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The influence of seasonality and multiple water source use on household water service levels

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ABSTRACT

Universal access to safely managed drinking water (SMDW) is important for human health, well-being, and development. It is reflected in Sustainable Development Goal (SDG) 6. In rural areas of low- and middle-income countries, 1.9 billion people lack access to SMDW. Multiple water source use and seasonal source switching may negate health and development gains from SMDW. Hence, achieving SDG 6 requires a better understanding of how these factors relate to household service levels. We explored this using data from 37,105 household surveys and 6395 household drinking water samples collected from rural areas of 14 low- and middle-income countries (Ethiopia, Ghana, Honduras, India, Kenya, Malawi, Mali, Mozambique, Niger, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe). A different primary water source was used in the rainy and dry seasons by 10% of households; seasonal source switching was most common in Kenyan households (29%) and least common in Zambian households (3%). Twenty-three percent of households used a secondary water source, and 37% of these secondary sources were unimproved (e.g., unprotected dug wells and surface water). Sixty-nine percent of household water samples contained *E. coli*. In 11 of 14 countries studied, fecally contaminated water was the water service parameter preventing households from having SMDW free from fecal contamination at the point of use. Overall, 7% of households had access to SMDW free from contamination at the point of use. Our results confirm that the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation, and Hygiene (JMP) substantively overstate the population benefiting from safely managed drinking water, and their reporting statistics should be interpreted with caution. Seasonal source switching and secondary water source use have an important influence in some countries and should be accounted for in monitoring and programming activities.

1. Introduction

Safely managed drinking water (SMDW) services are essential for human health, development, and well-being (Bartram and Cairncross, 2010). Safely managed drinking water services are "improved" water sources (i.e., water sources that have the potential to deliver safe water based on their design and construction, such as piped water and protected dug wells) that are continuously available on the household premises, and are free of fecal (e.g., *E. coli*) and priority chemical (e.g., arsenic, fluoride) contamination (WHO/UNICEF, 2017b). The importance of safely managed drinking water is reflected in Sustainable Development Goal (SDG) 6, which calls for "universal and equitable access to safe and affordable drinking water for all" by 2030 (United Nations General Assembly, 2015).

In 2020, the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation, and Hygiene (JMP) estimated that 26% of people worldwide did not use an SMDW service. The JMP estimated that 40% of people in rural areas did not use an SMDW service. The JMP reported that there were 771 million people who did not have access to basic water services, which are improved water sources within 30 minutes round trip of the household, including queuing time. Half of the people without basic water services lived in sub-Saharan Africa (WHO/UNICEF Joint Monitoring Programme for Water Supply, 2021).

Estimates of drinking water services only account for the primary water source used by households (WHO/UNICEF, 2017a) and do not account for the multiple sources that many households rely on for

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drinking water and other purposes, especially in low- and middle-income countries (LMICs) (Daly et al., 2021; Elliott et al., 2017; Harris et al., 2023; Özdemir et al., 2011; Priadi et al., 2022; Tucker et al., 2015; Vedachalam et al., 2017). Households use multiple water sources for convenience, taste, and cost and to increase the quantity of water available for drinking, for other productive uses, to cope with service unreliability, and to increase water quantity closer to home or work (Kelly et al., 2018; Özdemir et al., 2011; Pattanayak et al., 2005; Tucker et al., 2015). Households that use unsafe water sources as part of their portfolio of sources or combine safe and unsafe water in household storage containers may negate health benefits obtained from using a primary or safely managed water service (Daly and Harris, 2022; Harris et al., 2023; Hunter et al., 2009).

Another challenge related to multiple water source use is the influence of seasonality. Seasonality has long been known to influence water services, as shown in the landmark study of domestic water use in East Africa in the 1960s and the follow-up study in the 1990s (Thompson et al., 2001; White et al., 1972). Seasonality influences water quality, water source use, the quantity of water used by households, and water service availability (Elliott et al., 2017; Foster, 2013; Foster and Willetts, 2018; Hadjer et al., 2005; Kostyla et al., 2015; Pearson et al., 2016; Thomson et al., 2019; Tucker et al., 2015). Further, high temperatures and heavy precipitation due to climate change may be linked with higher levels of stored water contamination (Powers et al., 2023).

Despite these complexities, few datasets or studies document household access to safely managed drinking water and account for multiple water source use and seasonal source switching (Daly et al., 2021; Elliott et al., 2019; Priadi et al., 2022). Describing these patterns, levels, and trends would help inform monitoring and help practitioners understand household practices related to water source use in rural communities of LMICs to improve access to SMDW services. We used data from a 14-country study of rural water, sanitation, and hygiene (WaSH) programs of the international non-governmental organization (INGO), World Vision (WV). We describe household water service parameters: source type, distance to sources, availability, water quality, and quantity, and describe household water services relative to service level benchmarks.

2. Methods

2.1. Study population

The field study was conducted in 2017 in India, Honduras, and 12 sub-Saharan African countries (Ethiopia, Ghana, Kenya, Malawi, Mali, Mozambique, Niger, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe). These countries were selected by World Vision (WV), the project sponsor, because they are countries where they have large WaSH programs. The target population was World Vision Area Programs (APs). An AP is in a distinct geographical area and supports development activities for families and communities that address child well-being, including WaSH. World Vision was interested in understanding how the presence and activity of WaSH programming influenced WaSH services compared to other representative areas that did not have WV APs. This article does not compare World Vision area programs (APs) and representative comparison areas.

