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Predictors of household drinking water *E. coli* contamination: Population-based results from rural areas of Ghana, Malawi, Mozambique, Niger, Rwanda, Uganda, and Zambia

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ABSTRACT

Background: In sub-Saharan Africa, rural areas have lower rates of access to safe drinking water compared to urban areas. We investigated predictors of *Escherichia coli* contamination in drinking water of rural households in Ghana, Malawi, Mozambique, Niger, Rwanda, Uganda, and Zambia.

Methods: We used a population-based, cluster randomized sampling design to select rural households in each country. Household interviews on water access, sanitation, and hygiene (WaSH) practices and demographic characteristics were conducted and water samples from every fifth household were collected and enumerated for *E. coli*. Negative binomial regression models with survey sampling weights were run to evaluate predictors of *E. coli* contamination.

Results: A total of 18,747 rural household surveys (2,378–2,804 per country) were conducted and a total of 3,848 water samples (460–660 per country) were collected. Of surveyed rural households, 61–78% of households had high (11–100 *E. coli* cfu/100 mL) or very high (>100 cfu/100 mL) risk water quality in Ghana, Niger, and Uganda. Statistically significant WaSH predictors associated with lower *E. coli* incidence rates included using an improved-type primary water source (Mozambique), storing water in a narrow-mouthed container or container with a spigot (Niger), having continuous water supply during the dry season (Ghana), paying for water service (Rwanda), having soap or ash at handwashing points (Mozambique), having an improved-type household sanitation facility (Malawi), and attaining an education level greater than primary school (Niger and Zambia).

Conclusion: This study highlights the variability in WaSH access between rural areas of the study countries in association with microbial drinking water quality.

1. Introduction

Access to safe drinking water, sanitation, and hygiene (WaSH) reduces the spread of enteric and infectious diseases (Brown et al., 2013; Cairncross et al., 2010; Prüss et al., 2002) and has social benefits for gender equity, gender empowerment, and economic prosperity (Pommells et al., 2018; Tsinda et al., 2021). While Sustainable Development Goal 6 put forth by the United Nations aims for “clean water and sanitation for all” by the year 2030 (United Nations, n.d.), about two billion individuals in the world currently use a fecally contaminated

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drinking water source (Onda et al., 2012; WHO/UNICEF, 2021).

The presence of fecal bacteria, such as *Escherichia coli* (*E. coli*), in drinking water is widely used as a standard assessment of drinking water quality because it indicates contamination of external origin (Field and Samadpour, 2007; U.S. Environmental Protection Agency, 2012). Previous studies suggest that several factors are related to the fecal contamination of drinking water such as water source type, water continuity, and water storage and transfer practices. Prior studies report that water source types, such as piped systems or boreholes, have decreased odds of fecal contamination compared to other water source types, such as unprotected wells and springs (Bain et al., 2014). Access to a continuous, as opposed to intermittent, water supply has been associated with lower levels of bacterial indicators such as total coliforms and *E. coli* (Edokpayi et al., 2018; Kumpel and Nelson, 2013). This is shown to be related to water storage practices, as individuals who do not have access to a continuous drinking water supply are more likely to store their water in containers (García-Betancourt et al., 2015). Studies have also shown that the process of transporting and removing drinking water from storage containers is associated with fecal contamination of a drinking water source (Meierhofer et al., 2018; Rufener et al., 2010) and that safe hygiene practices, such as handwashing before removing drinking water from a storage container, is associated with decreased odds of having fecal indicators in a drinking water source (Too et al., 2016). While research has been conducted on how to implement infrastructural and behavioral changes to improve drinking water quality, sustaining these changes over time can be difficult for low socioeconomic and rural households, especially those in sub-Saharan Africa (Daniel et al., 2021; Silvestri et al., 2018).

Predictors of microbial drinking water quality may differ across geographic regions due to variability in population density, infrastructure, and investment (McDonald et al., 2011). To our knowledge, few studies have evaluated the factors that contribute to microbial drinking water quality across multiple countries as opposed to a single country or region (Bain et al., 2021; Fejfar et al., 2024). Using questionnaires, direct observation, and water sample collection, this study analyzed the predictors of drinking water quality, based on *E. coli* contamination, of rural households in Ghana, Malawi, Mozambique, Niger, Rwanda, Uganda, and Zambia.

2. Materials and methods

2.1. Sampling design

This study used a multi-stage, cluster-randomized sampling design, proportionate to population size, across seven countries (Fig. 1). This method was adopted from the Global Adult Tobacco Survey (WHO, 2012), an internationally accepted method for large, multi-country surveys, and was used to ensure generalization of the data to selected rural areas (Table 1).

National Statistics Offices (NSOs) in each country had previously divided their countries into primary sampling units (PSUs), which were defined as condensed, non-overlapping areas that are formed by boundaries such as state, county, or province borders. This study's sampling frame spanned PSUs in multiple rural districts and departments across each country. This also included PSUs where World Vision International (WV) worked and where WV did not work, as another aim of this research was to evaluate WV programming. WV is a non-governmental organization that works in international rural WaSH programming and in the countries analyzed in this study.

Selection stages involved randomly sampling PSU lists from predetermined rural areas provided by the NSOs of each country. Random selection was done using a random sample generator in Microsoft Excel. A random sample of 55 PSUs where WV worked and 55 comparison PSUs where WV did not work were selected in each country. From the selected PSUs, a random sample of 25 households was then selected from community household lists. This equated to a target sample size of 2,750 total household surveys (1,375 WV households and 1,375 comparison households) per country. From the selected households, every fifth household was selected for stored drinking water samples. This equated to a target sample size of 550 total water samples (275 WV water samples and 275 comparison water samples) per country. Data collection methods involved household interviews, direct observation, and water sample collection. Detailed recording of the probability of selection at each stage and appropriately sized sampling units were used

Fig. 1. Map of rural districts and departments surveyed and sampled (indicated in white), 2014-2015.

Table 1
Rural districts and departments surveyed and sampled in each country, 2014–2015.

African Region	Country	Country Region or Province	Country District or Department	Local Languages of Survey Translation
Western	Ghana	**Regions**	**Districts**	Akan
		Bono East	Anyima, Kintampo South	Dagbani English
		Northern	Bole, East Gonja, East Mamprusi, Gushegu Municipal, Karaga, Kumbungu, North Nanumba, South Nanumba, Tamale Metropolitan, Tolon, West Gonja Municipal, Yendi Municipal	
		Upper East	Bawku West, Builsa, Garu, Nabdam, Talensi, Tempane	
		Upper West	Jirapa Municipal, Lambussie-Karni, Lawra Municipal, Nadowli-Kaleo, Wa East, Wa West, Sissala West	
	Niger	**Regions**	**Departments**	Djarm
		Dosso	Boboye, Dioundiou, Dosso, Gaya, Tibiri (Doutchi)	French Hausa
		Maradi	Aguie, Dakoro, Gazaoua, Guidan Roumdji, Madarounfa, Mayahi, Tessaoua	
		Tahoua	Bagaroua, Birni-N'Konni, Madaoua, Malbaza, Tahoua	
		Tillabéri	Balléyara, Filingue, Gothèye, Kollo, Ouallam, Say, Téra, Tillabéri, Torodi	
		Zinder	Damagaram Takaya, Dungass, Goure, Kantche, Magaria, Mirriah, Takeita	
Southern	Malawi	**Regions**	**Districts**	English
		Central	Dedza, Dowa, Kasungu, Lilongwe, Machinga, Mchinji, Nkhotakota, Ntcheu, Ntchisi	French
		Northern	Karonga, Mzimba, Nkhata Bay, Rumphi	
		Southern	Balaka, Chikwawa, Mangochi, Mulanje, Mwanza, Neno, Nsanje, Phalombe, Thyolo, Zomba	
	Mozambique	**Provinces**	**Districts**	Portuguese
		Gaza	Chibuto, Guijá, Manjacaze, Xai-Xai	
		Nampula	Meconta, Muecate, Murrupula, Nacarôa	
		Tete	Angónia, Cahora-Bassa, Changara	
		Zambezia	Mocuba, Morrumbala, Namacurra	
Eastern	Rwanda	**Provinces**	**Districts**	French
		Eastern	Bugesera, Gasabo, Gatsibo, Kayonza, Kicukiro, Nyagatare	
		Northern	Gakenke Gicumbi, Rulindo	
		Southern	Gisagara, Huye, Nyamagabe, Nyaruguru	
		Western	Karongi, Ngororero, Rutsiro	
	Uganda	**Regions**	**Districts**	Luo
		Central	Luweero, Nakaseke, Nakasongola	Runyoro
		Northern	Amuru, Gulu, Oyam	
		Western	Buliisa, Hoima	
	Zambia	**Provinces**	**Districts**	Bemba
		Eastern	Chipata	
		Lusaka	Chongwe	
		Northern	Kasama, Mbala, Mpulungu	
		North-Western	Solwezi	
		Southern	Choma, Kalomo, Mazabuka, Monze, Sinazongwe	

to assign sampling weights to the data.

