Multiple water source use in low- and middle-income countries: a systematic review

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ABSTRACT

The Joint Monitoring Programme (JMP) 2017 Update and Sustainable Development Goals (SDGs) Baselines report classified 71% of the global population as having access to 'safely managed' drinking water. Current global monitoring efforts to track access to safely managed drinking water rely on collecting information on the 'primary' source of drinking water. However, there is evidence that households often rely on multiple sources to meet their water needs in many low- and middle-income countries (LMICs). This systematic review was designed to compile the literature related to the practice of multiple water source use (MWSU) for drinking water in LMICs. A total of 5,318 studies were collected, and after abstract and full-text review, 74 articles were identified for inclusion. Studies reviewed reported from 4 to 100% of the study populations practicing MWSU. Additionally, the practice of supplemental unimproved source use was reported globally, representing households with improved primary source water also accessing unimproved water sources throughout the year. These findings expose gaps in current global water monitoring efforts, revealing potential inflation of reports of 'safe drinking water access' and unaccounted exposure to drinking water from unimproved sources.

Key words | drinking water, low- and middle-income countries, multiple water source use, systematic review

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HIGHLIGHTS

- Multiple water source use has been identified in 43 countries and 4 continents, and in urban and rural areas.
- Many households reported supplementing improved water sources with unimproved water throughout the year.
- Current water access monitoring methods focus on a household's primary water source. Global estimates likely overestimate the proportion of the population using basic and safely managed drinking water sources.

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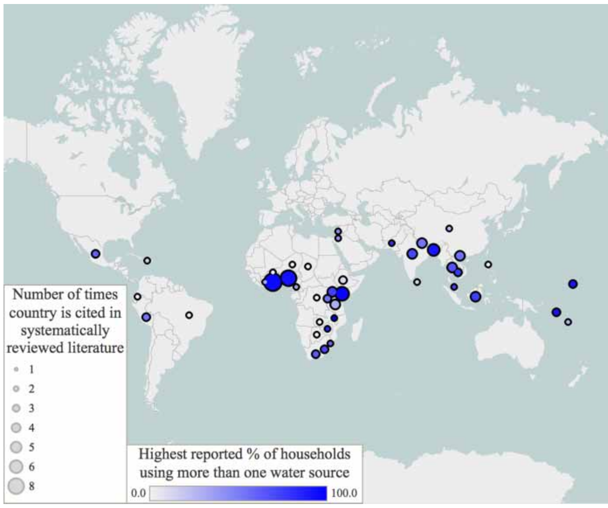
GRAPHICAL ABSTRACT



INTRODUCTION

The global impact associated with inadequate water, sanitation, and hygiene (WASH) access was estimated in 2016 to account for 5.3% of deaths for children under 5 years and 60% of the total diarrheal disease deaths (Prüss-Ustün *et al.* 2019). Diarrheal diseases are commonly caused by enteric pathogens, including rotavirus, *Vibrio cholerae*, *Shigella* spp., *Salmonella* spp., and enteropathogenic *Escherichia coli* (Petri *et al.* 2008). Drinking water has been identified as a dominant route of transmission of enteric pathogens, with many studies providing evidence that diarrheal illness can be reduced from improved water interventions (Reller *et al.* 2003; Fewtrell *et al.* 2005). Given the role drinking water plays in human health and well-being, access to safe drinking water is considered a human right (United Nations (UN) & World Health Organization (WHO) 2010), and extending safe drinking water provision to all people is on the global development agenda. The United Nations' Sustainable Development Goal (SDG) 6 outlines the 2030 objective of 'ensuring access to water and sanitation for all.' Target 6.1 is to, 'by 2030, achieve universal and equitable access to safe and affordable drinking water for all' (United Nations (UN) 2016). The indicator, by which the progress on targets is measured, for target 6.1 is SDG global indicator 6.1.1, 'proportion of population using safely managed drinking water services.' Through the use of household surveys and regression models (Bartram *et al.* 2014), the Joint Monitoring Programme (JMP), conducted by the United Nations Children's Fund (UNICEF) and the World Health Organization (WHO), monitors global access to WASH, along with the efforts of individual research studies (World Health Organization (WHO) & United Nations Children's Fund (UNICEF) 2019).

The household drinking water services ladder, as defined for SDG indicator 6.1.1, is classified by the JMP according to the following service levels, in decreasing quality: safely managed, basic, limited, unimproved, and no service. The highest level of service, safely managed, is defined as 'improved water source which is located on premises, available when needed and free of faecal and priority contamination,' while basic service is 'an improved source provided collection time is not more than 30 minutes for a roundtrip including queuing.' Limited service is defined as 'water from an improved water source where collection time exceeds 30 minutes for a roundtrip to collect water, including queueing.' Unimproved service is defined as 'water from an unprotected well or unprotected stream,' and no service is the use of various surface water sources (WHO & UNICEF 2017).

Access to safe drinking water has been improving over time. The JMP has documented that the percentage of the global population with access to safely managed drinking water has increased from 61 to 71% between 2000 and 2015 (WHO & UNICEF 2019). They also report in 2015 that about 90% have access to at least 'basic' water services or greater, and 93% have access to at least limited water services (WHO & UNICEF 2019). The rural coverage of safely managed drinking water has also increased from 39% in 2000 to 53% in 2015, closing the gap between rural and urban areas from 47 to 32 percentage points (WHO & UNICEF 2019). However, this means that approximately 7% of the global population still does not have access to an improved water source ('limited' or higher quality service), and must rely primarily on unimproved water sources to meet their needs, which is generally more likely to be contaminated compared to improved water sources (Bain *et al.* 2014).

Along with providing regular updates on progress toward such SGD targets, the WHO and UNICEF also provide recommended survey questions for WASH targets, including for drinking water access and sources. These 'core questions' focus only on the primary source of drinking water for a responding household, where only the additional expanded questions allow for 'select-all-that-apply' style questions for more than one source (WHO & UNICEF 2018). Relying only on data related to the primary water source for measuring access to safe drinking water may result in inaccurate classifications of safe water access. Studies exist suggesting that households in many settings access more than one source of drinking water (Vedachalam *et al.* 2017), and there is evidence that seasonality (Elliott *et al.* 2019), unreliable piped connections (Anthony 2007), and costs and distance barriers (Kosinski *et al.* 2016) influence water source decisions and the use of multiple sources. This reality would not be addressed by the primary core survey questions of asking only about a household's main or primary water source. To assess progress on SDG target 6.1, ensuring universal safe drinking water access, SDG indicator 6.1.1 is used, which does not capture members of the population using safely managed drinking water services primarily and other lower quality, potentially unsafe, water services in a supplemental manner. This systematic review was conducted to answer the following research questions: (i) What is the extent to which multiple water source use (MWSU) is practiced by households in low- and middle-income countries (LMICs)? (ii) What factors (cost and distance) influence this behavior?

METHODS

Search strategy

Studies analyzed in this review were obtained through a systematic review of literature, in adherence with PRISMA-P (Moher *et al.* 2015) guidelines and protocols, in the following databases: Web of Knowledge, PubMed, CINAHL EbscoHost, and Engineering Village (Compendex). Key word search terms were developed to capture literature that reports on all water sources individual households use to meet their drinking water needs. As different studies discuss this behavior in various ways (i.e., there is no established terminology for this behavior or type of study), an extensive key word search was developed to capture any literature on MWSU behavior. Using Boolean operators, the search terms follow the format: 'drinking water' AND 'water sources' AND 'multiple sources' AND 'LMICs.' For each of these four word groups, synonyms were included, as well as a list of LMICs according to the World Bank. Supplementary Information SI1 includes a detailed list of search terms. The systematic search of literature took place in December of 2018, and hand-picked literature was added to the review if published after the initial search. Based on the search terms, 6,528 articles were obtained from the listed databases. After the removal of 1,210 duplicate articles, 5,318 articles were identified for the review of titles and abstracts.