2.2. Sample design

Household-level data were collected using a cluster-randomized, population-based study design. For all countries except India, Tanzania, and Zimbabwe, households were selected from lists of subnational administrative sampling units (clusters). Each country's national census bureau or statistics office listed all clusters. Generally, clusters are heterogeneous, small-scale groups of households that can be used for survey sampling for population surveys such as the Demographic and Health Survey (DHS) and the Multiple Indicators Cluster Survey (MICS). The clusters were the primary sampling units (PSUs) for this study.

Primary sampling units in rural areas were selected from two strata (i.e., groups), WV APs, and comparison areas, using a probability proportional to size (PPS) method. World Vision APs were identified by overlaying PSUs on maps of WV AP boundaries. Area Programs were identified from pre-existing lists created by collaborating with UNC and WV country offices. Generally, WV APs align with subnational administrative areas (e.g., districts, counties). Comparison areas were selected from the rural PSUs not identified as a WV AP. Fifty-six sampling units were selected in WV AP areas and 56 in the comparison areas. If the selected PSU contained more than 200 households, it was subdivided into secondary sampling units (SSUs), and one sampling unit was chosen at random. PSUs of 100–200 households were ultimately selected. Enumerators mapped all households in each sampling unit, and 25 households were randomly selected within each sampling unit.

For India, Tanzania, and Zimbabwe, all districts containing WV APs were identified from pre-existing lists (as described above). Within these, one block (India), division (Tanzania), or ward (Zimbabwe) that did not contain a WV AP was selected at random for comparison for each WV AP block/division/ward per district. From a list of all clusters within these blocks/divisions/wards, WV and comparison areas were randomly selected using a PPS method. If necessary, PSUs of more than 200 households were subdivided into SSUs, and one SSU was chosen randomly. Fifty-six clusters in World Vision areas and 56 clusters in comparison areas were selected, and 25 households were randomly selected within each cluster.

2.3. Survey instrument

The survey instrument contained questions on water, sanitation, and hygiene (WaSH). The survey and dataset are available on the public Dataverse of the University of North Carolina at Chapel Hill (UNC) (The Water Institute at UNC & World Vision Inc, 2020). Other studies from this household survey have been published elsewhere (Fejfar et al., 2024; Moffa et al., 2021). Questions were asked about water sources used throughout the year (e.g., the same source used year-round or a different source each season), distance to sources, secondary sources used, the quantity of water collected, and water service availability (Table 1). The survey was translated into local languages for each country and verified by research consultants or World Vision staff in each country.

Surveys were programmed using mWater, a mobile survey tool. mWater is an open-source tool available online for download and use on mobile phones. The survey programming included skip patterns, automatic recording of GPS, value ranges to prevent enumerators from entering implausible values, and other quality assurance measures.

2.4. Training

Survey data were collected by in-country research supervisors and enumerators hired in each country who were experienced in data collection and mobile surveys. At one of five workshops led by the Water Institute at UNC, research supervisors were trained on the survey instrument, sampling, survey good practices, mWater, and data quality checks. Research supervisors practiced using mWater and the survey in demonstration communities. Before data collection, research supervisors trained field enumerators using the materials and lessons learned from the training workshops.

2.5. Data collection

Some survey questions were observations, and some were posed to the householders through an interview. Household survey questions were asked of the female heads of households. If she was not available, another adult household member was surveyed. If no one was available

Table 1
Data on water service parameters collected in a population-based household survey in 14 low- and middle-income countries.

Term	Definitions and survey question topic	Categorization and alternative definition for this study
Water service terminology		
Surface water	River, dam, lake, stream, or irrigation canal	Same
Improved water source	Includes piped water, boreholes/tubewells, protected dug wells, protected springs, rainwater, and packaged or delivered water	Same
Unimproved water source	Unprotected dug well or spring	Same
Multiple water source use	Use the same primary water point for drinking in dry and wet seasons.	Use the same source year-round; Use different sources in the wet or dry season.
Drinking water source type	The household uses the primary type of water point to get drinking water (year-round, in the wet season, in the dry season).	Piped water; Other improved; Unimproved; Surface water
Secondary drinking water source use	Do you use any water point for drinking water other than your primary water source? [If yes] What type(s) of secondary water point(s) does your household use?	Piped water; Other improved; Unimproved; Surface water
Distance to source	A primary source is on the plot Time spent on one round trip to the water point, including time from the household to the water point, wait time, and time from the water point back to the household.	The water source is on the household premises. On Plot; Off Plot less than 30 minutes; Off Plot more than 30 minutes
Collection burden (proxy for quantity)	[If the source is off-plot] How many visits to the water point does your household make per day (all members' trips added together)?	[number of visits]
Water service availability	Household water point has a continuous water service [If not continuous] Is it available when needed? Is the service scheduled or not?	Available to the household 24 hours a day Yes / No / Don't know (DK) Yes / No / Don't know (DK)
Water quality	The amount of *E. coli* colony forming units (CFUs) per 100 mL sample using the Compartment Bag Test (CBT)	Low risk (< 1 E. *coli* MPN per 100 mL); Intermediate risk (1–10 E. *coli* MPN per 100 mL); High Risk (>10–100 E. *coli* MPN per 100 mL); Very high Risk (>100 E. *coli* MPN per 100 mL)
Water service level definitions		
Safely managed water service	Drinking water from an improved water source that is located on-premises, available when needed, and free from fecal and priority chemical contamination (at the source)	Safely managed drinking water *free from contamination at the point of use* (Safely managed PoU): Drinking water from an improved water source located on-premises, available when needed, and free from fecal contamination *at the point of use.*
Basic water service	Drinking water from an improved source, provided collection time is not more than 30 minutes for a roundtrip, including queuing.	Same
Limited water service	Drinking water from an improved source for which collection time exceeds 30 minutes for a roundtrip, including queuing	Same

