Water Research 170 (2020) 115269

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Household coping strategies associated with unreliable water supplies and diarrhea in Ecuador, an upper-middle-income country

Gwenyth O. Lee [a,*], Holly J. Whitney [a], Annalise G. Blum [b], Noah Lybik [a], William Cevallos [c], Gabriel Trueba [d], Karen Levy [e], Joseph N.S. Eisenberg [a]

[a] Department of Epidemiology, University of Michigan School of Public Health, Ann Arbor, MA, USA
[b] Department of Earth and Planetary Science, Johns Hopkins University, Baltimore, MD, USA
[c] Instituto de Biomedicina, Carrera e Medicina, Universidad Central de Ecuador, Ecuador
[d] Institutito de Microbiología, Colegio de Ciencias Biológicas y Ambientales, Universidad San Francisco de Quito, Quito, Ecuador
[e] Department of Environmental Health, Emory University, Atlanta, GA, USA

A R T I C L E I N F O

Article history:
Received 14 June 2019
Received in revised form
29 October 2019
Accepted 1 November 2019
Available online 7 November 2019

Keywords:
Water supply
Water quality
Diarrhea/epidemiology
Humans
Case-control studies
Drinking water/microbiology

A B S T R A C T

The Sustainable Development Goals recognize that the availability and quality of improved water sources affect how households use and benefit from these sources. Although unreliability in piped water supplies in low- and middle-income countries (LMICs) has been described, few studies have assessed household coping strategies in response to unreliable water supplies and associated health outcomes. We characterized unreliability in the piped water supply of the town of Borbón, Ecuador over the twelve years following a major upgrade, as well as household coping strategies and associations with diarrhea. We examined trends in primary and secondary drinking water sources, water storage, and water treatment using longitudinal data collected from 2005 to 2012. In 2017, a follow-up survey was administered ($N = 202$) and a subset of 84 household water samples were tested for chlorine residual levels and microbial contamination.

From 2005 to 2017, access to a household water connection increased from 19.4% to 90.3%. However, reliability decreased over time, as in the latter half of 2009, households had access to piped water 79% of the time, compared to 63% by 2017. Piped water samples were highly contaminated with total coliforms (100% of samples) and *Escherichia coli* (89% of samples).

From 2005 to 2017, households less likely to report drinking water treatment (50.6%–5.0%). And from 2009 to 2017, bottled water was increasingly consumed as the primary drinking water source (18.8%–62.4%). From 2005 to 2012, having a household connection was not statistically significantly associated with diarrhea case status (OR: 0.86 95%CI: 0.53, 1.39). Neither household water treatment nor bottled water consumption were negatively associated with diarrhea. Increased water storage was associated with diarrhea (OR: 1.33 per 10L of water stored, 95%CI: 1.05, 1.69).

Household water treatment, and consumption of purchased bottled water, two coping strategies that households may have undertaken in response to an unreliable water supply, were not associated with a reduced likelihood of diarrhea. These data suggest a need to understand how impoverished rural households in LMICs respond to unreliable water supplies, and to develop heath messaging appropriate for this context.

1. Introduction

Creating sustainable water systems for rural communities in low- and middle-income countries (LMICs) has been a persistent challenge for the development sector. From 1990 to 2015, 2.6 billion people gained access to improved drinking water (WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, 2017). However, in setting and monitoring the 2030 Sustainable Development Goals, the international development community acknowledged that the availability, accessibility, and quality of improved water sources — including piped water supplies — is

* Corresponding author. University of Michigan (Johnson, 1996)School of Public Health, M5071 SPH II, 1415 Washington Heights, Ann Arbor, MI, 48109-2029
E-mail address: golee@umich.edu (G.O. Lee).

https://doi.org/10.1016/j.watres.2019.115269

variable. Globally, 17% of the world's population uses an improved water source defined as 'basic', in that it may not always be available when needed and may not be free from contamination (WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, 2017). Over a billion of these individuals may rely on a piped water system that is intermittent (Bivins et al., 2017). And, even as access to piped water increases globally, the *reliability* of piped water supplies, based on the average hours of supply provided, may be declining in some parts of the world (Thompson et al., 2001). In Latin America, Africa, and Southeast Asia, a third or more of piped water supplies (WHO and UNICEF, 2000) were estimated to be available for fewer than 24 h per day in the year 2000 (Bivins et al., 2017; Kumpel and Nelson, 2016). As rapid urbanization stresses resources for providing drinking water, the number of people receiving piped water intermittently is also predicted to increase (Kumpel and Nelson, 2016).

Unreliable water supplies may fail to provide health benefits (Adane et al., 2017; Ercumen et al., 2014; Hunter et al., 2009; Trudeau et al., 2018; Wolf et al., 2014). Here we assess "reliability" though dimensions of 1) intermittency (i.e. how often water is supplied), 2) quality, and 3) user satisfaction. Intermittency of supply and inadequate chlorination are risk factors for microbial contamination (Craun et al., 2010; Ercumen et al., 2014; Grady et al., 2015; Lee and Schwab, 2005; Shaheed et al., 2014; Trudeau et al., 2018). Unreliable water supplies may also drive users towards coping mechanisms (Majuru et al., 2016) including increased water storage, increased home treatment of water, and increased purchasing of water. The coping strategies households adopt are influenced by socio-economic status, the extent of unreliability, and other factors (Majuru et al., 2016). However, relatively few studies have investigated the impact of these coping strategies on diarrheal disease.

Similar to the global trend, there remains significant discrepancy in access to safe water between urban and rural parts of Ecuador. In 2015, 84% of the urban population in Ecuador had access to safely managed water, compared to only 55% of the rural population (World Bank, 2018). Ecuador also grapples with the challenge of keeping installed water supply infrastructure functioning. A 2006 study found that up to 38% of rural potable water systems were at major risk or had poor prospects for sustainability, based on a consideration of economic, organizational, political, social, technical and environmental factors. This evaluation also noted that systems at most serious risk were those in towns in the northern border regions of the country (CARE, 2006).

In this study we evaluate changes in piped water access and intermittency and household level responses over 12 years in the rural northern coastal town of Borbón, Ecuador. The community-managed water distribution system of this town was built in the late 1990s and was substantially upgraded in 2006 as part of the United States Agency for International Development (USAID) Northern Border Program (USAID, 2009). Water is pumped from the river below the confluence of the Santiago and Cayapas rivers, immediately upstream of the main population center. The plant is run by a community-led water committee, who receive technical assistance from the regional government. Chlorine and aluminum sulfate are added centrally, although supplies are not always available or may be used in less-than-recommended quantities. Chlorine residuals are not routinely monitored.

The objectives of this study were to examine how access to an unreliable water supply relates to household behaviors around water use, and to assess the association between access to an unreliable system, household water use behaviors, and diarrheal disease (Fig. 1).