Article selection criteria

Articles were selected for inclusion in this systematic review based on a unique set of criteria to obtain literature relevant to the practice of MWSU. The inclusion and exclusion criteria were the following: the study classifies household- or individual-level drinking water sources; the study is conducted in LMICs; and the study is structured to capture the household use of more than one drinking water source or evaluated all the water sources a household or individual used within the span of a year.

The first phase of screening was for titles and abstracts. Using the beta web application, Abstrackr (Wallace *et al.* 2012), from Brown University, each title and abstract was reviewed by two separate reviewers. There were seven reviewers for the first phase, with two lead reviewers supervising the process and assisting in conflict resolution in reviews. Any conflicts between review decisions when screening abstracts (about 4% of abstracts) were resolved via collaboration among the team of reviewers and lead reviewers. After the first phase of review, those determined to be eligible for inclusion and underwent a full-text review by three reviewers. The same inclusion and exclusion criteria were used, and all articles were screened by two separate reviewers. Any conflicts between review decisions when screening full texts were resolved via collaboration between two of the reviewers. No restrictions were placed on included articles based on study characteristics such as study type and sample size. Articles were additionally excluded if the full text could not be accessed ($n = 13$), and only articles in English were included (Figure 1).

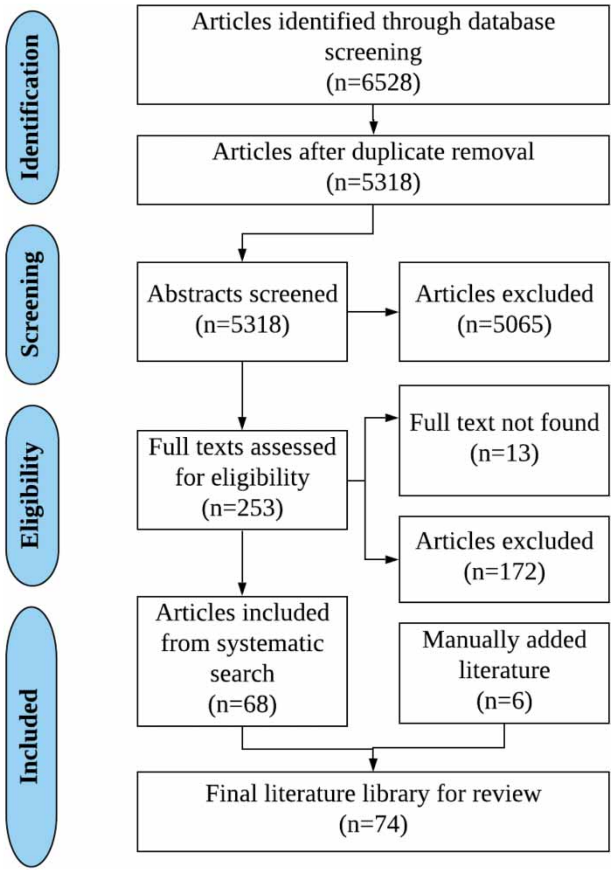


Figure 1 | Flowchart for review, established in accordance with PRISMA-P recommendations for systematic review publications.

Data extraction

Articles identified for review inclusion were read, and the following study attributes were extracted: general study characteristics, unit of analysis (i.e., household versus individual), location (urban and/or rural, as defined by the study's authors, or unclassified), study design (cross-sectional, longitudinal, intervention, and/or matched cohort), and sample size. The classification of study location between rural versus urban populations was based on the explicit description of the authors of each study. If a study included the classification of drinking water sources, but the study area was non-household, such as a university or community meeting, the unit of analysis was classified at the individual level. Otherwise, the characterization of water access was done at the household level.

Data extracted from each article on household drinking water sources and behaviors varied between studies due to differences in study scope and in reported results. The data extracted included, but were not limited to: the proportion of households reporting the use of improved, unimproved, improved and unimproved, and multiple sources of water; water sources accessed in both wet and dry seasons; and reported reasons for MWSU, source switching, or source choice. Upon the detailed review of the final library of literature, themes and gaps in knowledge were identified in the context of MWSU.

RESULTS

Search results and study characteristics

As seen in Figure 1, a total of 5,318 unique articles were identified through database searches, of which 5,065 were excluded based on the screening of their titles and abstracts, and 253 were read in full to determine their eligibility. Of these 253 full texts, 13 were either unavailable or not found (i.e., not found in full, in English, or were not found searching online databases or through the North Carolina State University Library systems), and 172 were excluded based on the established inclusion and exclusion criteria. In addition to 68 articles collected during the review process, six articles were manually added, which were either published after the review date or not available in online databases. Ultimately, 74 articles were included in this review (Supplementary Information SI2 and SI3 contain details regarding all included articles).

Global prevalence of MWSU

The practice of MWSU describes a household that uses more than one water source to provide drinking water to their home. This practice may occur in several different formats. Households may simultaneously use multiple sources (i.e., within the same day). Households may have secondary, alternative, or supplementary water sources to access when their primary supply is insufficient. The MWSU practice may also relate to the changing availability of water sources in different seasons. This means that a household may have one primary water source, but the source a household is 'primarily' using may change over the course of the year, or they may access one or more other sources during the year to supplement their drinking water supply. Based on this systematic search of the literature, the practice of MWSU has been recorded globally across multiple LMICs (Table 1).

Table 1 shows the number of collected articles and the range of reported MWSU in each SDG country region, also seen by country in Figure 2. In addition to studies collecting primary data in an individual country or small region, one article reported the results of a large survey campaign across multiple geographies in Asia and Africa, finding that 42.3% of households on average across the study populations used more than one source of water (Vedachalam *et al.* 2017). The country where the most studies collected in this review were conducted was the Republic of Ghana, where eight articles report MWSU rates between 53.8 and 96% of study households (Shier *et al.* 1996; Engel *et al.* 2007; Grönwall 2016; Kosinski *et al.* 2016; Vedachalam *et al.* 2017; Grönwall & Oduro-Kwarteng 2018; Guzmán & Stoler 2018; Kelly *et al.* 2018). While this provides evidence of MWSU globally, these findings are not necessarily representative of the global prevalence of the behavior. Many geographic areas and populations are not represented in the reviewed literature, highlighting the limited scope of investigation of this behavior.

Of the articles collected in this review, 30 were conducted in rural populations (as defined by the article's authors), 20 were conducted in urban or peri-urban populations, three were conducted in both rural and urban populations, and 19 did not classify their population (Supplementary Information SI2 and SI3 contain details). The studies conducted in rural, urban, and unclassified populations reported that 13–93, 6.7–100, and 4.2–85% of households used multiple sources, respectively. The range in rates of MWSU between the reported urban and rural populations is similar, and no clear trends emerged distinguishing urban and rural MWSU behaviors across the entire literature library generated from this review.