2.2. Ethics

This study gained approval by the Office of Human Research Ethics and Institutional Review Board of the University of North Carolina at Chapel Hill on June 3, 2014 (IRB Reference ID: 14–0763) and the national governing bodies of each country prior to the start of data collection. This included approval from the Director of Water at The Ministry of Water Resources, Works, and Housing (Ghana), Chairman of the National Health Sciences Research Committee in the Ministry of Health (Malawi), the Directorate of Water in the Ministry of Public Works and Housing (Mozambique), the Ministry of Hydraulics and Sanitation (Niger), the Minister of State in Charge of Energy and Water (Rwanda), the Uganda National Council for Science and Technology (Uganda), and the Permanent Secretary of The Ministry of Local Government and Housing (Zambia). The privacy rights of study participants were observed in this study and informed consent was obtained from each study participant before survey conduction.

2.3. Household survey

Household interview questions were adapted from the Joint Monitoring Programme (JMP) core questions for water and sanitation (WHO/UNICEF, 2006) and from the United States Agency for International Development (USAID) Demographic and Health Surveys program questions on WaSH (USAID, 2012).

Household interviews included questions about drinking water, sanitation, hygiene, and demographic variables. Drinking water questions asked about each household's primary water source. This included questions on water source type during dry seasons, rainy seasons, and year-round, and whether the water source was an improved-type or unimproved-type. As per the World Health Organization (WHO) definition, improved-type water sources referred to piped water into households or yards, public taps, boreholes with pumps, protected dug wells or springs, rainwater, and packaged water (WHO, 2024). Questions were also asked about water access (round trip time to travel to the water source, collect water, and return home), supply (estimated in liters of water per person per day), and storage (presence of covered stored water and storage container type). Water storage container type was defined as wide-mouthed (able to put one's hand into the container to retrieve water), narrow-mouthed (unable to put one's hand into the container to retrieve water), or containing a spigot. Questions were included on household water treatment (such as boiling, filtration, or use of chlorine), continuity (presence of continuous 24 hour per day water service and mean hours of available water service per day and per week during the dry season), reliability (water point breakdown in the past two weeks), and sustainability (presence of a water committee and presence of household water service payment). Questions on hygiene and sanitation focused on the presence of soap or ash at handwashing points and whether the household sanitation facility was an improved-type or unimproved-type. As per the WHO definition, improved-type sanitation facilities included flushable toilets to a piped sewer or septic system, ventilated pit latrines, pit latrines with a slab cover, or composting toilets (WHO, 2024). Questions on respondent demographics asked about the respondent's highest education level (no formal education, primary, secondary, technical, or university). Questions on household characteristics encompassed elements such as amenities, electricity access, cooking fuel type, and animal ownership.

Water removal from a storage container was evaluated using direct observation. Safe water removal was defined as water transfer through methods such as pouring from a storage container, using a spigot or tap, or using a long ladle. It did not include water transfer using a cup, jar, hands, or other container.

The questionnaire was translated into local languages (Table 1) and verified through back-translation into English. Sample interviews were conducted in each country and questionnaires were revised based on the results of the sample interviews. The same closed-form household survey was used in all the study countries.

2.4. Data collection

Data was collected from June 2014 to January 2015. The selection of enumerators and supervisors, their training in data collection, and their roles and responsibilities have been previously described (Morgan et al., 2017). Enumerators conducted surveys with the female heads of selected households in the local language and revisited households up to four times to collect survey responses. This method was adopted from the Global Adult Tobacco Survey (WHO, 2012) to yield the highest possible response rate. Household interviews consisted of enumerators reading each survey question and recording the results on paper during data collection in Ghana, Malawi, Niger, Rwanda, Uganda, and Zambia. Double data entry in an electronic database was conducted at a later time. In Mozambique, data were directly recorded on a handheld electronic device.

Household drinking water samples were taken from water storage containers and collected using sterile Whirl-pak® bags (Nasco, Modesto, California). Water samples were either immediately tested that day in a remote lab or stored on ice and tested off-site that same day. Each water sample was enumerated for *E. coli*, which was used as an indicator of fecal contamination from humans and animals. Aquagenx Compartment Bag Tests were used to quantify *E. coli* colony forming units (cfu) per 100 mL in Mozambique and Uganda using previously described methods (Stauber et al., 2014). Household water samples obtained from Ghana, Malawi, Niger, Rwanda, and Zambia were analyzed by national, certified laboratories and tested for *E. coli* cfu/100 mL.

2.5. Data entry and analysis

Survey answers were coded as categorical variables for all household survey responses (except for mean hours of available water service per day and per week during the dry season). Direct observations of drinking water removal and drinking water sample risk levels based on *E. coli* concentrations were also coded categorically. Risk levels were based off of classifications set by the WHO and included low risk (<1 *E. coli* cfu/100 mL), intermediate risk (1–10 *E. coli* cfu/100 mL), high risk (11–100 *E. coli* cfu/100 mL), and very high risk (>100 *E. coli* cfu/100 mL) (WHO, 2017).

2.6. Negative binomial regression model

We used a negative binomial regression model with survey sampling weights to evaluate potential predictors for household drinking water quality using *E. coli* concentrations as an indicator for fecal contamination. Additional predictors included whether the household was sampled from a WV PSU rather than a comparison PSU.

A bivariate analysis was conducted to reduce the number of potential risk factors for household drinking water *E. coli* contamination and covariates were included in our final models if they had a p-value of <0.10. Households and household drinking water samples with missing variables of interest were excluded from the model. Interaction terms were evaluated on the additive and multiplicative scales with examination of the Wald tests and computation of marginal effects. Incidence rate ratios (IRRs) and 95% confidence intervals (CIs) were generated for predictors of *E. coli* in household drinking water, which were used to measure a given exposure and to estimate the relative risk of the odds ratio if the occurrence was rare. Measurement of the incidence rate of an event was calculated by dividing the incidence rate among the exposed proportion of the population by the incidence rate among the unexposed proportion of the population. Results from the main effect analysis and stratum-specific effects where interaction was observed are presented. All statistical analyses were conducted using SAS 9.4 (SAS Institute Inc., Cary, NC, USA) and STAT 15.1 (StataCorp, College Station, TX, USA).

3. Results

3.1. Household and water samples

A total of 18,747 households (9,374 WV households and 9,373 comparison households) were surveyed and a total of 3,848 household water samples (1,906 WV samples and 1,942 comparison samples) were obtained from rural districts and departments throughout Ghana, Malawi, Mozambique, Niger, Rwanda, Uganda, and Zambia from June 2014 to January 2015. Based on a target sample size of 2,750 rural households per country, the mean collection rate of household interviews across all seven countries was 97% (Table 2). This ranged from an 86% household survey collection rate in Ghana to a 102% household survey collection rate in Zambia. Based on a target sample size of 550 drinking water samples per country, the mean collection rate of water samples across all seven countries was 100%. This ranged from an 84% water sample collection rate in Ghana to a 120% water sample collection rate in Niger. Demographic data did not differ significantly between WV and comparison households when comparing household characteristics such as amenities, electricity access, cooking fuel type, and animal ownership.

