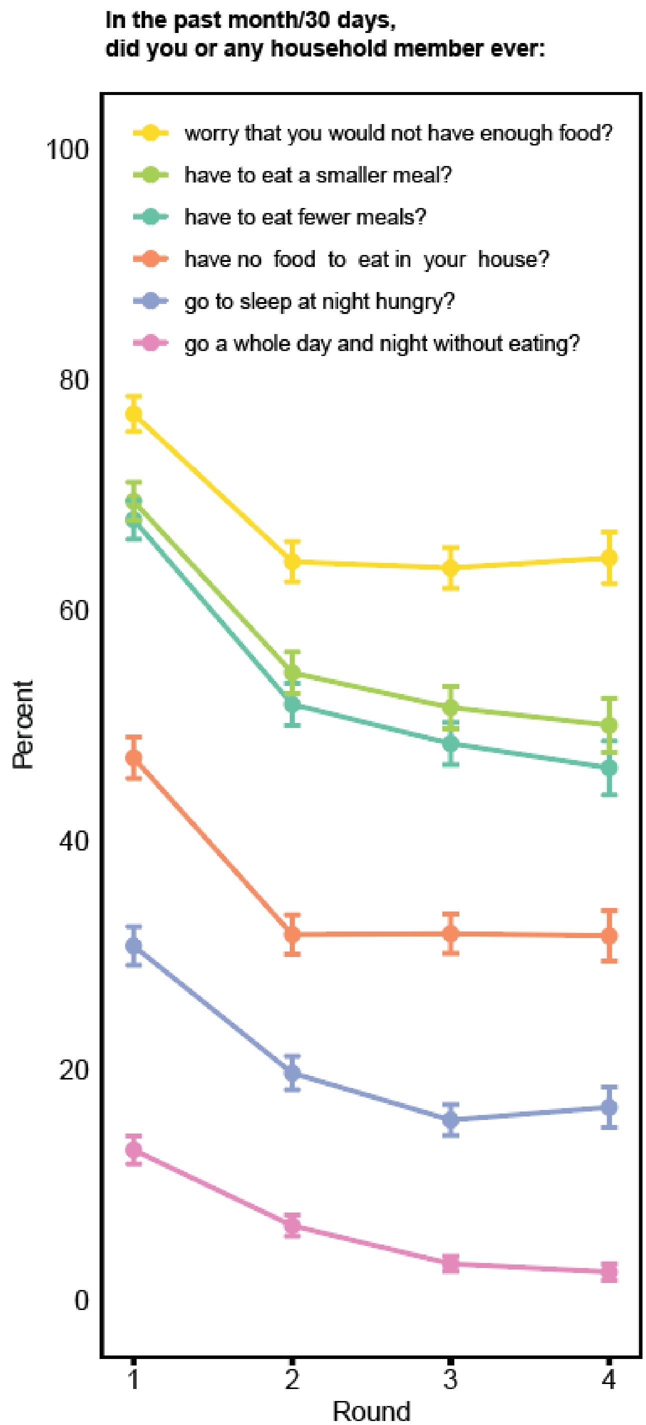


Figure C-5 Household food security by survey round.

Error bars show 95% confidence intervals.