or a household declined to respond, an alternative household was randomly selected from the cluster.

Within each cluster, up to five households (among the 25 selected for the survey) that stored or had drinking water available from a piped or other source on the plot were randomly selected for water quality testing.

Enumerators asked households to serve water as they would for drinking. A 100-mL water sample was collected for a Compartment Bag Test (CBT) (Aquagenx, Chapel Hill, NC, USA), a low-cost field water quality test for *Escherichia coli (E. coli)* (Stauber et al., 2014). Enumerators followed good practice guidelines for water quality testing, quality assurance, and quality control, including collecting blanks and duplicates.

Samples were processed immediately after each household interview. Samples were incubated for 48 hours at ambient temperature between 25 and 30 degrees Celsius and 24 hours wherever ambient temperature was above 30 degrees Celsius. In settings where the ambient temperature was not between 25 and 30 degrees Celsius, water samples were stored in an ice cooler until the end of daily fieldwork and were placed in an incubator for 24 hours at 35–37 degrees. Samples were categorized by risk level based on *E. coli* per 100 mL sample, as either conformity (<1 MPN *E. coli* per 100 mL) or non-conformity (1 or more MPN per 100 mL) by the World Health Organization guideline value *for E. coli* (B. Lloyd and Helmer, 1991; B. J. Lloyd and Bartram, 1991; WHO, 2017). The supervisor conducted water quality testing QA/QC based on the enumerator and supervisor manuals developed for this evaluation (Madsen et al., 2020; Madsen and Guo, 2020). Briefly, field blanks and duplicates were collected for a random sample of water samples. In-country field supervisors were responsible for QA/QC and ensuring the validity of field blanks and duplicates.

2.6. Data entry, processing, and analysis

Enumerators recorded the water quality data in a mWater survey separate from the household survey. The water quality survey and household survey were linked using a unique barcode. Data were exported from mWater into Stata 14.2 for cleaning and analysis. The Stata merge function matched the water quality dataset and household surveys.

Indicators and descriptive statistics were created using the survey questions in Table 1. For consistency with national surveys, such as the Demographic and Health Survey (DHS), indicators were calculated for responses 'at the time of the survey.' Where possible, indicators were estimated to account for year-round differences in responses.

Data on water source type were categorized using the improved and unimproved source type classification (World Health Organization / UNICEF, 2006). Water quality data were categorized by conformity or non-conformity with the WHO guideline value *for* E. *coli*; these data were also stratified by water quality risk levels (Table 1) (B. Lloyd and Helmer, 1991; WHO, 2017). Several water service availability questions followed skip logic patterns (is the water service continuous; if not, is it scheduled; if not, is it available), and these were combined into a single composite variable for analysis. Water service levels that matched the JMP service level definitions were calculated, with some changes based on data availability (see Table 1). A critical difference between this study and the JMP is for safely managed drinking water – water quality data from this study were collected from the household rather than the source (JMP method); therefore, results were labeled in this study as safely managed drinking water free from fecal contamination at the point of use (safely managed PoU as shorthand).

Alternative service level definitions were calculated (for direct comparison with the JMP service level definitions) using only the entire household survey dataset (water quality was excluded because water quality samples were only collected for a subset of households). Using the household survey data, the highest service level calculated was 'basic water service, available, on-plot.' Alternative service level definitions were calculated to account for seasonal source switching, secondary source use, and source switching and secondary source use combined. When accounting for source switching and secondary source use, households were categorized according to the 'worst' seasonal or secondary source used (e.g., if a household used a basic water service as their primary source and used an unimproved secondary source, the household was categorized as using an unimproved service).

Among the sub-set of household data with a water sample, all possible combinations of service levels between 'less than basic' and 'safely managed PoU' were enumerated. There are seven possible combinations: safely managed PoU; available basic water service, household water free of *E. coli*, but not on the plot; basic water service that is on plot, free of *E. coli*, but not available when needed; basic water service, on plot, available when needed but not free of *E. coli*; basic water service that is free of *E. coli* but not on plot nor available when needed; basic water service that is available when needed but not on plot nor free of *E. coli*; basic water service that is on plot but not available when needed nor free of *E. coli*; basic water service but not on plot, available when needed, nor free of *E. coli;* and a less than basic water service (i.e., a water service that does not meet the minimum requirements for basic water service).