Three collected articles report data collection efforts in both rural and urban environments (Onabolu *et al.* 2011; Cherunya *et al.* 2015; Vedachalam *et al.* 2017). In Kenya, Cherunya *et al.* (2015) reported that 86% ($n = 50$) of urban and 98% ($n = 48$) of rural study households use more than one source of domestic water. However, other articles do not indicate explicit differences in MWSU between urban and rural populations (Onabolu *et al.* 2011; Vedachalam *et al.* 2017). Onabolu *et al.* (2011) reported that an average of 58.1% of urban and rural Nigerian households used an unimproved source to supplement when their primary supply was unavailable but did not report significant differences in the number of sources used between urban and rural households. Vedachalam *et al.* (2017) surveyed households in several Asian and African geographies. They did not report the difference in MWSU rates between the urban and rural populations; however, they found that rural households were more likely than urban households (OR = 1.419; 95% CI [1.252–1.608]) to underreport the use of unimproved water to supplement a main water supply, suggesting potentially higher rates of MWSU (Vedachalam *et al.* 2017).

Rural households reported using up to four sources (Rodrigues Peres *et al.* 2020) of water. Benneyworth *et al.* (2016) reported that 16% of surveyed households in rural Bangladesh used three water sources, and Cook *et al.* (2016) reported that while 91% of rural households in

Table 1 | Number of collected studies and reported range of MWSU by SDG country region

SDG country region	Country code	Number of articles reporting MWSU	Range of reported MWSU (%)[a]	References
Central and Southern Asia	CASA	12	11.9–91.3	Briscoe *et al.* (1981), Naik *et al.* (1992), Madanat & Humplick (1993), Anthony (2007), Khan *et al.* (2011), Casanova *et al.* (2012), Md. Islam *et al.* (2013), Shrestha *et al.* (2013), Benneyworth *et al.* (2016), Guragai *et al.* (2017), Seifert-Dähnn *et al.* (2017), and Shrestha *et al.* (2018)
Eastern and South-Eastern Asia	ESEA	14	6.7–80.3	Kiyu & Hardin (1992), Choprapawon & Ajjimangkul (1999), Wong (2000), Wegerich (2006), Haraguchi *et al.* (2007), Herbst *et al.* (2009), Özdemir *et al.* (2011), White *et al.* (2013), Francisco (2014), Neumann *et al.* (2014), Shaheed *et al.* (2014), Huang *et al.* (2015), Nastiti *et al.* (2017), and Jiang & Rohendi (2018)
Latin America and the Caribbean	LAC	7	4.2–59.7	McClain *et al.* (2001), Duke *et al.* (2006), Furlong & Paterson (2013), Espinosa-García *et al.* (2015), Reyes *et al.* (2017), Ocampo-Fletes *et al.* (2018), and Rodrigues Peres *et al.* (2020)
Northern Africa and Western Asia	NAWA	2	39.9–43.1	Habib *et al.* (2013) and Coulibaly *et al.* (2014)
Oceania	O	3	26–92.1	MacDonald *et al.* (2016), Elliott *et al.* (2017), and Foster & Willetts (2018)
Sub-Saharan Africa	SSA	35	13–100	Blum *et al.* (1987), Thompson & Dixon (1993), Shier *et al.* (1996), Howard *et al.* (2002), Hoko (2005), Mazvimavi & Mmopelwa (2006), Engel *et al.* (2007), Peter (2010), Gwimbi (2011), Onabolu *et al.* (2011), Grace *et al.* (2013), Mellor *et al.* (2013), Smiley (2013), Cherunya *et al.* (2015), Krauth *et al.* (2015), Masanyiwa *et al.* (2015), Pearson *et al.* (2015), Uwera & Stage (2015), Coetzee *et al.* (2016), Cook *et al.* (2016), Grönwall (2016), Kosinski *et al.* (2016), Pearson *et al.* (2016), Adamu & Ndi (2017), Foster & Hope (2017), Kumpel *et al.* (2017), Sreenivasan *et al.* (2017), Grönwall & Oduro-Kwarteng (2018), Guzmán & Stoler (2018), Kelly *et al.* (2018), Paul *et al.* (2018), Velzeboer *et al.* (2018), Ngasala *et al.* (2019), Thomson *et al.* (2019), and Workman (2019)
Multiple geographies article	–	1	42.3	Vedachalam *et al.* (2017)

[a]Articles may provide evidence of MWSU, but not provide a summary statistic to be included in reported prevalence.

Kenya had access to between three and five sources of water, the average household used approximately two sources. Conversely, Cherunya *et al.* (2015) reported the use of a higher number of sources in urban populations compared to rural populations in Kenya, where 53% of urban households used three sources of water compared to 33% of rural households. Additionally, 8% of urban Kenyan households also reported using four different water sources, where no rural households reported using more than three sources (Cherunya *et al.* 2015). Uwera & Stage (2015) reported that 2% of urban households in Rwanda used three or more water sources. Some data suggest that urban households tend to rely more frequently on multiple water sources and a greater number of water sources compared to rural households. However, studies could be improved to investigate this comparison more thoroughly by controlling for potential confounders through statistical analysis or study sample selection.

The practice of supplemental unimproved source use (SUSU) is defined as when a household with a primary improved water source uses an unimproved water source at some point during the year for drinking. SUSU was

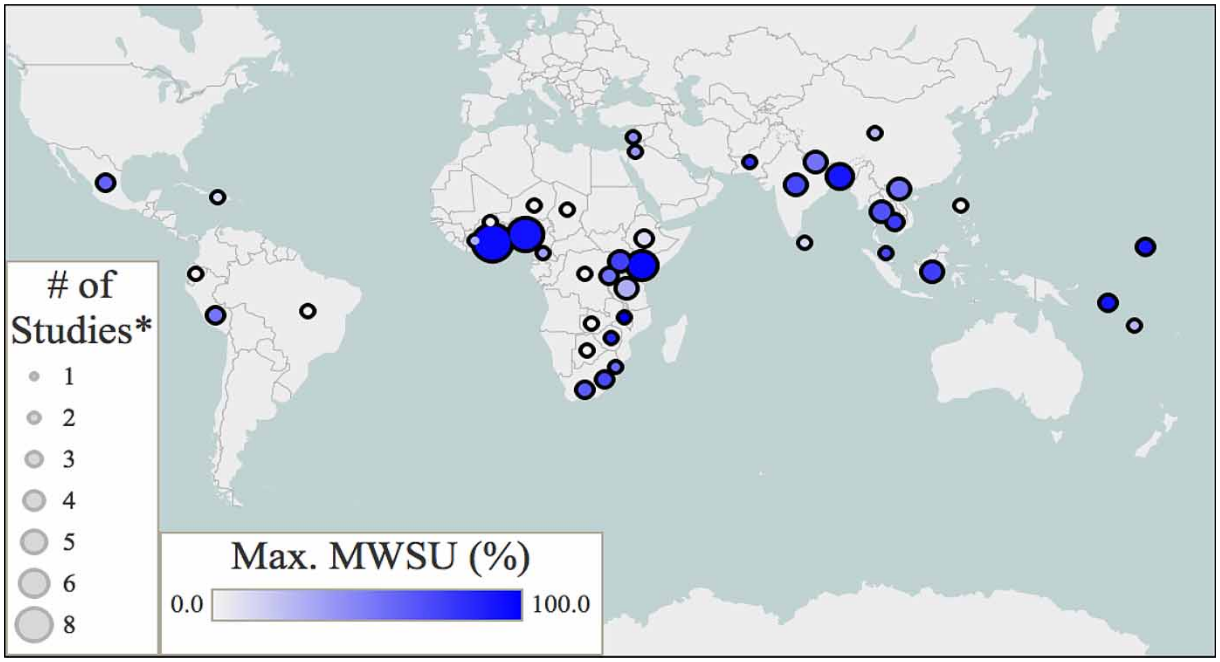


Figure 2 | Global prevalence of MWSU by the maximum reported percent of households in a given study in the country and the number of articles collected in a systematic review by low- and middle-income country ($n = 84$). *Study data are reported at the individual country level. Studies conducted in multiple countries represented on the figure in each study country. Articles which did not contain a summary statistic are represented on the map as 0%.

reported in studies conducted in many different countries, as seen in Figure 3, although several ($n = 47$ out of 74) studies collected in this review did not explicitly track this behavior.