2. Materials and methods

The town of Borbón is situated at the convergence of the Santiago, Cayapas, and Onzole rivers, as well as on the highway approximately midway between the major cities of Esmeraldas and San Lorenzo. Borbón is therefore a regional center for neighboring villages, although the permeation of road networks into the region over the past two decades has decreased its relative centrality. In 2001, the national census of Ecuador estimated the population in or study site to be around 6,203 individuals (approximately 1,200 households) (Instituto Nacional de Estadistica y Censos, 2001). A 2018 census by the study team identified 930 households (personal communication, J.N.S. Eisenberg), which suggests that the population of the town did not increase significantly over the study period of 2005–2017. Anecdotally however, several small villages outside of Borbón proper were connected to the water system during this time, increasing the total number of households receiving water through the system to around 1,800 (personal communication, J. Obando).

We utilized longitudinal data on sources of drinking and domestic water and diarrhea from a study of diarrheal disease and community remoteness, the results of which have been reported elsewhere (Bhavnani et al., 2016, 2012; Eisenberg et al., 2006). Briefly, 200 households (from 2005 to 2009) were enrolled using a stratified randomization scheme intended to proportionately represent each neighborhood of Borbón. In mid-2008, a further 200 households were added (400 total households from 2008 to 2012). Households continued to participate in the study from year to year, unless they left the study area, in which case they were replaced by a new household. Approximately once a year (see Supplemental Table 4 for survey dates), a case-control study of diarrhea was conducted (Bhavnani et al., 2016). The case-control study consisted of visiting each enrolled household daily over two weeks to prospectively capture cases of diarrhea. Diarrhea was defined as the passage of three or more semi-liquid or liquid stools over a 24-h period (Baqui et al., 1991). From 2005 to 2008, two household controls, and one community control, were selected for each case, while from 2009 to 2012, 10% of enrolled individuals were selected

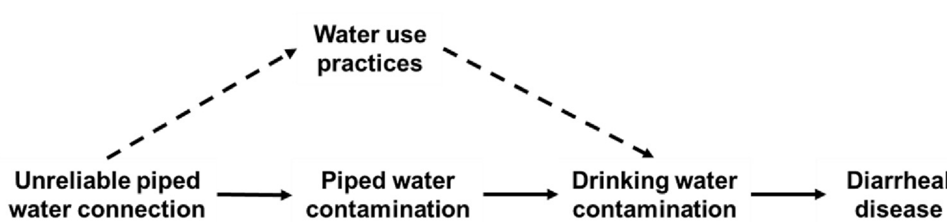

Fig. 1. Conceptual Diagram.
Intermittent access directly increases contamination, which may lead in turn to diarrheal disease. Unreliable water systems may cause households to change practices related to storage, treatment, or to rely more on secondary or alternative drinking water sources. These coping strategies have the potential to both increase, and decrease, the risk of consuming contaminated drinking water.

as community controls during each case-control study, and no household controls were selected (Fig. 2). The sample size for the study was calculated based on a primary comparison between diarrhea and community remoteness (with Borbón representing the 'least remote' comparator).

The Borbón water system was upgraded in 2006, between the first and second waves of data collection. From 2005 to 2009, data on water usage was collected from each case and control in the study, while, from 2010 to 2012, information on water use was collected from all participating households, regardless of whether individuals from that household were subsequently identified as cases or selected as controls.

To complement these diarrheal case-control data, two additional surveys were also conducted, the results of which are reported for the first time here (Fig. 2). First, in 2009, an in-depth household survey focused on the reliability of the water supply was conducted. All households present in the case-control study at the moment of the in-depth survey were invited to participate. This survey included detailed questions about intermittency (how many days water was available in the last week), satisfaction with the water system, the benefits to households of obtaining a piped water system, and coping strategies that were used when water was not available. Midway through 2009 data collection, a broken water pump that had adversely affected the quality of service was replaced, thus also allowing us to examine how households respond to a sudden decrease in intermittency.

Secondly, in 2017, a follow-up survey was conducted to assess reliability and level of satisfaction with the piped water system, as well as primary and secondary water sources, coping strategies and household demographic and socioeconomic factors. In this study, a new sample of households were selected through a stratified randomization scheme intended to provide proportional representation, similar to that used to select participants into the earlier case-control study (see Supplemental Table 1). Two-week diarrheal prevalence was not assessed.

In 2017, water samples were collected directly from piped water taps from a subset of surveyed households (42%). If piped water was not available at the time of the interview, up to two follow-up visits were conducted. Chlorine residual testing was conducted immediately using a Hach Pocket Colorimeter II. A 100-mL sample was collected in a Whirlpak Bag (Fort Atkinson, WI). To enumerate *E. coli* and total coliforms, the sample was taken to a temporary field laboratory and processed within 6 h by mixing with IDEXX Colilert Reagent and pouring it in an IDEXX Quanti-tray 2000 (Westbrook, ME). The trays were sealed with an IDEXX sealer and incubated at 35 °C for 24 h. A second household sample was processed only if the first sample was compromised. A Whirlpak bag filled with distilled water was carried by the fieldworkers each day and tested to check for potential contamination during the sample collection process, and laboratory controls of distilled water were processed every third day. Water quality results were quantified for risk levels for *E. coli* based on the most probable number (MPN) estimated per 100 ml of water: <1 ("low risk"), 1–10 ("moderate risk"), 10–100 ("high risk"); and >100 ("very high risk") (UNICEF and World Health Organization., 2013). The enumerators were students from the United States.

Trained field staff administered study surveys orally using paper forms in 2005–2012 and the Qualtrics software applet on handheld tablets in 2017. Informed consent was obtained from all households. Both the University of Michigan institutional review board and Universidad San Francisco de Quito bioethics committee approved the 2005–2012 and 2017 protocols. The protocol used in 2009 was also approved by the Stanford University institutional review board.

2.1. Statistical analysis

Trends in water availability, water storage, and water treatment were assessed over time, weighted by the inverse probability of sampling from 2005 to 2009 to adjust for the case-control design as previously described (Bhavnani et al., 2016), and unweighted study sample averages from 2010 to 2012 and in 2017.

To examine household coping strategies related to multiple drinking water sources (Study Aim 1), household drinking water sources, in order of use, were calculated from rankings of primary, secondary, and tertiary reported water sources. We also developed bivariate logistic regression models to determine the relationship between socioeconomic status and the odds of having a piped water connection in the home, and ordinal logistic regression models to determine the relationship between socioeconomic status and access (days per week of piped water). The predictors we considered were the number of children under five present in the household, household education (highest level achieved by any member of the household), household construction, summarized through an index of housing materials that has previously been validated in the region (Lopez et al., 2018) and a wealth index based on aggregate ownership of assets (Supplemental Table 2).