2.7. Ethical approval

This study was approved by the UNC-Chapel Hill Institutional Review Board (IRB #17–0663) and by the appropriate agencies within each country. These were: the National Regional Government of Oromia Planning and Economic Development Commission in Ethiopia (reference: WVE/ORO/0393/2017); the Ministry of Water Resources in Ghana (reference: TJMSW); the Secretary of Energy and Natural Resources in Honduras (reference: DMA-0220–2017); the SRM University School of Public Health in India (reference: SRMSPH/IEC001/2017/24/07/2017); the Ministry of Water and Irrigation in Kenya (reference: MWI/PARAS/10/62/(31)); the Director of Irrigation and Water Development in Malawi (reference: IWD/CONF/1/1); the University of Bamako Medical School in Mali (reference: 2017/105/CE/FMPOS); the National Institute of Statistics in Mozambique (reference: 2/DICRE/INE/900/2017); the Ministry of Water Resources in Niger (reference: 000008/MH/A/DGH); the Ministry of Infrastructure in Rwanda (reference: ND/JOBD/WASH/IPD/20/03/17); the National Institute for Medical Research in Tanzania (NIMR/HQ/R.8a/Vol. IX/2386); the Makarere University School of Biomedical Sciences ethics committee in Uganda (SBS-HDREC-437); the Ministry of Local Government and Housing in Zambia (MLGH/101/18/102); and the Medical Research Council in Zimbabwe (reference: MRCZ/A/2223). All participants' informed consent was obtained in their language before beginning the survey.

3. Results

In total, 37,105 household surveys and 6395 household water samples were collected in 14 countries. Twelve of 14 countries had a sample size of greater than 2500 households. Uganda (n=1478 surveys) and Zimbabwe (n=2168 surveys) had smaller sample sizes.

3.1. Water service parameters

On average, 10% of households in the 14 countries used a different water source each season, varying from 29% in Kenya to 3% in Zambia (Table 2). On average, 74% of households used an improved water source as their primary water source, varying from 87% in Honduras and Malawi to 50% in Tanzania. An average of 13% of households had a water source on the plot, and 57% used it within 30 minutes round trip (including queuing time) from their household. Households made, on average, 4.3 visits to their primary water source per day; households in Mali (6.5) and India (6) made the most trips, while households in

Table 2
Water service parameters measured in a 14-country household survey (reported at the time of survey).

Water service parameter	Water service parameter level	Ethiopia n = 2712	Ghana n = 2723	Honduras n = 2739	India n = 2907	Kenya n = 2817	Malawi n = 2803	Mali n = 2821	Moz. n = 2772	Niger n = 2729	Rwanda n = 2559	Tanzania n = 2780	Uganda n = 1477	Zambia n = 2853	Zimbabwe n = 2168	Overall n = 36860
Same source year-round	-	89.0%	86.3%	93.5%	95.1%	71.1%	90.9%	95.6%	92.9%	93.0%	87.0%	77.7%	95.1%	96.8%	88.6%	89.3%
Switch by Season	-	8.3%	13.6%	5.4%	4.4%	28.8%	9.0%	4.1%	7.1%	5.9%	12.9%	22.2%	4.1%	3.2%	11.3%	10.2%
Main source type	Surface water	6.6%	13.6%	1.5%	1.0%	20.6%	3.4%	1.1%	17.7%	4.1%	10.5%	26.2%	9.6%	14.1%	21.8%	10.7%
	Unimproved	14.4%	8.0%	7.6%	8.7%	13.2%	11.2%	34.9%	25.7%	32.0%	18.4%	29.5%	11.8%	11.0%	13.4%	17.4%
	Other improved	56.0%	64.5%	12.7%	49.8%	32.5%	80.0%	41.6%	46.0%	18.6%	40.3%	19.6%	69.3%	69.5%	59.1%	46.3%
	Piped	23.0%	13.9%	78.2%	40.5%	33.8%	5.4%	22.4%	10.6%	45.4%	30.7%	24.7%	9.2%	5.5%	5.7%	25.7%
Distance to source	On household plot	62.7%	10.2%	80.8%	55.7%	22.2%	9.6%	36.0%	10.2%	10.4%	8.0%	7.0%	12.6%	18.1%	12.4%	26.7%
	Off-household plot within 30 min	31.6%	80.9%	18.2%	42.5%	68.5%	75.3%	62.1%	62.2%	78.4%	59.7%	81.1%	68.8%	67.5%	71.7%	61.3%
	Off household plot more than 30 min	5.7%	8.9%	1.1%	1.7%	9.4%	15.1%	1.9%	27.6%	11.2%	32.3%	11.9%	18.5%	14.4%	15.9%	12.0%
Quantity (if off plot)	How many visits to the water point (average)	5.9	5.7	3.5	6.0	3.3	4.9	6.5	3.4	5.5	2.7	3.3	3.6	3.7	2.7	4.3
Secondary source use	Yes	19.1%	44.8%	17.9%	12.8%	34.6%	36.3%	19.2%	10.3%	19.3%	21.9%	21.8%	39.4%	13.5%	20.7%	23.1%
Secondary source type[a]	Surface water	5.3%	15.9%	2.0%	0.1%	6.2%	4.9%	0.6%	0.8%	2.6%	2.0%	4.6%	7.0%	2.0%	6.0%	4.1%
	Unimproved	5.8%	4.0%	3.4%	1.5%	5.3%	9.0%	7.7%	4.4%	9.6%	3.9%	6.0%	7.7%	2.1%	4.0%	5.2%
	Improved	5.8%	31.3%	11.2%	7.4%	23.7%	20.2%	9.1%	4.6%	4.1%	8.6%	8.3%	23.3%	9.0%	10.8%	12.3%
	Piped	4.2%	3.5%	2.1%	4.8%	8.1%	3.1%	2.3%	0.5%	4.0%	8.7%	4.0%	3.1%	0.5%	0.6%	3.6%