3.2. WaSH results

When analyzing the WV and comparison households collectively, more than 50% of primary drinking water source types used year-round by households were classified as an improved across all countries. This ranged from 51% of households in Mozambique to 76% of households in Ghana and Malawi (Table 3). When looking at water source type data by season, the primary improved-type water source used by most households during the rainy and dry season was a borehole with a hand pump in Ghana (rainy: 70%, dry: 72%), Malawi (rainy: 73%, dry: 72%), Mozambique (rainy: 38%, dry: 39%), Uganda (rainy: 50%, dry: 51%), and Zambia (rainy: 62%, dry: 63%) (Supplemental Table 1). A public tap was the improved-type water source type used by most households during both the rainy and dry season in Niger (rainy: 36%, dry: 36%) and Rwanda (rainy: 29%, dry: 30%). The proportion of respondents who reported taking more than 30 minutes round trip to collect their drinking water ranged from 26% (Niger) to 64% (Uganda) of households

Table 2
Number of rural household surveys (n = 18,747) and drinking water samples (n = 3,848) collected in each country, 2014–2015.

Region	Country		Household Surveys (n = 18,747)	Water Samples (n = 3,848)
Western	Ghana	WV	1,203	236
		Co	1,175	224
		Total	2,378	460
		Collection rate (%)	86	84
	Niger	WV	1,289	303
		Co	1,314	357
		Total	2,603	660
		Collection rate (%)	95	120
Southern	Malawi	WV	1,384	274
		Co	1,380	276
		Total	2,764	550
		Collection rate (%)	101	100
	Mozambique	WV	1,399	283
		Co	1,372	279
		Total	2,771	562
		Collection rate (%)	101	102
Eastern	Rwanda	WV	1,331	280
		Co	1,369	280
		Total	2,700	560
		Collection rate (%)	98	102
	Uganda	WV	1,364	261
		Co	1,363	248
		Total	2,727	509
		Collection rate (%)	99	93
	Zambia	WV	1,404	269
		Co	1,400	278
		Total	2,804	547
		Collection rate (%)	102	99

WV: World Vision.
Co: comparison.
Household survey collection rate (%) calculated based on a target sample size of 2,750 households per country.
Water sample collection rate (%) calculated based on a target sample size of 550 water samples per country.

in each country. Sufficient water supply was a challenge for some households; 79% of respondents in Uganda, 87% in Rwanda, and 90% in Mozambique reported that they collected less than 20 liters of water per person per day. The proportion of respondents who reported that they covered their stored water ranged from 64% (Malawi) to 91% (Zambia) of households in each country and the proportion of respondents who reported having a wide-mouthed water storage container ranged from 3% (Rwanda) to 76% (Malawi) of households in each country. Respondents in Mozambique and Ghana had the lowest proportion of households that treated their drinking water (3% and 6%, respectively), whereas Rwanda had the highest (62%).

In terms of water continuity, more than 50% of household respondents in all seven countries reported that they had continuous 24 hour per day water service during the dry season. This ranged from 51% of households in Niger to 86% of households in Ghana. Respondents in Rwanda and Zambia reported the lowest mean hours per week of available water service during the dry season (143 hours per week or 20 hours per day), while respondents in Niger reported the highest (168 hours per week or 24 hours per day). Three to 33% of respondents in Ghana, Malawi, Mozambique, Rwanda, Uganda, and Zambia reported that their primary household water point had broken down in the preceding two weeks (respondents in Niger were not asked this survey question). The proportion of respondents who reported the presence of a water committee for their primary drinking water source ranged from 28% (Rwanda) to 80% (Ghana). When asked if they paid for drinking water service, 19% (Ghana) to 54% (Zambia) of respondents in each country reported that they did.

Across all seven countries, 80% (Malawi) to 97% (Mozambique) of household respondents in each country reported always or sometimes having soap or ash at their handwashing points as opposed to never having it present. The lowest proportion of respondents who reported having an improved-type sanitation facility were in Ghana (8%), Mozambique (9%), and Niger (9%), while the highest proportion of respondents were in Rwanda (60%).

The majority of household respondents across all countries reported having no formal education or primary education as their highest level of education. This ranged from 69% of respondents in Zambia to 96% of respondents in Mozambique.

None of the of household respondents in Ghana, Malawi, or Zambia were observed safely removing their drinking water from a storage container. However, 1% of respondents in Uganda, 10% of respondents in Niger, 56% of respondents in Mozambique, and 59% of respondents in Rwanda did so.

More than 70% of the household water samples collected in Malawi (74%), Rwanda (81%), and Zambia (86%) were classified as low risk based on *E. coli* risk categorization (Fig. 2). Of the water samples collected, 2% in Zambia, 9% in Rwanda, 12% in Malawi, 18% in Niger, 47% in Mozambique, 61% in Uganda, and 74% in Ghana were classified as high risk. A proportion of water samples collected from households in Rwanda (2%), Ghana (4%), Malawi (5%) and Niger (43%) were classified as very high risk.

3.3. Negative binomial regression model

A total of 3,726 households and household drinking water samples were included in our model. Sampled Mozambican households with an improved-type primary water source compared to households with an unimproved-type primary water source had 0.42 (95% CI: 0.30, 0.61) times the incidence rate of *E. coli* (Table 4). Of the household water samples collected in Niger, households that stored drinking water in wide-mouthed containers had 1.56 (95% CI: 1.13, 2.16) times the incidence rate of *E. coli* compared to households that stored water in either narrow-mouthed containers or containers with spigots. Sampled households in Ghana that had continuous 24 hour per day water service during the dry season had 0.92 (95% CI: 0.87, 0.97) times the incidence rate of *E. coli* compared to households that did not have continuous 24 hour per day water service during the dry season. Sampled households in Rwanda that paid for water service had 0.06 (95% CI: 0.02, 0.22) times the incidence rate of *E. coli* compared to households that did not pay for their household water service.

Mozambican households with handwashing points that always or sometimes had soap or ash had 0.59 (95% CI: 0.40, 0.87) times the incidence rate of *E. coli* compared to households that never had soap or ash. In Malawi, households that had an improved-type sanitation facility had 0.34 (95% CI: 0.12, 0.94) times the incidence rate of *E. coli* compared to households in Malawi with an unimproved-type sanitation facility.

Household respondents' highest education levels were predictive of *E. coli* incidence rates in Niger and Zambia. In Niger, female heads of households with no formal education or a primary school education had household water samples with 1.56 (95% CI: 1.28, 1.89) times the incidence rate of *E. coli* in their drinking water compared to female heads of households who attended a secondary school, technical institute, or university as their highest level of education. Zambian female heads of households with no formal education or a primary school education had household water samples that had 11.64 (95% CI: 4.21, 32.01) times the incidence rate of *E. coli* compared to female heads of households who attended a secondary school, technical institute, or university as their highest level of education.

When comparing WV households to comparison households,

Table 3
Household survey responses (n = 18,747) and drinking water sample risk categorization (n = 3,848) by country, 2014–2015.