In mid-2009, damage to the water treatment system's water pump interrupted service for several weeks. Survey data captured households both before and after the pump was repaired. Two-sided *t*-tests were used to compare household water treatment, storage, and reliance on secondary sources between households surveyed during versus after the interruption. Because different households were surveyed before (N = 296) and after (N = 65) the pump repair, household socioeconomic status (level of education, asset score, and building materials score) was also compared

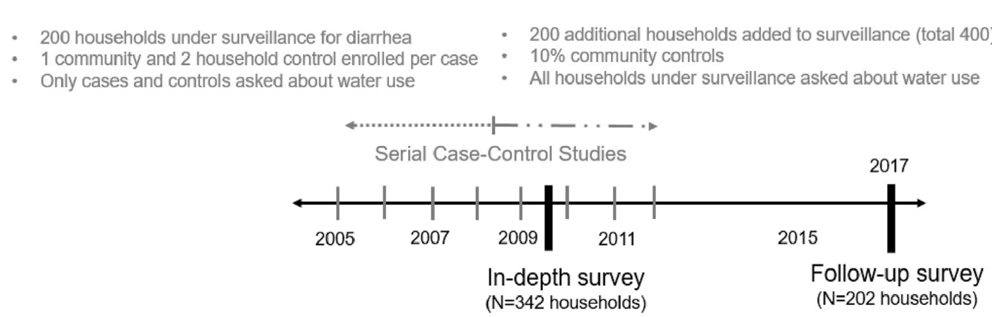

Fig. 2. Study Activities.
From 2005 to 2012, case-control studies of diarrheal disease were held approximately annually, and in 2009 and 2017, two in-depth surveys of water system reliability were also conducted. Changes to the study sampling scheme implemented in 2018 are described in gray.

during, versus after, the interruption to examine whether associations between water related behaviors and the timing of the pump repair may have been confounded by household socioeconomic status.

To describe the association between water system access, water use behaviors, and diarrheal disease (*Study Aim 2*), we developed logistic models where the outcome of interest was diarrheal case status and the dependent variables considered were access to a piped connection, drinking water source, water storage, and water treatment. Because cases and controls could come from the same households, these models included a random intercept to adjust for household membership as well as inverse-probability sampling weights to account for the study sampling scheme. To examine the impact of a piped water connection on diarrheal disease, we first developed bivariate models (A1-A4) examining the unadjusted association between a household piped water, water treatment, and primary drinking water source, on diarrhea. We then developed a set of multivariable logistic regression models adjusting for the age of the diarrheal case and the highest level of education achieved by any member of the household (B1−B4). To examine the association between household coping strategies and diarrhea disease among households with a piped water connection, we also developed a final set of adjusted models that were identical to the second set but were restricted to households that had a piped water connection (C1−C4). In both the second and third sets of models, age of a case or control was expressed as $\sqrt{A}+\ A$, where $A=$ age in years. This combination of terms was selected using fractional polynomial regression that identifies curvilinear relationships between age and diarrhea, selecting those polynomial terms that best describe the data (Royston et al., 1999),a In addition to age and household education, we also considered other potential confounders that were not included in our final models. These included household building materials, household assets, chronological year, and a first-order Fourier series to address potential seasonality. The determination of covariates to include in the final model was based on: 1) statistical significance of $p\leq 0.150$ in bivariate logistic regression models; 2) overall model fit, which were included regardless of statistical significance; and 3) overall model fit based on Akaike's criteria (AIC). Covariates that decreased the model AIC by > 4 were retained in final multivariable models (Burnham and Anderson., 2003)". We included variables related to our primary study questions of piped water access and household coping strategies in our bivariate models regardless of these criteria. Models are fully described in Supplemental Table 3.

All statistical analyses were conducted using SAS software version 9.4 (SAS Institute, Cary, North Carolina) or Stata software version 15.1 (College Park, Texas).

3. Results

From 2005 to 2012, 1,690 interviews, comprising 645 unique households, captured information about water sources (Supplemental Table 4). During the same time period, 1377 unique individuals from these households participated in the nested case-control studies. Of these, 1009 were included only once, 277 were included twice, 73 were included 3 times, and 18 were included 4 or 5 times. 557 unique households were represented in the case-control studies, of which 220 were included in only one case-control study, 159 were included in case-control studies in 2 years, and 178 were included in 3−5 case-control studies. From July to August 2009, 361 households participated in the in-depth survey of water supply reliability. The follow-up survey was administered from June 9 to July 20, 2017. Out of 205 households invited to participate in the 2017 survey, three declined, and 202 households were enrolled. Water was sampled from 84 of these households.

3.1. Trends in piped water access

In 2005, the primary reported household water sources (N = 147) were: river water (weighted percentage = 44.0%), well water (35.8%), piped water (16.7%), rainwater (0.5%), purchased water (2.5%) or unspecified other sources (0.5%). In 2006, immediately following the plant upgrade, the weighted percentage of individuals reporting river water, well water, piped water, rainwater, purchased water, or other unspecified primary water sources was 10.9%, 4.8%, 71.5%, 11.8%, 0.0%, and 1.0% (N = 131) respectively. Of the 147 individuals interviewed in 2005, 28 were also interviewed in 2006.

In 2009, households reported benefits resulting from the piped water connections they had obtained: 45.0% reported having newly installed a toilet, 49.4% reported having installed a shower, 76.2% reported washing their plates in the kitchen, 36.8% reported washing their clothes in the house, and 21.0% reported bathing in the house. Household wealth and education were associated with greater odds of access to a domestic water connection, while the presence of children under five in the household was associated with reduced odds of access to a domestic water connection (Supplemental Table 5).

By 2017, piped water coverage had expanded to 90.4% of the community (Fig. 3a). However, the mean number of days in which a household had at least some water in the past week decreased to 62.8% (4.4 days per week, standard error = 0.1), compared to 78.5% (5.5 days per week, standard error = 0.3) in the second half of 2009 (two-sided *t*-test *p*-value = 0.0003). 90.0% of households with a domestic piped water connection reported not having received any water on at least one day during the past week. No household received water more than 12 h a day. Less than a quarter (23.3%) of households said that they were satisfied with their piped water service, down from 68.8% in the second half of 2009 (two-sided *t*-test *p*-value<0.0001).