Table 2 shows the range of reported SUSU and the number of collected articles in each SDG country region.

Data collection methodologies to capture MWSU and SUSU

Of the 74 collected articles, there were 64 cross-sectional, five longitudinal, and four intervention impact evaluation studies (See Supplementary Information SI2 and SI3). Additionally, there was one matched cohort study included in this review. If the study type was not stated by the authors, it was considered cross-sectional if multiple survey rounds for the same subjects were not explicitly mentioned. Each of the longitudinal studies was conducted with two to three survey rounds targeting consecutive seasons and/or years. These longitudinal articles targeted the same populations multiple times, conducting surveys during one wet season and one dry season to analyze the seasonal variation in water source usage and/or quality. Uniquely, Shier *et al.* (1996) conducted three seasonal surveys, targeting the hot and dry, rainy, and cold and dry seasons in Ghana. Both cross-sectional surveys and longitudinal household surveys or interviews were administered in-person.

A subset of the reviewed literature collected data on household water use behaviors explicitly in a country's wet season, dry season, or in both. Some studies also intentionally based their survey timelines on season, such as the study conducted by Rodrigues Peres *et al.* (2020), who collected water source data in the wet season of Brazil. They selected the wet season for data collection, hoping that households would be less resistant to giving away water for analysis compared to during the dry season when water is scarcer. However, other cross-sectional survey articles, which were conducted in either the wet season or the dry season, asked households to report the water sources that they use during each season (Blum *et al.* 1987; Özdemir *et al.* 2011; Md. Islam *et al.* 2013; White *et al.* 2013; Benneyworth *et al.* 2016; Elliott *et al.* 2017; Guzmán & Stoler 2018). While enumerators did not visit the same households over both wet and dry seasons, this allowed them to collect water source usage data for both seasons individually.

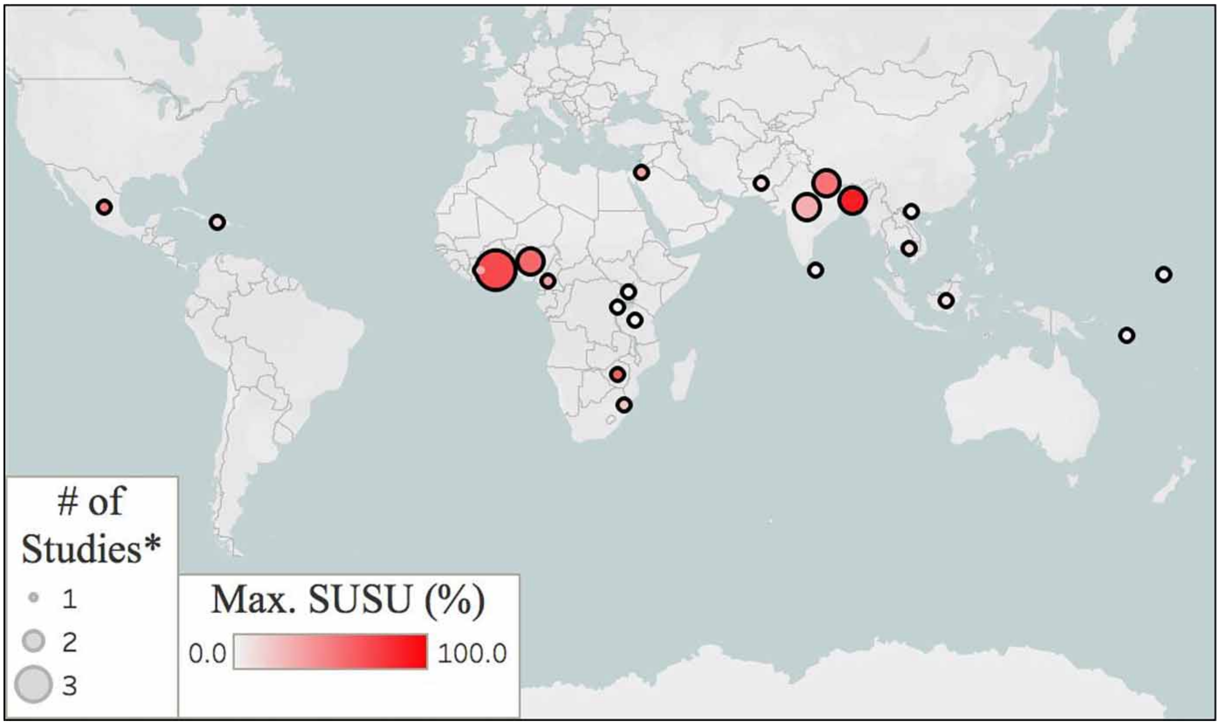


Figure 3 | Global prevalence of SUSU by the maximum reported percent of households in a given study in the country and the number of articles collected in a systematic review by low- and middle-income country$n = 28$. *Study data are reported at the individual country level. Studies conducted in multiple countries represented on the figure in each study country. Articles which did not contain a summary statistic are represented on the map as 0%.

Table 2 | Number of collected studies and reported range of SUSU) by SDG country region

SDG country region	Country code	Number of articles reporting SUSU	Range of reported SUSU (%)[a]	References
Central and Southern Asia	CASA	9	13.4–88.2	Naik *et al.* (1992), Madanat & Humplick (1993), Anthony (2007), Casanova *et al.* (2012), Md. Islam *et al.* (2013), Shrestha *et al.* (2013), Benneyworth *et al.* (2016), Guragai *et al.* (2017), and Seifert-Dähnn *et al.* (2017)
Eastern and South-Eastern Asia	ESEA	3	12.5	Wegerich (2006), Özdemir *et al.* (2011), and Jiang & Rohendi (2018)
Latin America and the Caribbean	LAC	2	13–49.2	Duke *et al.* (2006) and Ocampo-Fletes *et al.* (2018)
Northern Africa and Western Asia	NAWA	1	34.2	Coulibaly *et al.* (2014)
Oceania	O	1	–	Elliott *et al.* (2017)
Sub-Saharan Africa	SSA	11	20–71	Blum *et al.* (1987), Hoko (2005), Peter (2010), Onabolu *et al.* (2011), Krauth *et al.* (2015), Grönwall (2016), Kosinski *et al.* (2016), Pearson *et al.* (2016), Adamu & Ndi (2017), Guzmán & Stoler (2018), and Thomson *et al.* (2019)

[a]Articles provide evidence of SUSU, but may not provide a summary statistic to be included in reported prevalence.