			Ghana	Malawi	Mozambique	Niger	Rwanda	Uganda	Zambia
Household Survey		Sample Size	2,378	2,764	2,771	2,603	2,700	2,727	2,804
Water Source (%)	Dry season	Improved-type	80	77	51	53	58	74	77
		Unimproved-type	20	23	49	47	42	26	23
	Rainy season	Improved-type	80	78	52	53	67	73	76
		Unimproved-type	20	22	48	47	33	27	24
	Year-round	Improved-type	76	76	51	59	53	69	67
		Unimproved-type	24	24	49	41	47	31	33
Water Access (%)	Round-trip collection time	≤30 Min	62	54	53	74	53	36	69
		>30 Min	38	46	47	26	47	64	31
Water Supply (%)	Amount of available water	≤20 l/p/d	36	56	90	36	87	79	60
		>20 l/p/d	64	44	10	64	13	21	40
Water Storage (%)	Presence of covered stored water	Yes	70	64	74	87	73	88	91
		No	30	36	26	13	27	12	9
	Storage container type	Wide-mouthed	74	76	49	32	3	45	52
		Narrow-mouthed	20	22	51	33	96	53	48
		Container with spigot	4	2	0	1	1	1	0
		Multiple	2	0	0	34	0	1	0
Water Treatment (%)	Use of boiling, filtration, chlorine, or other	Yes	6	20	3	29	62	36	25
		No	94	80	97	71	38	64	75
Water Continuity	Continuous 24 hour per day water service during the dry season (%)	Yes	86	69	77	51	79	82	81
		No	13	31	23	48	21	18	19
	Mean hours of available water service during the dry season	Mean hours per day	22	21	21	24	20	22	20
		Mean hours per week	154	147	148	168	143	151	143
Water Reliability (%)	Primary household water point broke down in the past two weeks	Yes	18	33	3	NA	17	15	6
		No	81	67	97	NA	83	85	93
Sustainability of Water Access (%)	Presence of a water committee	Yes	80	78	39	47	28	68	59
		No	20	22	61	53	72	31	41
	Pay for water service	Yes	19	26	37	45	37	50	54
		No	80	74	61	54	63	50	46
Hygiene and Sanitation (%)	Presence of soap or ash at handwashing points	Always	51	26	29	24	38	28	46
		Sometimes	43	54	68	71	53	54	44
		Never	5	21	3	5	9	18	10
	Improved-type sanitation facility	Yes	8	28	9	9	60	34	22
		No	92	72	91	91	40	66	78
Respondent Demographics (%)	Highest education level of respondent	No formal education	71	9	0	82	1	13	6
		Primary	17	77	96	13	88	70	63
		Secondary	10	13	3	5	8	14	28
		Technical institute	1	0	0	0	1	2	2
		University	1	0	1	0	2	1	1
Safe Water Removal (%)	Pouring from a storage container, use of a spigot or tap, or use of a long ladle	Yes	0	0	56	10	59	1	0
		No	100	100	44	90	41	99	100
Water Samples		Sample Size	460	550	562	660	560	509	547
Water Quality (%)	*E. coli* cfu/100 mL	Low risk (<1)	12	74	24	10	81	7	86
		Intermediate risk (1–10)	10	9	28	29	7	33	12
		High risk (11–100)	74	12	47	18	9	61	2
		Very high risk (>100)	4	5	0	43	2	0	0

Percentages were rounded to the nearest whole number for simplicity, so any groups that do not add to exactly 100 are due to rounding.

Ugandan households sampled in the WV area had 1.49 (95% CI: 1.05, 2.12) times the incidence rate of *E. coli* compared to households sampled in the comparison area. A similar finding was found in sampled Zambian households, where households located in the WV area had 2.41 (95% CI: 1.14, 5.12) times the incidence rate of *E. coli* compared to households sampled in the comparison area.

4. Discussion

In this study, one of the larger studies of household microbial drinking water quality to date, a total of 18,747 surveys were conducted and 3,848 water samples were collected from rural households in Ghana, Malawi, Mozambique, Niger, Rwanda, Uganda, and Zambia. More than 50% of households across all of the study countries used an improved-type water source during the rainy and dry season. Additionally, more than 50% of households across all the study countries, except Uganda, reported having access to their primary drinking water source within 30 minutes round trip. However, household water supply remained insufficient for many households across all of the countries. A water fee for service, which can help provide funds for water source operation and maintenance costs, was also not common across the study countries. Microbial drinking water quality varied across the countries: 61–78% of households in Ghana, Niger, and Uganda had high or very high risk water quality. WaSH predictors associated with safer household microbial drinking water quality based on *E. coli* enumeration varied by country and included: using an improved-type primary water source (Mozambique), storing water in a narrow-mouthed container or container with a spigot (Niger), having access to a continuous water service (Ghana), paying for water services (Rwanda), having soap or ash at handwashing points (Mozambique),

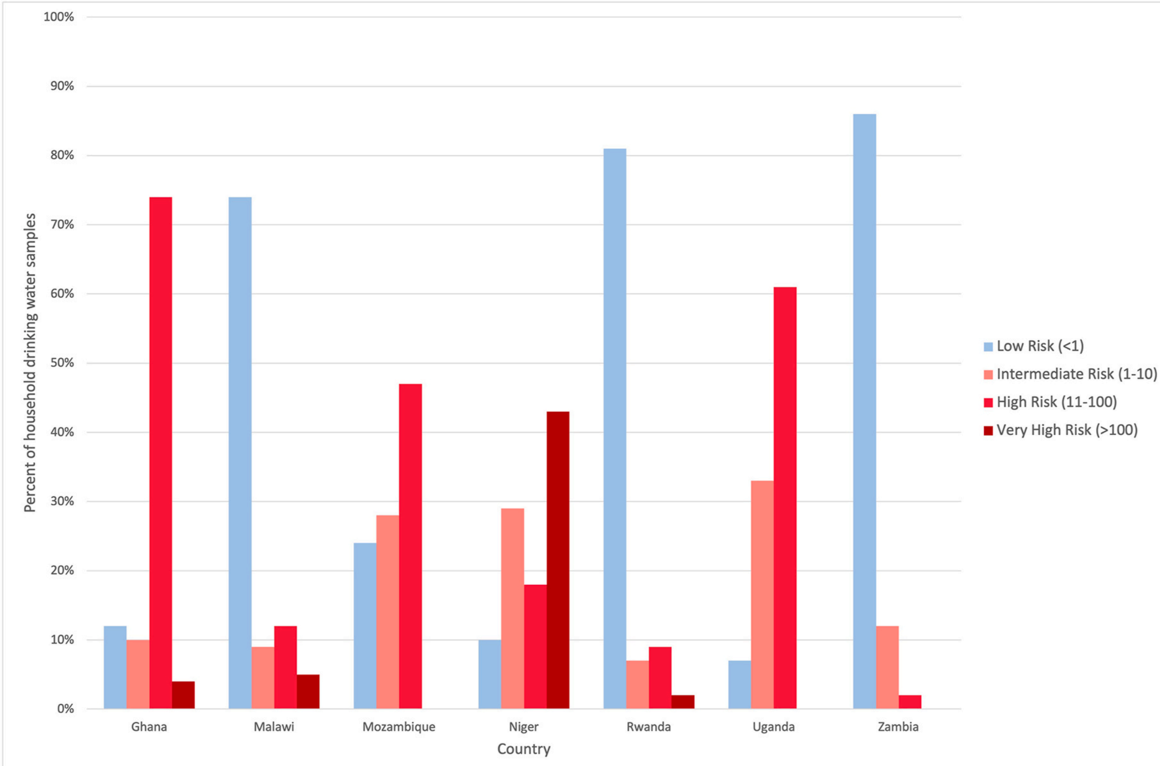

Fig. 2. Household drinking water sample risk categorization based on *E. coli* concentrations (cfu/100 mL) by country (n = 3,848), 2014-2015.

Table 4
Predictors of *E. coli* contamination in household drinking water by country (n = 3,726), 2014–2015.