3.2. Household coping strategies to intermittent piped water

In mid-2009, damage to the water treatment system's water pump interrupted service for several weeks. The household survey during this period enrolled 296 households while the pump was damaged (July 18-August 1), and 65 households after it was repaired (August 2−13). There was no evidence that households surveyed during versus after the interruption differed by level of education (8.1 years versus 7.9 years, two-sided *t*-test *p*-value: 0.73); asset scores (12.1 versus 11.0, two-sided *t*-test *p*-value: 0.17), and building material scores (3.8 versus 3.7, two-sided *t*-test *p*-value: 0.31). Households surveyed after service was restored were statistically less likely to report storing water (two-sided *t*-test *p*-value: 0.03), and less likely to report multiple water sources (two-sided *t*-test *p*-value: 0.03). Similar household water treatment practices were not statistically different before and after service was restored (two-sided *t*-test *p*-value: 0.87) (Fig. 4).

From 2009 to 2017 the percentage of households that reported that piped water was their primary drinking water source fell from 67.6% to 32.7% (two-sided *t*-test *p*-value<0.0001), while the percentage of households that reported that bottled water was their primary drinking water source rose from 18.8% to 62.3% (two-sided *t*-test *p*-value<0.0001, Fig. 3b). The proportion that reported drinking primarily river water, well water, or ground water fell from 13.0% to 5.0% (two-sided *t*-test p-value = 0.0035, Fig. 3b).

The percentage of the community treating their drinking water fell from a high of 50.6% in 2005, to 5.0% by 2017 (two-sided *t*-test *p*-value<0.0001). The percentage of households storing domestic water was 88.6% in 2009 and 57.4% by 2017 (two-sided *t*-test *p*-value<0.0001). Weighted and unweighted averages of primary

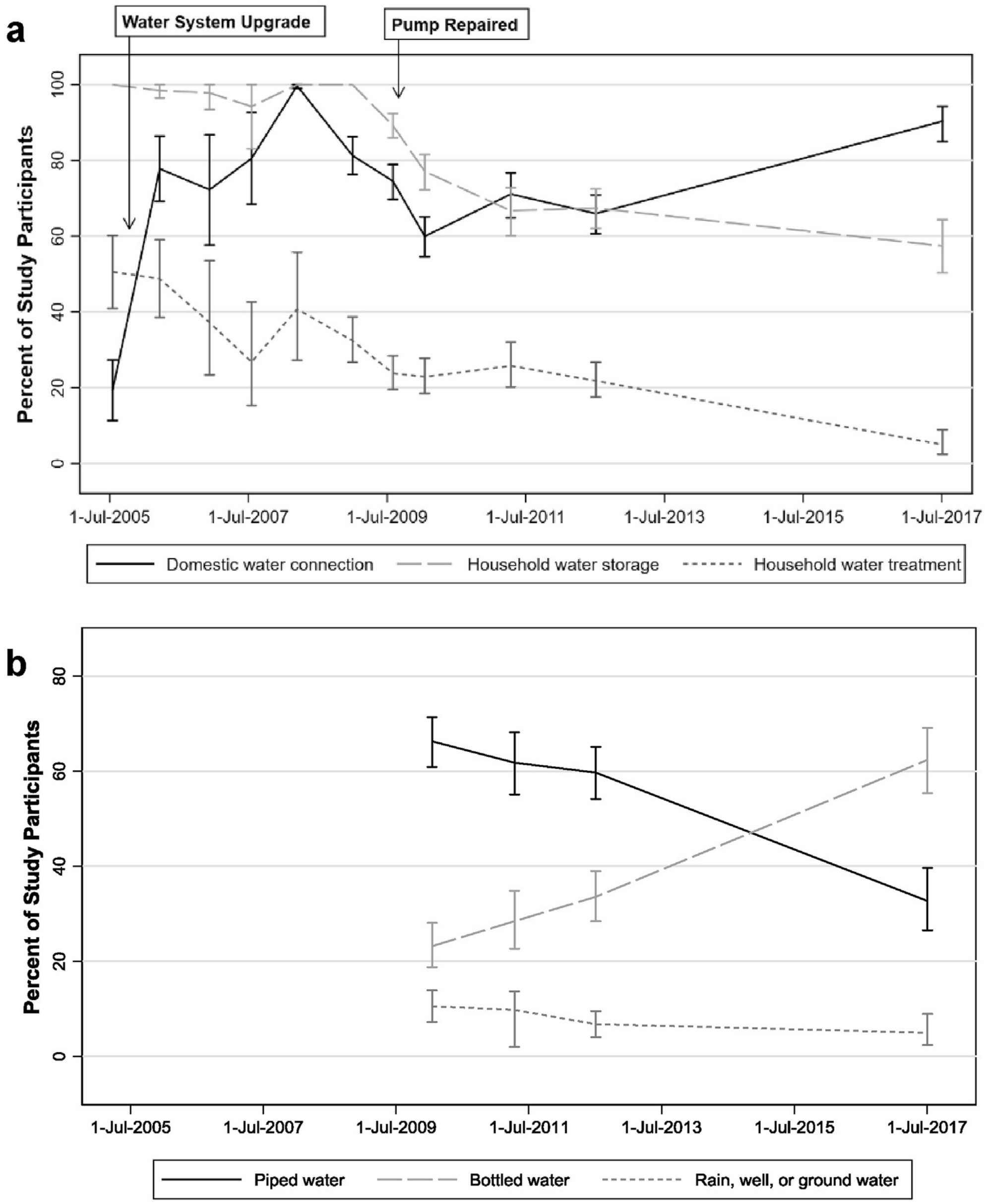

Fig. 3. Trends in household access to piped water, and household point-of-use water treatment, from 2005 to 2017
Data from the longitudinal study (2005–2012), the 2009 in-depth household survey, and the 2017 follow-up survey, is combined to estimate trends in water sources and water use behaviors over time. Data are weighted according to the study sampling scheme. Over time, an increasing proportion of households had access to a piped water connection (**3a**) but reported bottled water as their primary drinking water source (**3b**).

water source, household water storage, and household water treatment, by study year, are presented in Supplemental Table 4. Among households that treated their water in 2009, 79.5% used boiling, and 20.5% used chlorination. There was no evidence that these relative proportions varied over time (data not shown).

In 2017, 44.7% of households reported more than one drinking water source in the past week, up slightly from 38.6% in the second half of 2009 (two-sided t-test = 0.1633). Only two-thirds of households that described bottled water as their primary drinking water source had used this source exclusively in the past week. 18.3% of households had used both bottled and piped water in the past week, 7.4% had used piped water with another source, 7.4% had used bottled water with another source, and 8.4% had used one or more other sources (well water, river water, and rain water) (Table 1).

3.3. Water quality

Water samples collected in 2017 had a median free chlorine residual of 0.02 mg/l with a range of 0.00–0.09 mg/l. All samples (N = 83) were below the WHO standard of 0.20 mg/l (WHO, 2011). Only 10.8% (N = 9) of water samples had *E. coli* concentrations of <1 MPN/100 ml (low risk) and no samples had a total coliform concentration <1 MPN/100 mL (Table 2). The median total coliform concentration was 188.2 MPN/100 ml, and the median *E. coli* concentration was 3.1 MPN/100 ml. (Table 2).