[a] Reported as a percentage of all households in each country, not as a percentage of households that used a secondary water source

Rwanda (2.7) and Zimbabwe (2.7) made the least. On average, 23% of households used a secondary water source, and 37% of secondary water sources were unimproved. Use of the highest risk unimproved water source, surface water, was highest in Ghana (16%).

Seventy-nine percent of households used a water source that provided a continuous service. Of the 20% of households that used a discontinuous service, 56% of water sources provided a scheduled service. Half of the sources that provided a scheduled service were available when needed. Among households with discontinuous services that were not scheduled, half (52%) did not have water available when needed.

Water quality at the point of use varied by country (Fig. 1). On average, 69% of household water samples in the 14 countries contained levels of *E. coli* that did not conform with the WHO guideline value for *E. coli*. Ethiopia had the highest percentage of households with water that conformed with the WHO guideline value for *E. coli* (63%), while Kenya (17%) and Mali (11%) had the lowest. Use of high-risk household water (e.g., water sample with >100 fecal coliforms per 100 mL sample) was highest in Malawi (49%) and Kenya (47%) and lowest in Ethiopia (7%). Water quality varied by the reported primary source used by households. Samples that came from piped sources on the plot (38%) and basic sources on the plot (34%) were more compliant with the WHO guideline value for *E. coli* than water that came from unimproved (25%) and surface water sources (14%).

3.2. Accounting for seasonal source switching and multiple water source use

When accounting for seasonal source switching, household water service levels were lower in all 14 countries than the water source used at the time of the survey (descriptive statistics on this are available in the supporting information). Across all 14 countries, there was a four percentage point decrease in the use of improved water sources when comparing year-round use and use at the time of the survey. The percentage point decrease was greatest in Kenya (10% percentage point decrease) and Tanzania (8%) and lowest in Uganda (1% percentage point decrease). Accounting for seasonal source switching had less influence on higher service levels, including basic water services (an improved water source within 30 minutes round trip, a two percentage point decrease), basic water services on-premises (an improved water source available at the household, a one percentage point decrease), and basic water services on plot and available when needed (a one percentage point decrease).

Accounting for using an unimproved secondary source influenced water service levels (descriptive statistics available in the supporting information). There was an overall decrease of 8 percentage points in using an improved source at the time of the survey. This was greatest in Ghana (17 percentage points), Malawi (13 percentage points) and Uganda (13 percentage points) and lowest in India (2 percentage points). There were similar but less pronounced trends in basic water services, with a six percentage point decrease across all countries. The biggest decreases were in Ghana (14 percentage points) and Uganda (10 percentage points). Secondary source use had less influence on households with higher service levels. On average, there was a one percentage point difference in the "basic, on plot, available when needed" service level when accounting for unimproved secondary source use.

Overall, an average of 7% of households used safely managed drinking water free from fecal contamination at the point of use (safely managed PoU). This was highest in Ethiopia (25%) and lowest in Tanzania (0.2%). When accounting for unimproved secondary source use, household coverage of safely managed PoU decreased on average by 0.4 percentage points.

3.3. Water service parameter contributions to safely managed drinking water free from fecal contamination at the point of use

In the 14-country average, 2% of households had a basic water service that was not on plot, unavailable when needed, nor had household water free of E. *coli* at the point of use (Table 3, label 8). Among co-occurrences of water service parameters (e.g., households missing two of the three parameters to meet the benchmark for safely managed PoU; table labels 5, 6, 7), on average, 1% of households with a basic water service had water that was not available when needed nor free of E. *coli*; and 1% of households with a basic service did not have water on plot nor