	Ghana	Malawi	Mozambique	Niger	Rwanda	Uganda	Zambia
Sample Size	451	386	557	309	549	539	485
Predictor of *E. coli* contamination				IRR (95% CI)			
Households in WV PSUs	0.95 (0.56, 1.59)	0.71 (0.33, 1.53)	0.84 (0.57, 1.25)	0.92 (0.72, 1.18)	2.83 (0.90, 8.90)	**1.49 (1.05, 2.12)**	**2.41 (1.14, 5.12)**
Improved-type primary water source	1.11 (0.72, 1.69)	0.74 (0.31, 1.77)	**0.42 (0.30, 0.61)**	1.09 (0.76, 1.58)	2.52 (1.00, 6.38)	0.91 (0.67, 1.23)	0.58 (0.15, 2.27)
Covered water storage container	0.78 (0.48, 1.28)	–	1.43 (0.99, 2.05)	–	–	0.80 (0.56, 1.14)	–
Wide-mouthed water storage container	1.22 (0.89, 1.67)		0.91 (0.60, 1.38)	**1.56 (1.13, 2.16)**	–	1.04 (0.78, 1.38)	0.63 (0.30, 1.31)
Treated water	0.82 (0.57, 1.18)	–	1.39 (0.83, 2.33)	–	–	1.14 (0.86, 1.50)	–
Continuous 24 hour per day water service during the dry season	**0.92 (0.87, 0.97)**	–	–	–	1.14 (0.96, 1.35)	1.02 (0.99, 1.06)	1.11 (1.00, 1.24)
Water committee presence for primary drinking water source	–	–	0.92 (0.51, 1.68)	–	0.63 (0.20, 1.94)	–	–
Pay for water service	1.01 (0.75, 1.36)	–	1.63 (0.94, 2.83)	–	**0.06 (0.02, 0.22)**	–	0.69 (0.21, 2.24)
Presence of soap and ash (always or sometimes) at handwashing points	0.84 (0.56, 1.25)	–	**0.59 (0.40, 0.87)**	–	0.87 (0.24, 3.15)	1.16 (0.70, 1.91)	–
Improved-type sanitation facility	0.68 (0.46, 1.00)	**0.34 (0.12, 0.94)**	–	–	–	1.46 (0.98, 2.16)	–
Highest education level of respondent (primary school education or no formal education)	0.66 (0.47, 0.93)	–	–	**1.56 (1.28, 1.89)**	–	–	**11.64 (4.21, 32.01)**
Observed safe water removal	0.10 (0.01, 1.38)	–	0.80 (0.58, 1.10)	–	1.03 (0.34, 3.14)	–	–
Mean cluster-level E. coli	–	–	–	1.00 (1.00, 1.00)	1.00 (1.00, 1.01)	–	–

WV: World Vision.
PSU: primary sampling unit.
IRR: incidence rate ratio.
CI: confidence interval.
Bolded cells indicate statistically significant values (null value of 1.00 is not in the 95% CI).

having an improved-type sanitation facility (Malawi), and attaining a level of education greater than primary school (Niger and Zambia). Due to the breadth of this study's sample size and its extension over multiple rural areas in multiple countries, these findings suggest that the relationship between WaSH services, WaSH behaviors, and household microbial drinking water quality may vary by country.

Most of the respondents across all seven countries reported using an improved-type primary water source year-round (51–76%), with similar reported proportions of an improved-type primary water source used during the rainy and dry season. Previous research has reported that drinking water sources vary with the season (Kumpel et al., 2016), while other studies have found that seasonal variation in drinking water sources is not common (Nguyen et al., 2020). The results of our study could be due to our household survey being conducted in a single season as opposed to across many seasons. Only in Mozambique, however, was the use of an improved-type primary water source a statistically significant predictor of safer microbial drinking water quality, an association observed in rural healthcare facilities and schools in similar locations to the households sampled in this study (Guo and Bartram, 2019; Morgan et al., 2021). Improved-type drinking water sources are engineered and designed to provide safe drinking water and to prevent microbial contamination (WHO/UNICEF, n.d.). However, studies have also shown that the presence of an improved-type water source does not necessarily ensure that the water is free of fecal matter (Aiga et al., 2022; Baum et al., 2013; Heitzinger et al., 2015). A study by Alemayehu et al. (2020) also found that the bacterial load of *E. coli* and enterococci between improved-type water sources (boreholes, caped springs, and shallow wells) in Ethiopia greatly varied. The primary improved-type water source for respondents in Ghana, Malawi, Mozambique, Uganda, and Zambia during the rainy and dry season was a borehole with a hand pump (38–73%). While this water source type has been shown to be associated with a reduced risk of fecal contamination, *E. coli* contamination can still occur during water transport, storage, or removal from storage (Larson et al., 2023; Lutterodt et al., 2018).

Water storage in a narrow-mouthed container or the use of a container with a spigot predicted safer microbial drinking water quality in Nigerian households, as households with stored drinking water without these components had an increased incidence rate of *E. coli*. A study by Larson et al. (2023) had similar findings, reporting that among 314 households in Cajamarca, Peru, household water samples obtained from narrow-mouthed containers had a lower likelihood of thermotolerant coliform contamination in comparison to water samples obtained from wide-mouthed containers. A narrower mouth on a water storage container could be associated with lower rates of fecal contamination due to the decreased surface area as well as the reduced ability to withdraw water using one's hand (Amenu et al., 2016).

Between 51 and 86% of respondents in each country reported having access to continuous 24 hour per day water service during the dry season. However, this WaSH factor was a statistically significant predictor of safer microbial drinking water only in Ghanian households. A study that examined the water quality of 405 rural households in Limpopo province, South Africa had similar findings and found that households with continuous access to treated water inside the household or nearby had fewer total coliforms in their stored water than households that lacked a continuous water supply (Edokpayi et al., 2018). Studies on water continuity suggest that intermittent water supply contributes to the increased prevalence of indicators of fecal contamination (Kumpel and Nelson, 2013). Furthermore, an intermittent water supply is associated with increased rates of water storage, a factor that can also increase the risk of microbial drinking water quality contamination (Bivins et al., 2021; García-Betancourt et al., 2015; Kumpel and Nelson, 2015; Salehi, 2021). In our study, this association could be related to knowledge of the dry season duration in Ghana (Armstrong et al., 2022). Knowing when the dry season will end could result in individuals being less likely to store large quantities of their drinking water, reducing the risk of microbial contamination that is correlated with drinking water storage and removal.

Across the seven countries, 46–80% of the respondents reported that they did not pay for their water service. Payment for water service was found to be a predictor of safer microbial drinking water quality only in Rwandan households, where 37% of surveyed household members reported paying for their water service. This association could be due to increased functional stability of the water system where community members are expected to financially contribute to its operation and maintenance (Foster et al., 2012). Studies have found that income influences payment for water service in South Africa (Akinyemi et al., 2018). Additionally, Hope and Ballon (2019) found that higher payments are associated with faster water system repair times and that women with higher educational backgrounds are more willing to pay for safer water quality in Kenya.

Education levels of household respondents in Niger and Zambia had a statistically significant association with safer microbial drinking water in our study. In both countries, female heads of households who had no formal education or whose highest level of education was primary school had greater *E. coli* incidence rates in their drinking water compared to respondents who attained higher levels of education. Individuals who have access to education may be more likely to prioritize access to a safe drinking water source (Osei et al., 2015), have more knowledge of safe WaSH practices (Ssemugabo et al., 2019), or possess greater wealth (Zoungrana, 2020). Previous research has found an association between higher education levels of female heads of households and reduced fertility, decreased child mortality, decreased diarrheal diseases, and improved child nutrition (Demissie et al., 2021; Gakidou et al., 2010; Miller et al., 2017). However, few studies have looked at the association between education levels of female heads of households and safer microbial drinking water quality. This relationship could be further explored in future research.

Presence of soap and ash at handwashing points among households in Mozambique and improved-type sanitation facilities among households in Malawi were found to have a statistically significant association with safer microbial drinking water. This is consistent with the previously mentioned study by Morgan et al. (2021), which found that the presence of soap or ash at handwashing stations in Mozambican and Ugandan rural schools was associated with a lower incidence rate of *E. coli* in the schools' drinking water. Our study's finding may be due to individuals living in households that do not practice safe hygiene and sanitation similarly not engaging in safe drinking water practices (Shrestha et al., 2020; Sibiya and Gumbo, 2013). A lack of safe hygiene and sanitation practices has also been associated with increased *E. coli* contamination in stored drinking water (Wispriyono et al., 2021). Mulenga et al. (2017) examined households in Zambia and found that access to improved-type water sources and sanitation facilities was positively correlated with financial wealth, suggesting that there could be a socioeconomic component to our findings in Mozambique and Malawi.