3.4. Risk of diarrhea

The two-week prevalence of diarrhea was highest in the first years of the study (9.6% in 2005) and lower in later years (e.g. 4.4%

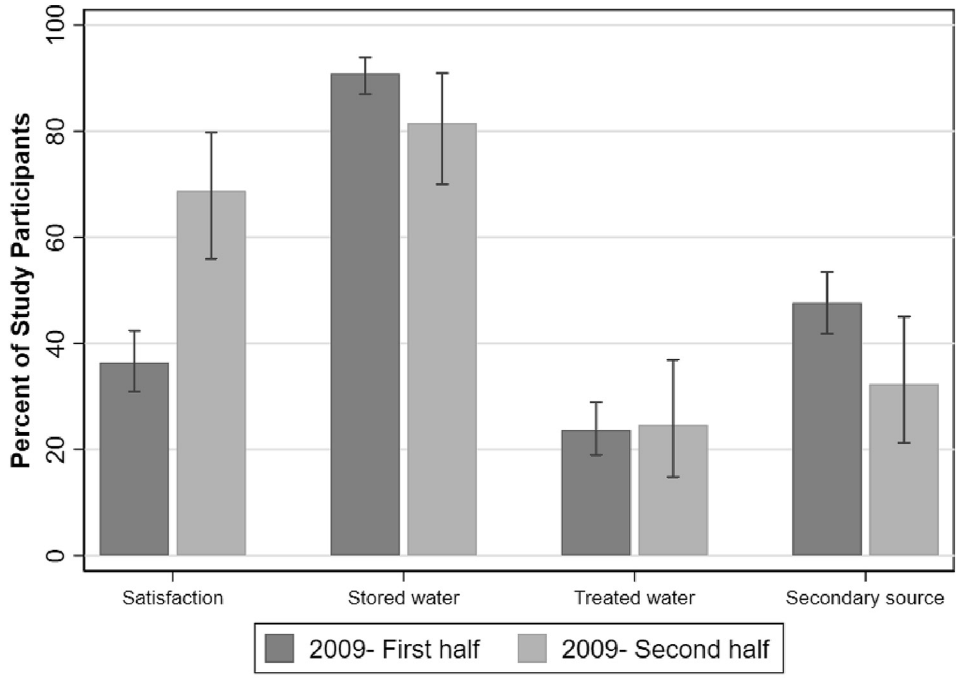

Fig. 4. Trends in household water practices after 2009 system repair.
In mid-2009, a water pump that had been broken for several weeks was repaired mid-survey. Households interviewed before the repair (from July 18 and August 1) reported service on 44% of days, and household interviewed afterwards (August 7 to August 13th) reported service on 79% percent of days.

Table 1
Community drinking water sources in order of reported use, 2017.
We determined these rankings based on the weighted frequency with which households listed water sources as primary, secondary, or tertiary drinking water sources.

Hierarchy of drinking water sources (N = 202)	Primary drinking water source in past week	Exclusively consumed In past week	Sometimes consumed in past week
Bottled Water	62.4%	40.1%	68.3%
Piped Water (household connection)	31.7%	18.3%	47.0%
Rain Water	2.0%	1.0%	6.9%
Well Water	2.0%	1.5%	5.9%
River Water	1.0%	0.0%	6.4%

in 2012, Supplemental Table 4).

Across all time points, households that were more educated, had more assets, and had higher building material scores, tended to be more likely to have a household connection (Supplemental Table 5). Households with young children (who are at the greatest risk of diarrhea) were less likely to have a water connection than households without young children odds of having a domestic water connection reduced by 30% for each additional child under five in the household (OR: 0.70; 95% CI: 0.56, 0.88). Access to a piped water connection was associated with a reduced odds of diarrhea in bivariate logistic regression models (OR: 0.65, 95% CI: 0.44, 0.98). However, after adjusting for the age of the case or control, this relationship was attenuated (OR: 0.86, 95% CI: 0.53, 1.39). Among households with a domestic water connection, each additional 10L

Table 2
Descriptive statistics of indicator bacteria from water samples collected in 2017
All samples were taken directly from piped water supplies (i.e. from the tap). The chlorine residual was undetectable (less than 0.2 mg/l) in all samples.

	Total Coliforms (MPN/100 mL)	*Escherichia coli* (MPN/100 mL)
N	83	83
Min	5.1	0
25% percentile	85.4	1
Median	188.2	3.1
50% percentile	498.8	12.1
Max	>2419.6	>2419.6
Risk Level (UNICEF and World Health Organization, 2013) **(*E. coli* concentration MPN/100 ml), % total**		
Very low risk (<1 MPN)	n/a	11%
Low risk (1–10 MPN)	n/a	63%
Medium risk (11–100 MPN)	n/a	25%
High risk (>100 MPN)	n/a	1%

* MPN = Most Probable Number, estimates the number of organisms per 100 mL, which is approximately equivalent to CFU/100 ml.

of water stored was associated with a 33% increase in the odds of diarrhea (OR: 1.33; 95% CI: 1.05, 1.69). Neither household treatment of drinking water, nor use of bottled water, was associated with diarrhea. Although not statistically significant, individuals who reported drinking bottled water trended toward an increased odds of being a diarrhea case versus those drinking piped water (OR: 2.23; 95% CI: 0.45, 11.15; Table 3).

4. Discussion

The strategies that study participants used to cope with unreliable water supply in our study site gradually shifted over time. Improvements to the water system in 2006 likely led households to shift from reliance on rain, well, and surface water toward piped water use. However, in the latter half of the study period, piped water consumption became less common, and purchased bottled water consumption increased. Household water storage and reliance on multiple drinking water sources remained common coping strategies over the entire 12-year period, while household water treatment, a common strategy early on, was gradually phased out. Households with a child under five were less likely to have a domestic water connection, and, after adjusting for differences in the age of diarrhea cases and controls, access to a domestic water connection was no longer statistically significantly associated with diarrhea. Household water storage, a coping strategy that households may have used to buffer themselves against an unreliable water supply, was associated with increased disease risk.

Many studies have examined the quality and availability of piped water systems in LMIC communities (Ercumen et al., 2015; Kumpel and Nelson, 2016; Simukonda et al., 2018), and several have described household coping strategies in response to unreliable water supplies (Katuwal and Bohara, 2011; Majuru et al., 2016; Pattanayak et al., 2005). However, few reports have examined how unreliable water supplies may impact household coping strategies over time or how they are affected by sudden changes in intermittency. Here, we examine both long- and short-term household coping strategies associated with an unreliable water supply. These data are complementary. The long-term trends in water use (i.e., increases in bottled water use) were likely influenced by changes in national income, policy, or technology over the same period. During this period we also observed a short-term change; i.e., in 2009, households surveyed immediately after a sudden improvement in the water system reported significantly less water storage, and less reliance on secondary sources, than households surveyed prior to the water system improvement. This change in behavior was likely influenced by the perceived changes in water reliability.