Without being the main focus of the study, MWSU data were collected in impact evaluation studies for the purpose of evaluating water filter use (Duke *et al.* 2006; Casanova *et al.* 2012) and monitoring water source and/or quality interventions (Peter 2010; Guzmán & Stoler 2018), for example. These studies revealed MWSU occurring, but did not directly report its extent. For example, some studies use the water source as the unit of analysis, so data were reported on the fraction of study households using a particular source, instead of which sources are used by a particular household or which households engage in MWSU. Ngasala *et al.* (2019) and Guragai *et al.* (2017) reported the water source use by the percent of households using each source; so, when the percentage exceeds 100%, it is clear that some households are using multiple sources, but a summary statistic for which a fraction of households are practicing MWSU and how many sources an individual household was using was not reported.

All of the collected literature used some form of household surveys or interviews/discussions for data collection, with some studies using mixed-method approaches to investigate water source selection behaviors as well. Six studies used observation techniques to identify the behaviors around and condition of water sources (Kelly *et al.* 2018), storage and collection techniques (Kosinski *et al.* 2016; Seifert-Dähnn *et al.* 2017), and which sources community members used by directly observing how households accessed and used water (Briscoe *et al.* 1981; Grönwall 2016; Grönwall & Oduro-Kwarteng 2018; Ngasala *et al.* 2019). Focus group discussions were used in four studies to determine which sources were used in the community (Grace *et al.* 2013), how communities managed water systems (Özdemir *et al.* 2011; Shaheed *et al.* 2014; Rodrigues Peres *et al.* 2020), and community perceptions and concerns surrounding water (Shaheed *et al.* 2014). Both focus group and observation methods were able to inform MWSU rates in study communities despite not directly targeting MWSU. These data collection methods also provided insight into the reasons households engage in MWSU or SUSU. The open-ended and qualitative nature of these studies helped reduce bias from a researcher *a priori* categorizing reasons and influencing factors for MWSU and SUSU (Reja *et al.* 2003).

Factors influencing MWSU – seasonality

Seasonality was found to influence household water source selection, particularly when harvested rainwater was used as a drinking water source. Rainwater is a prominent primary water source for LMIC households during the rainy season, but households often must seek out other sources for use during the dry season. Articles collected in this review reveal that, in some cases, households switch from rainwater in the wet season to other *improved* sources in the dry season including but not limited to: water kiosks in Malawi (Velzeboer *et al.* 2018), bottled water in Vietnam (Herbst *et al.* 2009) and Bangladesh (Benneyworth *et al.* 2016), piped water in Ghana (Guzmán & Stoler 2018) and Mexico (Ocampo-Fletes *et al.* 2018), and boreholes in Ghana (Shier *et al.* 1996). These improved sources are not preferred in the rainy season for reasons such as rainwater abundance/convenience during the rainy season (Özdemir *et al.* 2011), distance from household to source (Blum *et al.* 1987), and/or piped water supply times/queues (Ocampo-Fletes *et al.* 2015). Alternatively, in some cases, households reported relying on *unimproved* sources in the dry season, and thus practice SUSU; for example, households relied on surface water in the Solomon Islands (Elliott *et al.* 2017), Mexico (Ocampo-Fletes *et al.* 2018), Vietnam (Özdemir *et al.* 2011), and Bangladesh (Md. Islam *et al.* 2013; Benneyworth *et al.* 2016) and on unprotected wells in Uganda (Pearson *et al.* 2016), the Marshall Islands (Elliott *et al.* 2017), and Mexico (Ocampo-Fletes *et al.* 2018). Notably, these studies were either conducted in rural or unclassified environments, suggesting that the lack of centralized water infrastructure could contribute to the use of natural sources such as rainwater and surface water. There are also scenarios where households have to supplement rainwater during the wet season as well. Ocampo-Fletes *et al.* (2018) surveyed rural households in Mexico, reporting 100% of households collected rainwater, specifically for drinking during the wet season, but many households concurrently collected water from a variety of sources such as piped supplies (59.7%), deep wells (50.8%), hand-dug wells and surface water (49.2%), and bottled water (38.1%).

Seasonal drivers also influence water source selection for households relying on sources other than rainwater. Kumpel *et al.* (2017) reported that some households in

Nigeria relied on borehole water in the wet season, but switched to packaged water, such as sachet and bottled, during the dry season. It was not borehole breakdown (i.e., drying up) during the dry season which drove users to packaged water; instead, Kumpel *et al.* (2017) suggested perceptions of decreased borehole water quality in the dry season influenced the shift to packaged water, as well as convenience and outdoor temperatures during the dry season. While Benneyworth *et al.* (2016) reported a majority of surveyed households in Bangladesh using rainwater in the wet season, they also reported that 44% use river water; 100% of the households relying on river water then used bottled water in the dry season, and some used tube wells and ponds in the dry season as well. They found that dry-season conditions promoted the stagnation of surface water sources (Benneyworth *et al.* 2016). Kelly *et al.* (2018) conducted interviews and focus group discussions with community members and leaders in rural Kenya, and reported that flooding during heavy rain events caused breakdowns of handpumps, and that excessive heat and dryness damaged the pipes of water systems. They also found that road flooding during the rainy season prevented the transport of externally supplied vendor water; thus, a variety of seasonal drivers led to households switching sources (Kelly *et al.* 2018).

In addition to the supply of water, seasonality can also impact the aesthetics and user perceptions of water sources, which then, in some cases, influences household choices in water source use (Kiyu & Hardin 1992; Shaheed *et al.* 2014; Seifert-Dähnn *et al.* 2017). Özdemir *et al.* (2011) interviewed Vietnamese households, reporting slight decreases in the use of rainwater and well water from the wet to dry season and the increased use of bottled water in the dry season. These trends were not due only to physical scarcity, but to the decrease in the users' opinion of the taste, smell, and color of well water and harvested rainwater during the dry season (Özdemir *et al.* 2011). Additionally, these households rated the taste, odor, and color of unimproved sources such as vendor/tanker and surface water higher in the dry season compared to the wet season, when the prominent source of rainwater – used by 88% of households – is less available (Özdemir *et al.* 2011).

MWSU allows households to adapt to seasonal shifts in water availability and quality by adapting and supplementing their primary supply with other sources; however, the safety and quality of the supplemental sources may vary from the primary source the household was using.

Factors influencing MWSU – insufficiencies in primary water sources

Beyond the seasonal influence on water source selection, some households choose to supplement their primary water source throughout the year for other reasons, including breakdown or intermittency. Studies reported 10–84% of households engaging in MWSU due to the lack of access to, intermittency of, and/or insufficient quantity of a primary supply (Kiyu & Hardin 1992; Madanat & Humplick 1993; Hoko 2005; Wegerich 2006; Anthony 2007; Peter 2010; Onabolu *et al.* 2011; Shrestha *et al.* 2013; Smiley 2013; Coulibaly *et al.* 2014; Neumann *et al.* 2014; Cherunya *et al.* 2015; Pearson *et al.* 2015; Uwera & Stage 2015; Kosinski *et al.* 2016; Adamu & Ndi 2017; Guragai *et al.* 2017; Nastiti *et al.* 2017; Seifert-Dähnn *et al.* 2017; Vedachalam *et al.* 2017; Jiang & Rohendi 2018; Kelly *et al.* 2018; Ocampo-Fletes *et al.* 2018). Hoko (2005) reported that while 100% of study individuals in one community in rural Zimbabwe have access to a borehole, 21.4% described it as unreliable due to breakdowns, and 14.2% used alternative sources of water. Onabolu *et al.* (2011) reported that 40.5% of survey households in Nigeria experienced a major breakdown in their primary source of water in 2 weeks prior to survey, and 58.1% used unimproved water to supplement their supply during these events. On the other hand, intermittent water supply occurred in some areas on a scheduled and intentional basis. Anthony (2007) found that 64% of urban Indian households that had access to a piped network only had water available for 1–3 h per day, which resulted in the use of supplemental sources. When primary water sources broke down and/or were insufficient, households in various geographies reported using alternative sources to supplement their supply, and in some cases, these alternative sources were lower quality, unimproved sources (Anthony 2007; Peter 2010; Onabolu *et al.* 2011; Neumann *et al.* 2014; Pearson *et al.* 2015; Kosinski *et al.* 2016; Adamu & Ndi 2017; Seifert-Dähnn *et al.* 2017; Ocampo-Fletes *et al.* 2018; Paul *et al.* 2018).