Ugandan and Zambian households sampled in the WV area where WaSH programming had occurred had 1.49 and 2.41 times the incidence rate of *E. coli* in their drinking water, respectively, than households sampled in the comparison area. It is possible that the comparison areas had WaSH programming and interventions conducted by governmental or other non-governmental organizations.

Two previous studies have examined predictors of household drinking water quality across multiple countries. A cross-sectional study by Bain et al. (2021) analyzed household surveys from 27 low- and middle-income countries to examine risk factors for *E. coli* contamination in household drinking water. Similar to our results, they reported that the majority of surveyed households (84%) used an improved-type drinking water source and that an improved-type water source was associated with a lower prevalence of *E. coli*. A cross-sectional study by Fejfar et al. (2024) analyzed predictors of *E. coli* in 4,499 household water samples across nine sub-Saharan African countries (Malawi, Mozambique, Zambia, Ghana, Mali, Niger, Kenya, Rwanda, and

Tanzania) using elimination regression. Similar to our findings in Mozambique, Fejfar et al. reported that an unimproved-type water source was associated with *E. coli* contamination in their pooled model. In the reduced models that looked at regional African Union (AU) groupings, researchers found that factors associated with greater odds of *E. coli* contamination included a lower education level in the Southern AU region (Malawi, Mozambique, and Zambia) as well as a wide-mouthed water storage container and absence of water service payment in the Eastern AU region (Kenya, Rwanda, and Tanzania).

Using *E. coli* concentration as an indicator for fecal contamination of drinking water, we analyzed predictors of *E. coli* contamination at the country level. This was done to avoid bias by cross-level interactions, such as country wealth, due to the small number of countries included in our sample, as previous research has cited that a sample size of less than 50 can lead to biased estimates (Giesselmann and Schmidt-Catran, 2018; Maas and Hox, 2005; Stegmueller, 2013). Furthermore, country differences regarding WaSH, economic, and social factors were difficult to control for as this research was conducted in only some of the rural areas of the countries we studied. Therefore, our results do not represent the entire country or all of the rural areas in each country (Supplemental Table 2). Cultural differences between countries, along with variations in economies and policies, could contribute to some of the differences seen in microbial water quality predictors (World Bank Group, 2022).

4.1. Limitations

As this was a cross-sectional survey, we do not capture the variability in water source use and *E. coli* concentrations in household drinking water sources across time. Seasonality, precipitation specifically, has been shown to be associated with *E. coli* contamination of drinking water (Fejfar et al., 2024; Sokolova et al., 2021; Robert et al., 2021). Future water quality studies could collect multiple drinking water samples and sources from rural households throughout the year to assess the variability of water quality over time and its relationship to WaSH predictors. Answers to household interview questions were also self-reported, which could have introduced measurement error of the predictors. The same closed-form household survey was used across all countries, enabling data pooling and analysis, but precluding responses outside those that were predefined.

Aside from investigating characteristics such as the presence of an improved-type water source or sanitation facility, other hardware investments, such as infrastructural or technological components of water sources, were not examined. Additionally, while we analyze the presence of water committees and user fees, other software investments, such as training in water source administration, operation, and financial management (George-Williams et al., 2024; Sonego et al., 2013), were not examined. These areas could be assessed in future water quality research.

5. Conclusion

In this large study of 18,747 households across Ghana, Malawi, Mozambique, Niger, Rwanda, Uganda, and Zambia, we investigate rural household WaSH access and the factors that predict microbial drinking water quality in a subset of 3,726 households. We found that further attention is needed in all rural areas of study on improving water quantity and sustainable water service through the presence of water service fees. This is one of only a few studies to examine microbial water quality predictors of rural households in multiple countries. We did not observe the same WaSH attributes to predict microbial drinking water quality across all countries; instead, we found that individual attributes stood out by country. Our results highlight the association between female head of household education level and microbial drinking water quality in Niger and Zambia, a topic that should be explored in future research. With a standardized approach across multiple countries, this study highlights the variability in rural household WaSH access, particularly in association with microbial drinking water quality.

CRediT authorship contribution statement

Audrey R. Yang: Writing – review & editing, Writing – original draft, Resources, Project administration, Conceptualization. **James M. Bowling:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Camille E. Morgan:** Writing – review & editing, Writing – original draft, Methodology. **Jamie Bartram:** Writing – review & editing. **Georgia L. Kayser:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Georgia Kayser reports financial support was provided by National Institute of Environmental Health Sciences. Pete Kolsky (listed in acknowledgments) reports financial support was provided by World Vision International. Co-author currently serving on the editorial board for the International Journal of Hygiene and Environmental Health - Jamie Bartram If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2024.114507.

References

Aiga, H., Nomura, M., Mahomed, M., Langa, J.P.M., 2022. Microbiological contamination of improved water sources, Mozambique. Bull. World Health Organ. 100 (9), 534–543. https://doi.org/10.2471/BLT.22.288646.

Akinyemi, B.E., Mushunje, A., Fashogbon, A.E., 2018. Factors explaining household payment for potable water in South Africa. Cogent Social Sciences 4 (1), 1464379. https://doi.org/10.1080/23311886.2018.1464379.

Alemayehu, T.A., Weldetinsae, A., Dinssa, D.A., Derra, F.A., Bedada, T.L., Asefa, Y.B., Mengesha, S.D., Alemu, Z.A., Serte, M.G., Teklu, K.T., Woldegabriel, M.G., Kenea, M. A., van den Berg, H., de Roda Husman, A.M., 2020. Sanitary condition and its microbiological quality of improved water sources in the Southern Region of Ethiopia. Environ. Monit. Assess. 192 (5). https://doi.org/10.1007/s10661-020-08297-z.

Amenu, K., Shitu, D., Abera, M., 2016. Microbial contamination of water intended for milk container washing in smallholder dairy farming and milk retailing houses in southern Ethiopia. SpringerPlus 5 (1). https://doi.org/10.1186/s40064-016-2841-x.

Armstrong, A., Dyer, E., Koehler, J., Hope, R., 2022. Intra-seasonal rainfall and piped water revenue variability in rural Africa. Global Environ. Change 76, 102592. https://doi.org/10.1016/j.gloenvcha.2022.102592.

Bain, R., Cronk, R., Wright, J., Yang, H., Slaymaker, T., Bartram, J., 2014. Fecal contamination of drinking-water in low- and middle-income countries: a systematic review and meta-analysis. PLoS Med. 11 (5), e1001644. https://doi.org/10.1371/journal.pmed.1001644.

Bain, R., Johnston, R., Khan, S., Hancioglu, A., Slaymaker, T., 2021. Monitoring drinking water quality in nationally representative household surveys in low- and middle-income countries: cross-sectional analysis of 27 multiple indicator cluster surveys 2014–2020. Environmental Health Perspectives 129 (9). https://doi.org/10.1289/ehp8459.

Baum, R., Stauber, C., Sobsey, M., Kayser, G., 2013. Assessing the microbial quality of improved drinking water sources: results from the Dominican republic. Am. J. Trop. Med. Hyg. 90 (1), 121–123. https://doi.org/10.4269/ajtmh.13-0380.

Bivins, A., Lowry, S., Wankhede, S., Hajare, R., Murphy, H.M., Borchardt, M., Labhasetwar, P., Brown, J., 2021. Microbial water quality improvement associated with transitioning from intermittent to continuous water supply in Nagpur, India. Water Res. 201, 117301. https://doi.org/10.1016/j.watres.2021.117301.

Brown, J., Cairncross, S., Ensink, J.H., 2013. Water, sanitation, hygiene and enteric infections in children. Arch. Dis. Child. 98 (8), 629–634. https://doi.org/10.1136/archdischild-2011-301528.