Unreliable water supplies may have both positive and negative effects. The low levels of free chlorine residual and presence of total coliforms and *E. coli* detected in piped water samples from 2017 are similar to many other studies of LMIC communities (Bain et al., 2014; Grady et al., 2015; Shaheed et al., 2014; Sorlini et al., 2013). Compared with similar studies, our results showed a smaller percentage of samples with no *E. coli* contamination (<1 MPN/100 ml) but also a smaller percentage that were classified as high risk (Grady et al., 2015; Shaheed et al., 2014). However, the available alternatives of well water, ground water, and stored rainwater were likely of even poorer quality (Levy et al., 2008). The unreliable water supply may also have nevertheless led to indirect improvements in sanitation and hygiene, as participants reported that domestic water connections had enabled them to install flush toilets and showers and to wash clothing and plates more easily. On the other hand, our results support many other studies that have shown that unreliability leads to increased home water storage (Pattanayak

Table 3
Association between diarrheal disease and coping strategies related to unreliable water systems
This table shows the odds of diarrheal disease associated with household coping strategies from 2005 to 2012, based on bivariate (unadjusted) and multivariable (adjusted) logistic regression models. Model details are described in Supplemental Table 5.

	2005–2012 Diarrheal Disease		
	Models A1-A4: Bivariate logistic regression	Models B1–B4: Multivariable logistic regressions*	Models C1–C3: Multivariable logistic regression*, households with a domestic connection only
1. Domestic water connection	0.65 (0.44, 0.98) (p = 0.038)	0.86 (0.53, 1.39) (p = 0.547)	n/a
2. Number of liters stored/50L	1.03 (0.88, 1.20) (p = 0.700)	1.06 (0.83, 1.36) (p = 0.620)	1.33 (1.05, 1.69) (p = 0.020)
3. Household treatment of drinking water = yes	0.99 (0.63, 1.55) (p = 0.970)	0.84 (0.47, 1.50) (p = 0.562)	0.75 (0.37, 1.51) (p = 0.415)
4. Primary drinking water: source:			
= bottled	2.26 (0.66, 7.67) (p = 0.192)	3.52 (0.91, 13.70) (p = 0.069)	2.23 (0.45, 11.15) (p = 0.330)
= other	1.27 (0.55, 2.92) (p = 0.578)	0.83 (0.32, 2.13) (p = 0.698)	n/a

Each cell shows the odds ratio, 95% confidence internal, and p-value.
*adjusting for age and maximum household education.
***Ref = domestic water connection**. Using data from 2010 to 2012 only.

et al., 2005). We demonstrate that the quantity of water stored was associated with the odds of diarrhea case status (OR: 1.33 per 10L stored; 95% CI: 1.05, 1.69), likely due to recontamination (Levy et al., 2008; Wright et al., 2004). The impact of these water management practices likely reduced the derivative health benefits of the water supply.

Our results also highlight the extent to which reliance on multiple drinking water sources creates risks for vulnerable households. While we observed decreases in the percentage of households that primarily relied on rainwater, well water, and ground water over time, our data also suggests that these continued to be common secondary sources, both for domestic use and for consumption. Even occasional exposure to contaminated water increases disease risk (Enger et al., 2013), which may explain why household water treatment was not statistically significantly protective against diarrhea in our population.

Our finding that, over time, study participants increasingly preferred bottled water as a drinking water source is also reflective of broader national trends. Twenty-one percent (21%) of people in Ecuador rely on bottled water as a primary drinking source, even though 97% of the population has access to another improved water supply such as piped water (WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, 2017). In 2017, the JMP reversed its previous position on bottled water and now accepts it as an 'improved' source. A recent study from the same region of Ecuador found that 73% of reusable bottled water and 25% of non-reusable bottles were contaminated (Mills et al., 2018), so bottled water in this context should be defined as a 'basic' or 'limited' improved source, as it is both i) potentially contaminated and ii) not consistently accessible. Bottled water consumption also tended to be associated with an increased, rather than a decreased, risk of diarrhea, although this was not statistically significant (odds ratio: 2.23 for those primarily drinking bottled versus piped water; 95% confidence interval: 0.45, 11.15). Other have reported that socioeconomic status is a strong predictor of preferred coping strategies (Hamoudi et al., 2012; Jalan and Somanathan, 2008). For reference, 20L of bottled water may be purchased in Borbón for approximately USD 1.00–1.25. In comparison, 20L of chlorinated water piped water cost approximately USD 0.03–0.15 over the study period.[1] Our results reinforce the notion that bottled water should not be considered a sustainable solution for increasing access to safe water (Cohen and Ray, 2018). Dependence on this source is inherently inequitable, and lower economic status households are particularly vulnerable to fluctuations in availability, cost, and quality (Cohen and Ray, 2018).

Our study has several limitations. We describe trends in water access and usage over an extended (12-year) period. However, these data are assembled from several sources, including studies with changing sampling methods and surveys. None of these data collection activities were designed, or powered, with the *a priori* intention of testing associations between unreliable water systems and diarrhea, and several key pieces of information are unavailable. Specifically, although our evidence shows that the 2006 system upgrade improved coverage (from 16.7% to 77.8%), data on the reliability of this supply prior to 2009 is limited. Information on secondary drinking water sources was only collected during the 2009 and 2017 surveys, both in the same season. As a result, our ability to examine the impact of seasonality on secondary drinking water sources is limited. In 2017 we performed a cross-sectional survey, rather than a diarrheal case-control study, and therefore, we are unable to relate water coverage or household coping strategies to diarrhea at this time point. We did not test piped water for chemical or heavy metal contaminants that affect the quality of the water source, although gold mining activities upstream of the water collection site makes this a concern (Rebolledo Monsalve, 2017). Our results are also limited by the small number of houses surveyed after the system repair in 2009, as well as only having water quality test results for a small number of households ($N = 84$) at a single timepoint (2017). We also did not assess water supply *predictability*, whether users knew when water would be available, although this is another important dimension of reliability (Majuru et al., 2016). Perhaps the most significant limitation is that little information was collected related to knowledge and attitudes over time, including how and why households made decision related to water use. For example, survey respondents were not asked why they chose to treat, or not treat, their drinking water, or what motivated preferences for piped or purchased bottled water. We speculate that community members assumed that piped water had already been sufficiently treated, or that health education messages emphasized the treatment of river, rain, or well water, rather than the potential utility of treating piped water. It is also unclear why household water storage was reported less frequently from 2009 to 2017, even as the water supply apparently became less reliable. We also did not capture household expenditures related to water, which, given increasing reliance on bottled water, likely increased over time. Future work should aim to better understand household decision-making around water use.