Within the literature, some water source types appear to be common supplemental or alternative water sources, such as packaged or transported water. It is reported that 2.2–92% of study households in LMICs used packaged or transported water to supplement their drinking water supply (Madanat & Humplick 1993; Anthony 2007; Peter 2010; Onabolu *et al.* 2011; Furlong & Paterson 2013; Smiley 2013; White *et al.* 2013; Neumann *et al.* 2014; Shaheed *et al.* 2014; Pearson *et al.* 2015; Benneyworth *et al.* 2016; Guragai *et al.* 2017; Kumpel *et al.* 2017; Nastiti *et al.* 2017; Reyes *et al.* 2017; Seifert-Dähnn *et al.* 2017; Jiang & Rohendi 2018; Kelly *et al.* 2018; Ocampo-Fletes *et al.* 2018). Reyes *et al.* (2017) found that 92% of surveyed urban households in Ecuador used bottled water when their improved primary source was intermittently available. Coulibaly *et al.* (2014) found that 39.9% of surveyed urban Jordanian households supplemented piped supplies with bottled, vended, or tanker water. Ocampo-Fletes *et al.* (2018) reported that 38.1% of surveyed rural households in Mexico supplemented their drinking supplies with bottled water, spending an average of 92.40 USD per week. Grace *et al.* (2013) found that while 64.6% of Nigerian study households used wells and 13.8% used boreholes for drinking, 21.1% of them purchased bottled or sachet water to cope with shortages.

Unreliability is a main driver for households with improved piped connections to practice MWSU. Several studies reported households with piped water supplies engaging in MWSU ($n = 23$) (Kiyu & Hardin 1992; Naik *et al.* 1992; Madanat & Humplick 1993; Howard *et al.* 2002; Hoko 2005; Wegerich 2006; Anthony 2007; Peter 2010; Casanova *et al.* 2012; Shrestha *et al.* 2013; Coulibaly *et al.* 2014; Neumann *et al.* 2014; Espinosa-García *et al.* 2015; Huang *et al.* 2015; Uwera & Stage 2015; Grönwall 2016; Adamu & Ndi 2017; Guragai *et al.* 2017; Nastiti *et al.* 2017; Reyes *et al.* 2017; Seifert-Dähnn *et al.* 2017; Jiang & Rohendi 2018; Ocampo-Fletes *et al.* 2018), and nine of them reported unreliability as their reason for practicing SUSU (Madanat & Humplick 1993; Wegerich 2006; Anthony 2007; Shrestha *et al.* 2013; Coulibaly *et al.* 2014; Adamu & Ndi 2017; Guragai *et al.* 2017; Jiang & Rohendi 2018; Ocampo-Fletes *et al.* 2018). Additionally, households with piped, on-plot water, the top of the water source quality ladder described by the WHO (WHO & UNICEF 2017), were not exempt from practicing MWSU or even SUSU. Casanova *et al.* (2012) reported that approximately 4.0% of study households in Sri Lanka had a water tap inside their home, but still accessed wells which were mostly shallow and hand-dug. Seifert-Dähnn *et al.* (2017) surveyed nine villages in rural India and found that an average of 56% of households across villages had piped tap water directly into their dwelling; however, 71% of respondents accessed an alternative water source, including open wells or surface water. While safely managed piped supplies are considered among the highest quality classifications of water sources by the JMP, due to breakdowns and insufficiencies, many households across multiple regions supplement their piped, on-plot supplies with unimproved sources throughout the year (i.e., engage in SUSU).

Factors influencing MWSU – other

While primary water sources do not always meet households' quantity needs, causing households to use supplementary sources, other factors (i.e., aesthetics and cost) can also influence MWSU. Aesthetics, outside of those influenced by seasonal changes, and quality perceptions can have significant impacts on the water source selection behaviors of households in LMICs (Kiyu & Hardin 1992; Wong 2000; Hoko 2005; Herbst *et al.* 2009; Smiley 2013; Espinosa-García *et al.* 2015; Grönwall 2016; Kosinski *et al.* 2016; Guragai *et al.* 2017; Grönwall & Oduro-Kwarteng 2018). Kosinski *et al.* (2016) conducted household surveys in rural Ghana, documenting that 53.8% of households used improved borehole water due to its perceived, not actual, health benefits, in addition to using river water over borehole water for its taste. Kumpel *et al.* (2017) also reported that households in Nigeria switched away from borehole water due to its perceived quality. Espinosa-García *et al.* (2015) also found that 11.3% of respondents in Mexico City used bottled water in addition to tap water, with 26% of households citing a perceived lack of trust in tap water quality, as well as 54.1% citing a preference for the taste and odor of bottled water.

Distance to and cost of higher quality water are also reasons that users may switch to other, lower quality water sources within the same year. Adamu & Ndi (2017) described a water access situation in urban Cameroon, where low-income households lacked access to the piped network and were less able to afford expensive treatment options needed to improve the quality of water coming from handpumps and tube wells. They also cited the cost of tanker-delivered water as a problem, which has influenced 97% of households to use neighborhood ponds for drinking water (Adamu & Ndi 2017). Grace *et al.* (2013) described that 80.5% of study households in Nigeria claimed vended water to be unaffordable at certain times, leading them to seek out other alternatives such as bottled water and surface water. Supply times or long lines were also reported to dissuade users from using improved water sources, such as piped supplies in Mexico by Ocampo-Fletes *et al.* (2018), or from borehole water in rural Ghana by Kosinski *et al.* (2016) and in Malawi by Velzeboer *et al.* (2018). Kelly *et al.* (2018) interviewed community members in rural Zambia, finding that individuals primarily used boreholes, but also chose to use shallow wells as an alternative because the borehole was farther away. Physical distance to source and convenience have been reported as driving users to supplement specifically with packaged or transported water in Thailand (White *et al.* 2013), Ghana (Grönwall 2016; Kosinski *et al.* 2016; Grönwall & Oduro-Kwarteng 2018), and Peru (Furlong & Paterson 2013).