Cairncross, S., Hunt, C., Boisson, S., Bostoen, K., Curtis, V., Fung, I., Schmidt, W.-P., 2010. Water, sanitation and hygiene for the prevention of diarrhoea. Int. J. Epidemiol. 39. https://doi.org/10.1093/ije/dyq035.

Daniel, D., Djohan, D., Nastiti, A., 2021. Interaction of factors influencing the sustainability of water, sanitation, and hygiene (WASH) services in rural Indonesia: evidence from small surveys of wash-related stakeholders in Indonesia. Water 13 (3), 314. https://doi.org/10.3390/w13030314.

Demissie, G.D., Yeshaw, Y., Aleminew, W., Akalu, Y., 2021. Diarrhea and associated factors among under five children in sub-Saharan Africa: evidence from demographic and health surveys of 34 sub-Saharan countries. PLoS One 16 (9), e0257522. https://doi.org/10.1371/journal.pone.0257522.

Edokpayi, J.N., McQuade, E.T.R., Kahler, D.M., Hill, C.A., Reynolds, C., Nyathi, E., Odiyo, J.O., Samie, A., Bessong, P.O., Dillingham, R., 2018. Challenges to sustainable safe drinking water: a case study of water quality and use across seasons in rural communities in Limpopo province, South Africa. Water 10 (2), 159. https://doi.org/10.3390/w10020159.

Fejfar, D., Tracy, W., Kelly, E., Moffa, M., Bain, R., Bartram, J., Anderson, D., Cronk, R., 2024. Identifying predictors of E. coli in rural household water in sub-Saharan Africa using elimination regression. Environ. Sci. J. Integr. Environ. Res.: Water Research and Technology 10 (5), 1147–1159. https://doi.org/10.1039/d3ew00915g.

Field, K.G., Samadpour, M., 2007. Fecal source tracking, the indicator paradigm, and managing water quality. Water Res. 41 (16), 3517–3538. https://doi.org/10.1016/j.watres.2007.06.056.

Foster, T., Hope, R., Thomas, M., Cohen, I., Krolikowski, A., Nyaga, C., 2012. Impacts and implications of mobile water payments in East Africa. Water Int. 37 (7), 788–804. https://doi.org/10.1080/02508060.2012.738409.

Gakidou, E., Cowling, K., Lozano, R., Murray, C.J., 2010. Increased educational attainment and its effect on child mortality in 175 countries between 1970 and 2009: a systematic analysis. Lancet 376 (9745), 959–974. https://doi.org/10.1016/s0140-6736(10)61257-3.

García-Betancourt, T., Higuera-Mendieta, D.R., González-Uribe, C., Cortés, S., Quintero, J., 2015. Understanding water storage practices of urban residents of an endemic dengue area in Colombia: perceptions, rationale and Socio-Demographic Characteristics. PLoS One 10 (6), e0129054. https://doi.org/10.1371/journal.pone.0129054.

George-Williams, H.E.M., Hunt, D.V.L., Rogers, C.D.F., 2024. Sustainable water infrastructure: visions and options for sub-saharan Africa. Sustainability 16 (4), 1592. https://doi.org/10.3390/su16041592.

Giesselmann, M., Schmidt-Catran, A.W., 2018. Getting the within estimator of cross-level interactions in multilevel models with pooled cross-sections: why country dummies (sometimes) do not do the job. Socio. Methodol. 49 (1), 190–219. https://doi.org/10.1177/0081175018809150.

Guo, A.Z., Bartram, J.K., 2019. Predictors of water quality in rural healthcare facilities in 14 low- and middle-income countries. J. Clean. Prod. 237, 117836. https://doi.org/10.1016/j.jclepro.2019.117836.

Heitzinger, K., Rocha, C.A., Quick, R.E., Montano, S.M., Tilley Jr., D.H., Mock, C.N., Carrasco, A.J., Cabrera, R.M., Hawes, S.E., 2015. "Improved" but not necessarily safe: an assessment of fecal contamination of household drinking water in rural Peru. Am. J. Trop. Med. Hyg. 93 (3), 501–508. https://doi.org/10.4269/ajtmh.14-0802.

Hope, R., Ballon, P., 2019. Global water policy and local payment choices in rural Africa. Npj Clean Water 2 (1). https://doi.org/10.1038/s41545-019-0045-y.

Kumpel, E., Cock Esteb, A., Duret, M., De Waal, D., Khush, R., 2016. Seasonal variation in drinking and domestic water sources and quality in Port Harcourt, Nigeria. Am. J. Trop. Med. Hyg. 96 (2), 437–445. https://doi.org/10.4269/ajtmh.16-0175.

Kumpel, E., Nelson, K.L., 2013. Comparing microbial water quality in an intermittent and continuous piped water supply. Water Res. 47 (14), 5176–5188. https://doi.org/10.1016/j.watres.2013.05.058.

Kumpel, E., Nelson, K.L., 2015. Intermittent water supply: prevalence, practice, and microbial water quality. Environmental Science & Technology 50 (2), 542–553. https://doi.org/10.1021/acs.est.5b03973.

Larson, A.J., Haver, S., Hattendorf, J., Salmon-Mulanovich, G., Riveros, M., Verastegui, H., Mäusezahl, D., Hartinger, S.M., 2023. Household-level risk factors for water contamination and antimicrobial resistance in drinking water among households with children under 5 in rural San Marcos, Cajamarca, Peru. One Health 16, 100482. https://doi.org/10.1016/j.onehlt.2023.100482.

Lutterodt, G., Van De Vossenberg, J., Hoiting, Y., Kamara, A., Oduro-Kwarteng, S., Foppen, J., 2018. Microbial groundwater quality status of Hand-Dug wells and boreholes in the Dodowa area of Ghana. Int. J. Environ. Res. Publ. Health 15 (4), 730. https://doi.org/10.3390/ijerph15040730.

Maas, C.J.M., Hox, J.J., 2005. Sufficient sample sizes for multilevel modeling. Methodology 1 (3), 86–92. https://doi.org/10.1027/1614-2241.1.3.86.

McDonald, R.I., Douglas, I., Revenga, C., Hale, R., Grimm, N., Grönwall, J., Fekete, B., 2011. Global Urban Growth and the geography of water availability, quality, and delivery. Ambio 40 (5), 437–446. https://doi.org/10.1007/s13280-011-0152-6.

Meierhofer, R., Bänziger, C., Deppeler, S., Kunwar, B., Bhatta, M., 2018. From water source to tap of ceramic filters—factors that influence water quality between collection and consumption in rural households in Nepal. Int. J. Environ. Res. Publ. Health 15 (11), 2439. https://doi.org/10.3390/ijerph15112439.

Miller, L.C., Joshi, N., Lohani, M., Rogers, B., Mahato, S., Ghosh, S., Webb, P., 2017. Women's education level amplifies the effects of a livelihoods-based intervention on household wealth, child diet, and child growth in rural Nepal. Int. J. Equity Health 16 (1). https://doi.org/10.1186/s12939-017-0681-0.

Morgan, C.E., Bowling, J.M., Bartram, J., Kayser, G.L., 2021. Attributes of drinking water, sanitation, and hygiene associated with microbiological water quality of stored drinking water in rural schools in Mozambique and Uganda. Int. J. Hyg Environ. Health 236, 113804. https://doi.org/10.1016/j.ijheh.2021.113804.

Morgan, C.E., Bowling, J.M., Bartram, J., Kayser, G.L., 2017. Water, sanitation, and hygiene in schools: status and implications of low coverage in Ethiopia, Kenya, Mozambique, Rwanda, Uganda, and Zambia. Int. J. Hyg Environ. Health 220 (6), 950–959. https://doi.org/10.1016/j.ijheh.2017.03.015.

Mulenga, J.N., Bwalya, B.B., Kaliba-Chishimba, K., 2017. Int. J. Dev. Sustain. 6 (8), 746–762.