5. Conclusion

Water systems that provide intermittent or otherwise suboptimal service for extended periods, like the one we describe here, are clearly undesirable. There is a need for locally appropriate water supplies that meet current and future capacity needs and can be sustainably maintained. However, given that unreliable water supplies are both common, and that the number of people dependent on such supplies is expected to increase, there is also a need to understand how households cope with these systems.

- In communities with unreliable water systems, studies should aim to capture data about drinking water storage, treatment, and secondary drinking water sources alongside information about primary drinking water source.
- Bottled water should not be considered a sustainable mechanism for increasing access to safe drinking water.
- There is a need to better understand why impoverished rural households choose bottled water over lower-cost home treatment, and to develop low-cost strategies to promote more effective coping strategies in this context.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project was supported by the National Institutes of Health [R01-AI050038]. HW and NL were supported by the University of Michigan Office of Global Health and the University of Michigan International Institute. AB was supported by the Stanford Vice Provost for Undergraduate Education (VPUE) Undergraduate Advising and Research (UAR) Student Grant #3072. KL was

[1] In 2009, users were charged a flat monthly rate of USD 5.60 for the first 1000 m^3 of piped water used, and then volumetrically at USD 0.56/m^3 for additional water. By 2017, the payment scheme had shifted and service was free for all households.

supported by National Institute of Allergy and Infectious Diseases [1K01AI103544]. The content is solely the responsibility of the authors and does not necessarily represent the official views of the funders. We would like to thank Jorge Obando for his time in showing us the Borbón water plant and explaining operations; the field staff in Borbón, especially Javier Borja, for assistance in conducting field research and collecting and testing water samples; the Ecología, Desarrollo, Salud y Sociedad (EcoDess) project research team for their contributions to previous data collection and administrative support; and the study participants for their time and involvement in the study. We would also like to thank Dr. Jenna Davis at Stanford University for her support of the project, Dr. Nancy Love at the University of Michigan for providing technical assistance and Nikki Beetsch and NSF International for providing the equipment that made this project possible.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watres.2019.115269.

References

Adane, M., Mengistie, B., Medhin, G., Kloos, H., Mulat, W., 2017. Piped water supply interruptions and acute diarrhea among under-five children in Addis Ababa slums, Ethiopia: a matched case-control study. PLoS One 12, e0181516. https://doi.org/10.1371/journal.pone.0181516.

Bain, R., Cronk, R., Hossain, R., Bonjour, S., Onda, K., Wright, J., Yang, H., Slaymaker, T., Hunter, P., Prüss-Ustün, A., Bartram, J., 2014. Global assessment of exposure to faecal contamination through drinking water based on a systematic review. Trop. Med. Int. Health 19, 917–927. https://doi.org/10.1111/tmi.12334.

Baqui, A.H., Black, R.E., Yunus, M., Hoque, A.R., Chowdhury, H.R., Sack, R.B., 1991. Methodological issues in diarrhoeal disease epidemiology. Definition of diarrhoea episodes. Int. J. Epidemiol. 20, 1057–1063.

Bhavnani, D., Bayas Rde, L., Lopez, V.K., Zhang, L., Trueba, G., Foxman, B., Marrs, C., Cevallos, W., Eisenberg, J.N., 2016. Distribution of enteroinvasive and enterotoxigenic Escherichia coli across space and time in northwestern Ecuador. Am. J. Trop. Med. Hyg. 94, 276–284. https://doi.org/10.4269/ajtmh.14-0337.

Bhavnani, D., Goldstick, J.E., Cevallos, W., Trueba, G., Eisenberg, J.N.S., 2012. Synergistic effects between rotavirus and coinfecting pathogens on diarrheal disease: evidence from a community-based study in northwestern Ecuador. Am. J. Epidemiol. 176, 387–395. https://doi.org/10.1093/aje/kws220.

Bivins, A.W., Sumner, T., Kumpel, E., Howard, G., Cumming, O., Ross, I., Nelson, K., Brown, J., 2017. Estimating infection risks and the global burden of diarrheal disease attributable to intermittent water supply using QMRA. Environ. Sci. Technol. 51, 7542–7551. https://doi.org/10.1021/acs.est.7b01014.

Burnham, K.P., Anderson, D.R., 2003. Model Selection and Multimodel Inference: a Practical Information-Theoretic Approach. Springer Science & Business Media.

CARE, 2006. Estudio de Sostenibilidad de Los Sistemas de Potable water Rural. Agua, saneamiento y salud ambiental para el desarrollo human sostenible. Quito, Ecuador.

Cohen, A., Ray, I., 2018. The global risks of increasing reliance on bottled water. Nat. Sustain. 1, 327–329. https://doi.org/10.1038/s41893-018-0098-9.

Craun, G.F., Brunkard, J.M., Yoder, J.S., Roberts, V.A., Carpenter, J., Wade, T., Calderon, R.L., Roberts, J.M., Beach, M.J., Roy, S.L., 2010. Causes of outbreaks associated with drinking water in the United States from 1971 to 2006. Clin. Microbiol. Rev. 23, 507–528. https://doi.org/10.1128/CMR.00077-09.

Eisenberg, J.N., Cevallos, W., Ponce, K., Levy, K., Bates, S.J., Scott, J.C., Hubbard, A., Vieira, N., Endara, P., Espinel, M., Trueba, G., Riley, L.W., Trostle, J., 2006. Environmental change and infectious disease: how new roads affect the transmission of diarrheal pathogens in rural Ecuador. Proc. Natl. Acad. Sci. 103, 19460–19465. https://doi.org/10.1073/pnas.0609431104.

Enger, K., Nelson, K., Rose, J., Eisenberg, J.N.S., 2013. The joint effects of efficacy and compliance: a study of household water treatment effectiveness against childhood diarrhea. Water Res. 47, 1181–1190.

Ercumen, A., Arnold, B.F., Kumpel, E., Burt, Z., Ray, I., Nelson, K., Colford, J.M., 2015. Upgrading a piped water supply from intermittent to continuous delivery and association with waterborne illness: a matched cohort study in urban India. PLoS Med. 12, 1–24. https://doi.org/10.1371/journal.pmed.1001892.

Ercumen, A., Gruber, J.S., Colford, J.M.J., 2014. Water distribution system deficiencies and gastrointestinal illness: a systematic review and meta-analysis. Environ. Health Perspect. 122, 651–660. https://doi.org/10.1289/ehp.1306912.