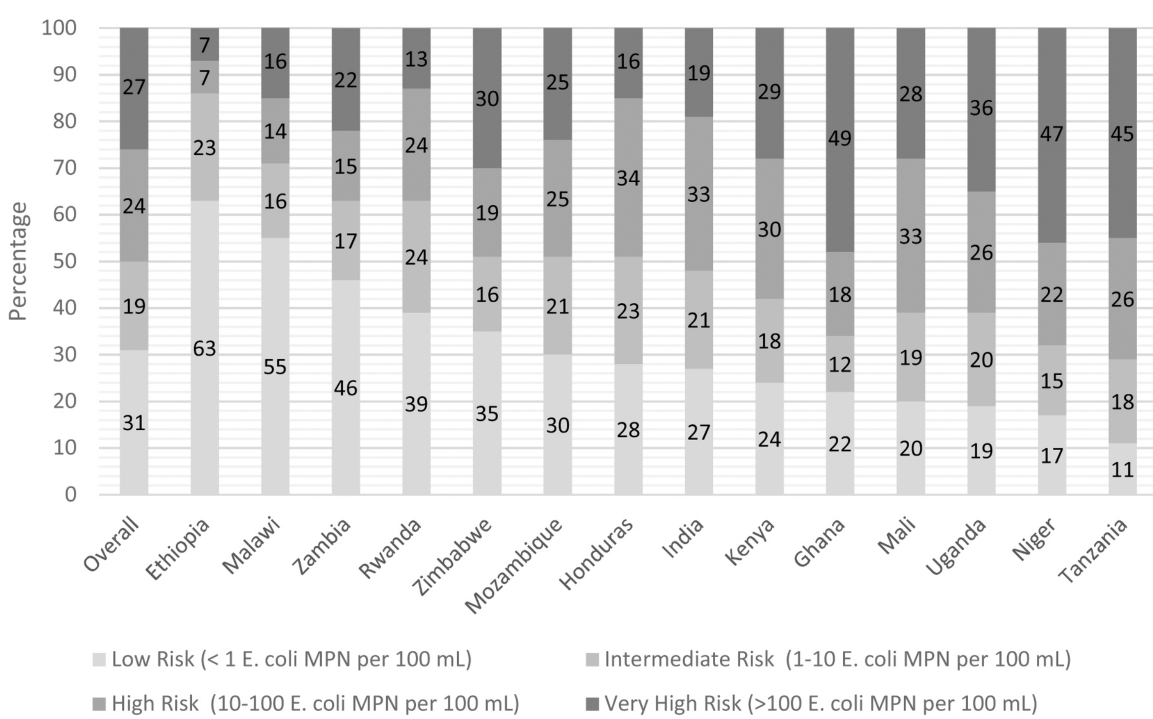

Fig. 1. Risk levels for water quality at the point of use by country from a 14-country household survey.

Table 3
Changes in water service levels when accounting for different water service parameters using data from a 14-country dataset. Rows sum to 100%.

	Safely managed drinking water free from fecal contamination at the point of use (label: 1)	Basic water service that is available, household water free of E. coli, but not on plot (2)	Basic water service that is on plot, free of E. *coli*, but not available when needed (3)	Basic water service that is on plot and available but not free of E. *coli* (4)	Basic water service that is free of *E. coli* but not on plot nor available when needed (5)	Basic water service that is available when needed but not on the plot nor free of *E. coli* (6)	Basic water service that is on the plot but not available when needed nor free of *E. coli* (7)	basic water service but not on plot, not available when needed, nor free of E. *coli* (8)	Less than a basic water service (9)
Basic water source	✓	✓	✓	✓	✓	✓	✓	✓	
No contamination	✓	✓	✓		✓				
Available	✓	✓		✓		✓			
On plot	✓		✓	✓			✓		
Overall	7.1%	12.2%	1.0%	11.6%	1.4%	25.4%	1.2%	2.2%	37.8%
Ethiopia	24.9%	8.0%	8.0%	9.1%	9.7%	11.1%	3.3%	3.3%	22.4%
Ghana	1.4%	13.8%	0%	6.4%	0%	44.9%	0%	0.8%	32.7%
Honduras	19.2%	1.9%	0.8%	51.9%	0.8%	7.3%	2.7%	1.9%	13.5%
India	14.1%	7.7%	2.2%	32.4%	0.4%	20.8%	4.5%	3.7%	14.1%
Kenya	5.3%	9.1%	0.5%	10.5%	1.8%	25.5%	1.4%	3.1%	42.8%
Malawi	4.8%	35.3%	0%	2.4%	1.2%	24.0%	0.4%	0.4%	31.5%
Mali	5.4%	8.4%	0.2%	12.9%	0.6%	31.1%	0.2%	1.3%	39.9%
Mozambique	4.5%	11.2%	0.2%	3.6%	0%	21.0%	0.2%	1.1%	58.2%
Niger	1.1%	10.9%	0.0%	7.2%	1.4%	51.3%	0%	4.3%	23.8%
Rwanda	3.2%	13.8%	2.4%	1.6%	3.0%	19.3%	1.2%	2.6%	52.7%
Tanzania	0.2%	2.6%	0%	3.9%	0.6%	23.6%	1.3%	4.3%	63.6%
Uganda	3.4%	9.2%	0%	5.7%	0.4%	36.3%	0.8%	2.7%	41.6%
Zambia	8.1%	22.4%	1.0%	4.6%	1.4%	23.4%	0%	1.2%	37.9%
Zimbabwe	5.6%	15.5%	0%	4.2%	0.4%	23.9%	0%	1.1%	49.3%

available when needed. Twenty-six percent of households with a basic service were available when needed but not on-plot or free of E. *coli*. Of the countries missing one parameter of safely managed PoU (table labels 2, 3, 4), 1% of households with at least a basic water service were unavailable, 12% were free of E. *coli*, and 12% were not on plot. Of the countries missing one parameter of safely managed PoU, the most commonly missing parameter in eight of 14 countries was an on-plot water source (Ghana, Malawi, Mozambique, Niger, Rwanda, Uganda, Zambia, and Zimbabwe). In six of 14 countries, it was water containing *E. coli* (Ethiopia, Honduras, India, Kenya, Mali, Tanzania).