Nguyen, K.H., Operario, D.J., Nyathi, M.E., Hill, C.L., Smith, J.A., Guerrant, R.L., Samie, A., Dillingham, R.A., Bessong, P.O., McQuade, E.T.R., 2020. Seasonality of drinking water sources and the impact of drinking water source on enteric infections among children in Limpopo, South Africa. Int. J. Hyg Environ. Health 231, 113640. https://doi.org/10.1016/j.ijheh.2020.113640.

Onda, K., LoBuglio, J., Bartram, J., 2012. Global access to safe water: accounting for water quality and the resulting impact on MDG progress. Int. J. Environ. Res. Publ. Health 9 (3), 880–894. https://doi.org/10.3390/ijerph9030880.

Osei, L., Amoyaw, J., Boateng, G.O., Boamah, S., Luginaah, I., 2015. The paradox of water accessibility: understanding the temporal and spatial dimensions of access to improved water sources in Rwanda. J. Water, Sanit. Hyg. Dev. 5 (4), 553–564. https://doi.org/10.2166/washdev.2015.029.

Pommells, M., Schuster-Wallace, C., Watt, S., Mulawa, Z., 2018. Gender violence as a water, sanitation, and hygiene risk: uncovering violence against women and girls as it pertains to poor wash access. Violence Against Women 24 (15), 1851–1862. https://doi.org/10.1177/1077801218754410.

Prüss, A., Kay, D., Fewtrell, L., Bartram, J., 2002. Estimating the burden of disease from water, sanitation, and hygiene at a global level. Environmental Health Perspectives 110 (5), 537–542. https://doi.org/10.1289/ehp.02110537.

Robert, E., Grippa, M., Nikiema, D.E., Kergoat, L., Koudougou, H., Auda, Y., Rochelle-Newall, E., 2021. Environmental determinants of E. coli, link with the diarrheal diseases, and indication of vulnerability criteria in tropical West Africa (Kapore, Burkina Faso). PLoS Neglected Trop. Dis. 15 (8), e0009634. https://doi.org/10.1371/journal.pntd.0009634.

Rufener, S., Mäusezahl, D., Mosler, H.-J., Weingartner, R., 2010. Quality of drinking-water at source and point-of-consumption - drinking cup as a high potential recontamination risk: a field study in Bolivia. J. Health Popul. Nutr. 28 (1). https://doi.org/10.3329/jhpn.v28i1.4521.

Salehi, M., 2021. Global water shortage and potable water safety; Today's concern and tomorrow's crisis. Environ. Int. 158, 106936. https://doi.org/10.1016/j.envint.2021.106936.

Shrestha, A., Six, J., Dahal, D., Marks, S., Meierhofer, R., 2020. Association of nutrition, water, sanitation and hygiene practices with children's nutritional status, intestinal parasitic infections and diarrhoea in rural Nepal: a cross-sectional study. BMC Publ. Health 20 (1). https://doi.org/10.1186/s12889-020-09302-3.

Sibiya, J., Gumbo, J., 2013. Knowledge, Attitude and Practices (KAP) survey on water, sanitation and hygiene in selected schools in Vhembe District, Limpopo, South Africa. Int. J. Environ. Res. Publ. Health 10 (6), 2282–2295. https://doi.org/10.3390/ijerph10062282.

Silvestri, G., Wittmayer, J., Schipper, K., Kulabako, R., Oduro-Kwarteng, S., Nyenje, P., Komakech, H., van Raak, R., 2018. Transition management for improving the sustainability of wash services in informal settlements in Sub-Saharan Africa—an exploration. Sustainability 10 (11), 4052. https://doi.org/10.3390/su10114052.

Sokolova, E., Ivarsson, O., Lillieström, A., Speicher, N.K., Rydberg, H., Bondelind, M., 2021. Data-driven models for predicting microbial water quality in the drinking water source using E. coli monitoring and hydrometeorological data. Sci. Total Environ. 802, 149798. https://doi.org/10.1016/j.scitotenv.2021.149798.

Sonego, I.L., Huber, A.C., Mosler, H., 2013. Does the implementation of hardware need software? A Longitudinal study on Fluoride-Removal Filter use in Ethiopia. Environmental Science & Technology 47 (22), 12661–12668. https://doi.org/10.1021/es402787s.

Ssemugabo, C., Wafula, S.T., Ndejjo, R., Oporia, F., Osuret, J., Musoke, D., Halage, A.A., 2019. Knowledge and practices of households on safe water chain maintenance in a slum community in Kampala City, Uganda. Environ. Health Prev. Med. 24 (1). https://doi.org/10.1186/s12199-019-0799-3.

Stauber, C., Miller, C., Cantrell, B., Kroell, K., 2014. Evaluation of the compartment bag test for the detection of Escherichia coli in water. J. Microbiol. Methods 99, 66–70. https://doi.org/10.1016/j.mimet.2014.02.008.

Stegmueller, D., 2013. How many countries for multilevel modeling? A comparison of Frequentist and Bayesian approaches. Am. J. Polit. Sci. 57 (3), 748–761. https://doi.org/10.1111/ajps.12001.

Too, J.K., Kipkemboi Sang, W., Ng'ang'a, Z., Ngayo, M.O., 2016. Fecal contamination of drinking water in Kericho District, western Kenya: role of source and household water handling and hygiene practices. J. Water Health 14 (4), 662–671. https://doi.org/10.2166/wh.2016.137.
Tsinda, A., Abbott, P., Chenoweth, J., Mucyo, S., 2021. Understanding the political economy dynamics of the water, sanitation and hygiene (WASH) sector in Rwanda. Int. J. Urban Sustain. Dev. 13 (2), 265–278. https://doi.org/10.1080/19463138.2021.1881787.
United Nations. (n.d.). Water and sanitation - united nations sustainable development. United Nations. Retrieved August 20, 2022, from https://www.un.org/sustainabledevelopment/water-and-sanitation/.
U.S. Environmental Protection Agency, 2012. 5.11 Fecal Bacteria. EPA. https://archive.epa.gov/water/archive/web/html/vms511.html.
USAID, 2012. Demographic and health survey model questionnaires. http://www.measuredhs.com/What-We-Do/Questionnaires.cfm.
WHO, 2012. Global Adult Tobacco Survey (GATS): Country Report [PDF file].
WHO, 2017. Guidelines for drinking-water quality. Fourth Edition Incorporating the First Addendum. https://iris.who.int/bitstream/handle/10665/254637/9789241549950-eng.pdf?sequence=1&isAllowed=y.
WHO, 2024. Improved Sanitation Facilities and Drinking-Water Sources. World Health Organization. https://www.who.int/data/nutrition/nlis/info/improved-sanitation-facilities-and-drinking-water-sources#:~:text=Improved/20drinking/2Dwater/20sources/20are,protected/20springs/20and/20rainwater/20collection.
WHO/UNICEF, 2006. Core questions on drinking-water and sanitation for household surveys. Geneva. https://iris.who.int/bitstream/handle/10665/43489/9789241563260_eng.pdf.
WHO/UNICEF. (n.d.). Drinking water. Joint Monitoring Programme. https://washdata.org/monitoring/drinking-water.
WHO/UNICEF, 2021. Progress on Household Drinking Water, Sanitation and Hygiene, 2000-2020: Five Years into the SDGs [PDF file].
Wispriyono, B., Arsyina, L., Ardiansyah, I., Pratiwi, L.D., Arminsih, R., Hartono, B., Nurmalasari, N., Novirsa, R., 2021. The role of hygiene and sanitation to the Escherichia coli contamination in drinking water in depok city, Indonesia. Open Access Macedonian Journal of Medical Sciences 9 (E), 641–644. https://doi.org/10.3889/oamjms.2021.6152.
World Bank Group, 2022. Overview. The world bank in Africa. from. https://www.worldbank.org/en/region/afr/overview. (Accessed 20 August 2022).
Zoungrana, T.D., 2020. The effect of wealth on the choice of household drinking water sources in West Africa. Int. J. Finance Econ. 26 (2), 2241–2250. https://doi.org/10.1002/ijfe.1903.