Grady, C.A., Kipkorir, E.C., Nguyen, K., Blatchley, E.R., 2015. Microbial quality of improved drinking water sources: evidence from western Kenya and southern Vietnam. J. Water Health 13, 607–612. https://doi.org/10.2166/wh.2014.206.

Hamoudi, A., Jeuland, M., Lombardo, S., Patil, S., Pattanayak, S.K., Rai, S., 2012. The effect of water quality testing on household behavior: evidence from an experiment in rural India. Am. J. Trop. Med. Hyg. 87, 18–22. https://doi.org/10.4269/ajtmh.2012.12-0051.

Hunter, P.R., Zmirou-Navier, D., Hartemann, P., 2009. Estimating the impact on health of poor reliability of drinking water interventions in developing countries. Sci. Total Environ. 407, 2621–2624. https://doi.org/10.1016/j.scitotenv.2009.01.018.

Instituto Nacional de Estadistica y Censos, 2001. Cantón Eloy Alfaro. Quito, Ecuador.

Jalan, J., Somanathan, E., 2008. The importance of being informed: experimental evidence on demand for environmental quality. J. Dev. Econ. 87, 14–28. https://doi.org/10.1016/j.jdeveco.2007.10.002.

Katuwal, H., Bohara, A.K., 2011. Coping with poor water supplies: empirical evidence from Kathmandu, Nepal. J. Water Health 9, 143–158. https://doi.org/10.2166/wh.2010.151.

Kumpel, E., Nelson, K.L., 2016. Intermittent water supply: prevalence, practice, and microbial water quality. Environ. Sci. Technol. 50, 542–553. https://doi.org/10.1021/acs.est.5b03973.

Lee, E.J., Schwab, K.J., 2005. Deficiencies in drinking water distribution systems in developing countries. J. Water Health 3, 109–127.

Levy, K., Nelson, K.L., Hubbard, A., Eisenberg, J.N., 2008. Following the water: a controlled study of drinking water storage in northern coastal Ecuador. Environ. Health Perspect. 116, 1533–1540. https://doi.org/10.1289/ehp.11296.

Lopez, V.K., Dombecki, C., Trostle, J., Mogrovejo, P., Castro Morillo, N., Cevallos, W., Goldstick, J., Jones, A.D., Eisenberg, J.N.S., 2018. Trends of child undernutrition in rural Ecuadorian communities with differential access to roads, 2004-2013. Matern. Child Nutr., e12588 https://doi.org/10.1111/mcn.12588.

Majuru, B., Suhrcke, M., Hunter, P.R., 2016. How do households respond to unreliable water supplies? a systematic review. Int. J. Environ. Res. Public Health 13, 1222. https://doi.org/10.3390/ijerph13121222.

Mills, K., Golden, J., Bilinski, A., Beckman, A., McDaniel, K., Harding, A., France, A., Tobar, H., Vecitis, C., 2018. Bacterial contamination of reusable bottled drinking water in Ecuador. J. Water, Sanit. Hyg. Dev. 8, 81–89.

Pattanayak, S.K., Yang, J.C., Whittington, D., Bal Kumar, K.C., 2005. Coping with unreliable public water supplies: averting expenditures by households in Kathmandu, Nepal. Water Resour. Res. 41, 1–11. https://doi.org/10.1029/2003WR002443.

Rebolledo Monsalve, E., 2017. Monitoreo de calidad de agua en el periodo de 2015-2017 en la zona de influencia minera del norte de esmeraldas.

Royston, P., Ambler, G., Sauerbrei, W., 1999. The use of fractional polynomials to model continuous risk variables in epidemiology. Int. J. Epidemiol. 28, 964.

Shaheed, A., Orgill, J., Ratana, C., Montgomery, M.A., Jeuland, M.A., Brown, J., 2014. Water quality risks of “improved” water sources: evidence from Cambodia. Trop. Med. Int. Health 19, 186–194. https://doi.org/10.1111/tmi.12229.

Simukonda, K., Farmani, R., Butler, D., 2018. Intermittent water supply systems: causal factors, problems and solution options. Urban Water J. 15, 1–13. https://doi.org/10.1080/1573062X.2018.1483522.

Sorlini, S., Palazzini, D., Mbawala, A., Ngassoum, M.B., Collivignarelli, M.C., 2013. Is drinking water from “improved sources” really safe? A case study in the Logone valley (Chad-Cameroon). J. Water Health 11, 748–761. https://doi.org/10.2166/wh.2013.017.

Thompson, J., Porras, I.T., Tumwine, J.K., Mujwahuzi, M.R., Katui-Katua, M., Johnstone, N., Wood, L., 2001. Drawers of Water II: 30 Years of Change in Domestic Water Use and Environmental Health in East Africa. International Institute for Environment and Development, London, UK.

Trudeau, J., Aksan, A.M., Vásquez, W.F., 2018. Water system unreliability and diarrhea incidence among children in Guatemala. Int. J. Public Health 63, 241–250. https://doi.org/10.1007/s00038-017-1054-6.

UNICEF and World Health Organization, 2013. Second Meeting of the WHO/UNICEF JMP Task Force on Monitoring Drinking-Water Quality.

USAID, 2009. La Frontera Norte se Esfuerza por Crecer en Paz. Ecuador. Plan Ecuador & USAID.

WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, 2017. Progress on Drinking Water. sanitation and hygiene, Geneva, Switzerland. https://doi.org/10.1111/tmi.12329.

WHO, 2011. Guidelines for Drinking-Water Quality, fourth ed. https://doi.org/10.1016/S1462-0758(00)00006-6 Geneva, Switzerland.

WHO, UNICEF, 2000. Global Water Supply and Sanitation Assessment 2000 Report. Water Supply, 87. http://www.who.int/water_sanitation_health/monitoring/globalassess/en/.

Wolf, J., Pruss-Ustun, A., Cumming, O., Bartram, J., Bonjour, S., Cairncross, S., Clasen, T., Colford Jr., J.M., Curtis, V., De France, J., Fewtrell, L., Freeman, M.C., Gordon, B., Hunter, P.R., Jeandron, A., Johnston, R.B., Mausezahl, D., Mathers, C., Neira, M., Higgins, J.P., 2014. Assessing the impact of drinking water and sanitation on diarrhoeal disease in low- and middle-income settings: systematic review and meta-regression. Trop. Med. Int. Health 19, 928–942. https://doi.org/10.1111/tmi.12331.

World Bank, 2018. People Using Safely Managed Drinking Water Services (% of Population). World Bank Gr. Data [WWW Document].

Wright, J., Gundry, S., Conroy, R., 2004. Household drinking water in developing countries: a systematic review of microbiological contamination between source and point-of-use. Trop. Med. Int. Health 9, 106–117. https://doi.org/10.1046/j.1365-3156.2003.01160.x.