DISCUSSION

MWSU commonly practiced but currently neglected in global monitoring

Current JMP global monitoring for the UN SDG 6 (target 6.1) captures only the primary source of water a household uses for drinking, while this review suggests that many households in LMICs may have different 'primary' sources depending on which season they are surveyed and often use more than just one source of water to meet their needs over the course of the year. The practice of SUSU (i.e., supplementing improved primary water sources with water from unimproved sources), in particular, needs to be captured in global monitoring efforts for tracking access to safely managed drinking water. Neglecting the practice of SUSU in global monitoring may cause overestimates in global access to safely managed drinking water. In their African and Asian study geographies, Vedachalam *et al.* (2017) estimated that true unimproved water use may be underreported by up to 13.9% compared to DHS survey results when considering other water sources households used beside the primary source. As water from unimproved sources is more likely to contain fecal contamination compared to water from improved sources (Bain *et al.* 2014), SUSU represents a pathway for exposure to waterborne contamination and its associated health risks are currently not captured in global monitoring efforts which focus on primary sources of water only. Additionally, household water storage can be a pathway to exposure (Clasen *et al.* 2007), as it is possible for households using both improved and unimproved water to mix both in the same storage container (Shaheed *et al.* 2014; Ngasala *et al.* 2019; Rodrigues Peres *et al.* 2020), contaminating their improved household drinking water. This review reports evidence that many households in LMICs with access to improved primary water sources, including those with piped on-plot supplies – among the highest of the JMP drinking water service ladder – still access unimproved water sources. The practice of SUSU may have serious implications for health. Hunter *et al.* (2009) reported that even a few days per year of consuming contaminated water, due to the improved water supply system being interrupted, may negate the annual health benefits of consuming safe drinking water. They found that the yearly risk of enterotoxic *E. coli* infection reaches 99% after 34 days of interruption, and that the yearly risk of Cryptosporidium and Rotavirus infection reaches 100% after more than just 1 day of interruption. This underscores the importance of capturing SUSU, even if occurring infrequently.

While this review does highlight evidence of MWSU and SUSU in various geographies, there are still significant limitations in our current understanding of the true prevalence of these behaviors. Bias in the selection of study regions (e.g., the potential that certain areas are more frequently selected for water interventions, therefore more likely to contain studies reporting MWSU), review criteria (e.g., key word search, accepting only English-published studies), and the under-studied nature of this issue all contribute to our review results not being representative of the global situation. The factors that we discussed influencing MWSU are likely context-specific, and the exclusion of many geographies and populations, due to limited studies investigating this topic, prevents the full characterization of factors. In countries where MWSU data are accessible, differences in water source selection between and within studies conducted during the wet season and the dry season reveal the potential for seasonal bias in cross-sectional studies collecting data on drinking water sources. For example, rainwater is predominantly reported as a primary drinking water source in studies conducted in the wet season; however, this may reflect the availability of rainwater in the wet season and thus over-emphasizes a household's yearly reliance on rainwater. These differences between wet- and dry-season survey results are also reflected in the different seasonal source usage reported across studies that are conducted in both wet and dry seasons. This suggests that cross-sectional, season-specific survey techniques may not capture a household's full scope of sources accessed over the year, but instead reflect the source (i.e., current primary source) used during the season during which the survey was conducted.

Current efforts to capture the reliability of primary drinking water sources would miss different household experiences regarding MWSU, including seasonal source water switching. The part of the WHO definition for safely managed drinking water, described in SDG indicator 6.1.1, is that the source is 'available when needed' (WHO & UNICEF 2017). Kumpel & Nelson (2016) synthesize WHO estimates, stating that approximately one-third of piped water supply systems in Latin America and Africa and over half of systems in Asia are intermittently functioning. This review presents evidence that intermittent, unreliable, or unavailable primary sources can cause households to resort to SUSU. However, there is limited data on the threshold of availability of the primary source that results in negative health outcomes if the household supplements with an unimproved source (SUSU), a behavior currently not explicitly captured in the global monitoring of safe drinking water access. Some proposed indicators of reliability include survey questions such as: 'Do you have water continuously,' 'Does water arrive seven days a week,' and 'Has your municipal water supply been interrupted at any time during the last 12 months?' (WHO & UNICEF 2017). The current recommended global benchmark, however, is if a water service is available for at least 12 h per day (WHO & UNICEF 2017). Importantly, some households may practice SUSU, even if their primary source is technically available, so these questions would not capture SUSU in full. In addition, not all supplemental improved water sources are safe, as there is also evidence that packaged water, a common supplemental water source, can be contaminated with feces. Kumpel *et al.* (2017) found 24% of sachet water samples in Nigeria positive for *E. coli*, a fecal indicator bacteria. As global monitoring questions for safe drinking water access do not account for seasonal changes in water sources or infrequent source switching due to insufficiencies with primary water supplies or other reasons, SUSU remains a currently neglected, yet potentially hazardous, practice that needs to be captured in global monitoring efforts.

MWSU and designing successful water interventions

Many non-governmental organizations (NGOs) and governmental organizations design and implement interventions to improve access to safe drinking water. Water infrastructure interventions are one such strategy where new water supplies are provided to households (Fewtrell *et al.* 2005; Clasen *et al.* 2007). MWSU can impact the effectiveness and sustainability of new water infrastructure, particularly related to the negative health impacts of SUSU and the reduced revenue stream from households not using the projected quantity of water of the new, improved water infrastructure.

Water infrastructure upgrades and payment schemes are often designed assuming a certain level of use by community members (African Development Bank 2010), given that the system is designed to recover costs. However, MWSU can decrease the accuracy of quantity estimates resulting in a less reliable payback period for new investments. With the previously stated prevalence of the MWSU behavior globally, consumers will likely draw less water from a single piped supply than a service provider estimated and thus incur less user fees (contingent on a volumetric pricing structure). While user fees rarely reflect the true cost of water due to heavy government subsidies (Majumdar & Gupta 2009), they still represent an important revenue stream. These particular financial impacts of MWSU have not been widely studied, but incorporating MWSU behaviors of consumers could be important for designing successful, financially viable, water interventions.

There is evidence that households in many low-income country contexts often have several options for water sources (e.g., vended water, neighbor's water, and many shared water points that are within a reasonable distance), and water fetchers must undergo a complex decision-making process to select a source to use on a particular occasion (Nauges & Whittington 2010; Gross & Elshiewy 2019; Smiley & Stoler 2020). For example, Cook *et al.* (2016) describe that while 91% of their study population in Kenya have access to three to five drinking water sources, the average household uses just 1.9 sources per year and 1.4 sources per week. Water source selection decisions are thought to be guided by assessing the resource efficiency, where households are assessing trade-offs between different characteristics of the source options, such as cost, collection time, and distance to source (Nauges & Whittington 2010, Gross & Elshiewy 2019; Smiley & Stoler 2020). Nauges & Whittington (2010) describe a particular scenario, where a household water collector must estimate the value of their time that is spent collecting water, in order to determine whether purchasing expensive water or spending long periods of time collecting free/inexpensive water is the most resource efficient. These decisions may also interact with the conditions currently of the household, such as income, other household demands (e.g., health of household members and other utility costs), and relationship with community members (e.g., feud with neighbor, relationship with water vendors, and social status relative to other users of a water source) (Smiley & Stoler 2020). Thus, when implementing a water infrastructure intervention, it is important to recognize that households will likely continue to have 'access' to many different sources. Understanding their decision-making process for source selection can help inform the extent to which households will solely rely on new water infrastructure, as well as informing the design of new infrastructure based on the characteristics of the system installed and of the target population.