In 11 of 14 countries, the water service parameter preventing households from having safely managed PoU was water that was not free of E. *coli*. Among co-occurrences, water available when needed had the lowest influence on household water not being safely managed PoU, with a 14-country average of 1% of households having a basic water service free of E. *coli* and on-plot.

4. Discussion

We present the results of a 14-country, 37,105-household survey on the influence of seasonality and multiple water source use on household water service levels. Most households used an improved water source (74%). On average, 8% of households switched water sources each season. One in four households used a secondary water source, and 37% of the secondary sources were unimproved. Only 7% of households in the 14 countries had a safely managed drinking water service at the point of use.

These results suggest that many households in LMICs have a long road ahead to achieve universal access to safely managed drinking water and year-round basic water services when accounting for the entire portfolio of water sources households use. Our 'time of survey' estimates for basic drinking water services are like those produced by the JMP for rural areas in these 14 countries. However, our estimates that account for seasonal switching of primary sources and secondary source use show that levels of access to basic water services are lower by as many as 17 percentage points in some countries (Ghana). Our results confirm that the WHO/UNICEF Joint Monitoring Programme for Water Supply, Sanitation, and Hygiene (JMP) substantively overstate the population benefiting from safely managed drinking water, and their reporting statistics should be interpreted with caution.

Our water quality findings were consistent with previous studies and filled gaps in data availability. In their systematic review and meta-analysis on fecal contamination of source water and household drinking water in LMICs, Shields et al. (2015) used 12,523 water samples compiled from 45 studies. They found that 46% of source water samples were non-compliant with WHO guidelines for *E.* coli, and 75% of household water samples were non-compliant with the WHO guidelines (Shields et al., 2015). Our results were consistent with this meta-analysis, with 69% of household water samples not conforming with the WHO guideline value for *E. coli*. Our results, which included 6395 household water samples, add further confirmatory evidence that safe water at the point of use is a persistent challenge in LMICs.

Our estimates of the influence of seasonality and multiple water source use on household water service levels were consistent with studies from other countries in sub-Saharan Africa that attempted to capture water source use beyond the primary source used. Our findings provide extensive detail on the magnitude of patterns and levels of water source use, which provides additional context to case study findings. A study in Ethiopia showed that the quantity of water collected varied by season as water sources dried up in the dry season. Households used similar amounts of water for drinking and cooking year-round but less for hygiene in the dry season (Tucker et al., 2015). Among pastoralist populations in Tanzania and Uganda, seasonal variation meant that a third of households switched their primary drinking water source, and households were more likely to switch from a source with a higher risk of contamination in the rainy season to one with a lower risk of contamination in the dry season (Pearson et al., 2016). In a study in Benin, there was less water available during the dry season, household members had to travel farther to obtain water, and households used less water per capita (Hadjer et al., 2005).

Among the more extensive quantitative studies on multiple water source use, Vedachalam et al. 2017 found that, on average, surface water use was underreported by 5.5% (with a range of 2.7–11.5 percentage points for countries in their study) (Vedachalam et al., 2017) which was consistent with our findings. Household use of multiple sources was much higher in Pacific Island countries than in our study. A study in the Republic of the Marshall Islands and the Solomon Islands showed that the season influenced households' water source and water availability from secondary sources and found that 90% of households used multiple sources (Elliott et al., 2017).

Season and multiple water source use had substantially less influence on households that used the highest water service levels, such as basic water services available on plot and safely managed PoU. Households with higher service levels may have more resilient services than those with lower service levels. Households with higher service levels have more resilient water system types (e.g., hand pumps, piped water systems) available when needed and on household premises, giving households more control over maintaining their services than communal sources. There are substantially fewer households with this level of service in rural areas of the 14 countries studied.

4.1. Study limitations and future survey improvements

There were several limitations to this study. Because of our study design, our data represent most rural areas in most countries. However, generalizations can only be made from this study for some rural areas in each country. All the household survey results were unweighted per household basis because reliable data for household weighting was not collected in every country.

There were several potential sources of bias in the survey questionnaire. Survey questions about year-round water source use were asked to householders, which introduces recall bias, though our method of asking about this was consistent with another study (Elliott et al., 2017). Householders may need more technical knowledge to answer questions about water service availability. Households were asked about the distance to the source and the number of trips to water points, which may introduce recall bias.

The survey would have benefited from several improvements and additions to the survey questions. For example, household water insecurity is an important health and development problem (Young et al., 2019). While some aspects of water security were described in this study, others, such as household-to-household water sharing (Stoler et al., 2018), water available for other productive uses (such as cooking and bathing), and gendered and intra-household access to water services would be beneficial to incorporate into future monitoring and evaluation activities (Wutich and Ragsdale, 2008).

Water quality was measured at one point in time. However, there is evidence of seasonal and daily variation in water quality, so the results presented in this study may need to be updated (Harris et al., 2023; Kostyla et al., 2015). We measured water quality at the point of consumption rather than collection, which is different from the JMP. Samples from both settings would indicate the quality of the water delivered at the source and the quality of household water service.

Data on priority chemical contaminants (including arsenic and fluoride, per the JMP definition) were not collected at the household level.

Only five randomly selected households out of the 25 selected in each cluster for a survey had a water quality test, so our sample sizes for all our reported statistics that include water quality only represent the households with a water quality test.

5. Conclusion: implications for policy, monitoring, and practice

We describe the results of one of the most extensive assessments on rural household water source use in 14 LMICs, which accounts for multiple water source use and seasonal source switching. Our results reveal that water service parameters, primarily water sources on plot and water quality, need improvement to improve access to safely managed drinking water. Our findings demonstrate important priorities for households and actors supporting policy, practice, monitoring, and research to achieve universal access to safely managed drinking water services.

This study shows the patterns and levels of seasonal source switching and secondary source use by households in each country. Seasonality influences water service parameters, including quality, availability, and household practices around water source use. This is particularly true of households who rely on basic services such as handpumps or protected dug wells or springs, which are neither on the household premises nor available when needed and, therefore, fall short of the "safely managed" level of service. When seasonal variation results in people reverting to water from unsafe sources, the expected health gains from investments in better water services may be eliminated (Hunter et al., 2009), and progress toward achieving SDG 6 is undermined.

Achieving universal access to safely managed drinking water services will require substantial investments in infrastructure, financing systems, human resources, and other enabling environment factors to support service delivery and progressive improvements in service levels, especially in rural areas of low- and middle-income countries (LMICs) (Hutton and Varughese, 2016; World Health Organization, 2017). Aid alone will be insufficient to achieve this goal – Bain et al. (2013) found that the impact of aid on water services is often negligible (Bain et al., 2013). Local and national investments will be the primary sources of change. Governments and external support actors (e.g., donors) may seek to target resources more strategically, based on credible data demonstrating impact, where some programs may have a greater impact than others if they can quantify the effect.

A substantial hurdle to achieving this is little comparable data on effective programs (implemented by external support or government actors). Data from implementers on the number of users per water source are often overstated by neglecting to account for sources that were available to households before implementation, sources available outside the community, rehabilitated sources, and accurately accounting for the water service delivered at the point of use (and explicitly accounting for water quality). These data are often not comparable. The lack of comparability impedes decision-making, over-states benefits, and impedes sector planning, quality improvement, and sector credibility. Improved, credible, and harmonized data collection systems that accurately account for water services are crucial to progress.

The data collected to measure progress towards SDG 6 do not necessarily account for seasonal variation in water services. Surveys are more likely to be conducted in the dry season, and many exhibit "dry season bias" (Bain et al., 2021; Wright et al., 2012). This results in an incomplete picture of access to and use of drinking water services. Despite inherent logistical challenges, enhanced monitoring is needed to consider seasonal variation in estimating drinking water access and the portfolio of secondary sources used by households and document seasonality's impacts on other parameters. This will allow decision-makers to understand better how to ensure that households choose to use basic water services at a minimum throughout the year. Data collection agencies should account for seasonal source use and multiple source use in monitoring instruments to understand patterns, levels, and trends. There may be opportunities to include satellite and remote sensing data with household survey data. Data collection agencies might hire and deploy enumerators based on a sampling cluster to monitor households more routinely. This may reduce costs rather than hire a national enumerator team who must travel extensively. Having these data available can help inform decision-makers and enable them to pinpoint problems, direct interventions, investments, capacity-building efforts, and other resources to improve the situation.

Safe household drinking water quality and sustained, consistent, and correct use of water treatment technologies are persistent challenges in low- and middle-income countries (Brown & Clasen, 2012). Operational research using this 14-country dataset and other monitoring data would help identify potential determinants of fecally contaminated drinking water at the point of use and appropriate practices associated with household water treatment options and improved water quality.

Secondary source use was documented as an essential household practice in the 14 countries and remains largely understudied. Understanding the determinants of secondary source use would be beneficial to inform policy and practice decision-making on predicting where problems may occur and to identify good practices that may ensure and enable households to always use safer water sources.

Researchers should test alternative water service delivery survey questions to measure better secondary source use and seasonal variation in water service parameters, water security, and other important determinants of water services so that data collection agencies – such as the Demographic and Health Survey Program and National statistical offices – can incorporate these into monitoring instruments that more fully capture household water use practices. Researchers should leverage available water service datasets to conduct operational research to understand the patterns and determinants of household practices related to water source use. Researchers should collaborate with practitioners to leverage the findings of operational research studies and conduct collaborative implementation projects to understand better the enablers, barriers, and processes to secure access to safely managed drinking water services and to identify pathways to improve service delivery, especially in rural areas of LMICs.

CRediT authorship contribution statement

Jamie Bartram: Supervision, Methodology, Funding acquisition, Conceptualization. **J. Wren Tracy:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Ryan Cronk:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ryan Cronk, Jamie Bartram, Wren Tracy reports financial support was provided by World Vision

Data availability

The data used in this study are available at the UNC-Chapel Hill Dataverse: https://doi.org/10.15139/S3/XALHIY

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.clwat.2024.100012.

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