The MWSU behavior also has the potential to skew recorded health impacts of water infrastructure interventions. Reviews of such interventions have found a range of health benefits from improved maternal health to reduced diarrheal illness (WHO & UNICEF 2017; Luby *et al.* 2018), with some interventions resulting in no clear improvements to rates of diarrheal disease and child stunting (Pickering *et al.* 2019). The practice of MWSU and in particular SUSU, among numerous factors pertaining to sanitation and hygiene conditions, could help explain the limited gains. A household drawing even a small portion of their water from an unimproved water source could open an unmonitored pathway of exposure to pathogens (Hunter *et al.* 2009) since unimproved sources are more likely to be of poorer microbiological quality (Bain *et al.* 2014). This behavior could explain the persistence of diarrheal illness rates even after the installation of an improved community water source. Another behavior, which could skew health impacts of a particular intervention, is the mixing of source waters in storage containers. This practice has been commonly documented in multiple regions and is generally regarded as degrading overall water quality (Ngasala *et al.* 2019; Rodrigues Peres *et al.* 2020). SUSU in combination with mixing source waters could exacerbate this degradation and serve to nullify the impact of improved storage containers on protecting stored water quality.

The impacts of MWSU and SUSU on the success of interventions have not been rigorously evaluated. Future work is needed to provide concrete evidence of the financial and health implications of MWSU and SUSU in the context of water infrastructure interventions.

MWSU in a changing climate

The narrative of MWSU and SUSU as seen through the lens of a changing climate and seasonality is highly contextual. The effect of climate change varies by geographic region and exacerbates weather events, such as changes in El Niño events leading to increased drought in southern Africa and increased precipitation and flooding in eastern Africa (Yeh *et al.* 2009; Siderius *et al.* 2018). Climate change and climate factors can influence water source accessibility by causing flooding or destroying paths to sources during the rainy season (Shier *et al.* 1996; Kelly *et al.* 2018), causing inaccessibility during dry-season drought (Kelly *et al.* 2018; Luetkemeier & Liehr 2018), changing water quality (Vineis *et al.* 2011; Benneyworth *et al.* 2016), and changing water aesthetics (taste, smell, and color) (Özdemir *et al.* 2011; Vineis *et al.* 2011). In years to come under a changing climate, it is expected that these events will be more frequent and extreme (IPCC 2014), leading to more occurrences of sources being inaccessible (Howard *et al.* 2016; Luetkemeier & Liehr 2018; Guo *et al.* 2019).

Several factors, including but not limited to geographic location, urban versus rural settings, aesthetic perceptions, cost, and convenience influence a household's decision to engage in MWSU and SUSU in response to climate change. Source-choice decisions influenced by these factors may include switching primary drinking water sources or supplementing through MWSU or SUSU when a water source is influenced by climate change (e.g., by changes in aesthetics, quantity, cost, and convenience) (Howard *et al.* 2016; Elliott *et al.* 2019). Flooding can cause households to rely on more convenient, but often unimproved, sources such as surface water (Shier *et al.* 1996; Kelly *et al.* 2018). Under drought, households may abandon drought-prone sources, such as rainwater (Luetkemeier & Liehr 2018; Elliott *et al.* 2019), and use more reliable dry-season sources such as public taps or water vendors. Having access to more than one water source can offer resilience to water scarcity but often comes at a greater financial cost (de Queiroz *et al.* 2013; Francisco 2014).

Total household coping costs due to climate change are expected to increase, whether it is paying for vended water or accounting for time lost to collecting water from more reliable sources at greater distances (Rai *et al.* 2019). Even within countries, the coping costs of water scarcity can vary significantly, as it is reported that annual average household coping costs associated with purchasing water from the market are NPR 925.67 (USD 7.58) in Dhulikhel, Nepal and NPR 5866.51 (USD 48.03) in Dharan, Nepal (Rai *et al.* 2019). Similarly, across Kenya, it is reported that households using different primary water sources experience different monthly coping costs associated with purchasing vended water (Cook *et al.* 2016). Households with a public well as their primary source had an average monthly coping cost for the vended water of KSH 367 (USD 3.43) in the dry season, and households with a private piped supply had an average monthly coping cost for the vended water of KSH 15 (USD 0.14) in the dry season.

Additionally, households may cope with scarcity in other ways, including borrowing water from others. Rosinger *et al.* (2020) describe survey results from 19 LMICs that suggest that a significant number of households may regularly borrow water from other households when faced with water scarcity, spreading the scarcity burden from the household level to the neighborhood or community level. Furthermore, Smiley & Stoler (2020) discuss evidence that households may be barred from accessing certain sources based on social status (e.g., caste and income group), that households with personal relationships with water vendors/utilities may receive preferential treatment, and that inter-household relationships may negatively impact the ability to trade/borrow water during times of scarcity. Climate-induced water scarcity will likely place a further strain on these coping mechanisms, and households with lower financial resources, fewer community connections, or of lower social status may be at a higher risk of experiencing water scarcity.

When considering the potential positive and negative outcomes of using MWSU as a common water management practice in a changing climate, it is crucial to understand the regional context and work to capture it in its entirety. If resources are available, conducting longitudinal studies instead of cross-sectional studies offers advantages in covering household water source use and coping strategies across seasons and weather events exacerbated by climate change. Water safety plans developed by the WHO can also be expanded to incorporate MWSU in climate resilience plans (Davison *et al.* 2005). While MWSU offers opportunities to build climate resilience to water insecurity perpetuated by seasonality and a changing climate, it can also lead to various health and financial implications. SUSU can occur as a household steps down on the water services ladder defined by the JMP in response to climate change-induced water source failure, leading to greater health risk (WHO & UNICEF 2017). In a case where a household moves up the ladder to a safely managed water source, such as going from surface water to vended water during drought, the health risk is decreased but at a greater financial cost as households pay for services (Cook *et al.* 2016). When incorporating MWSU into water safety plans, the health and financial implications specific to a regional context must be accounted for. Climate-induced MWSU and SUSU draw attention to SDG indicator 6.1.1, in which it is important to capture the reliability of water sources. Households that rely on water sources that are not accessible when needed may be particularly susceptible to climate-induced MWSU or SUSU, and coping costs are anticipated to increase as a result of changing temperature and rainfall patterns (Cook *et al.* 2016).

Knowledge gaps, recommendations, and a path forward

Currently, MWSU and its implications are rarely investigated. As a relatively unexplored topic, there are significant gaps in knowledge surrounding MWSU challenges by the global region, common types of secondary/alternative sources, and potential health risks and increased exposures. As the JMP tracks access and progress to safe and safely managed drinking water via household surveys, this systematic review reveals some characteristics of modern survey and monitoring practices that have contributed to the lack of knowledge on this behavior. As surveys are developed to be as short and streamlined (and low cost) as possible, most involve a single-time point collection and focus on primary water sources, rather than capturing the full profile of water sources a household may use over a year. However, in order to address potential health risks due to MWSU and SUSU during interventions or studies where water source quality is analyzed, we strongly recommend that surveys incorporate questions on MWSU, including determining the proportion of water taken from different sources, particularly distinguishing between improved and unimproved sources. The WHO's Core Questions for Water, Sanitation, and Hygiene Household Surveys (WHO & UNICEF 2018) include targeting a household's 'main' water source, and only the extended questions capture a household's use of multiple sources. Adding these extended questions to the list of core questions would promote the importance of this issue and capture the risky practice of SUSU, and thus better characterize safe drinking water access globally.

Additionally, the studies captured in this review suggest that there are differences in reported water source usage depending on when, seasonally, a study takes place (Kiyu & Hardin 1992; Shier *et al.* 1996; Furlong & Paterson 2013; Benneyworth *et al.* 2016; Kumpel *et al.* 2017; Guzmán & Stoler 2018; Paul *et al.* 2018). With the evidence that households commonly switch sources or use multiple sources seasonally, their answer to a question, such as 'what is the primary/main source of drinking water?', would change depending on the season. Longitudinal studies, as mentioned earlier, would allow for the higher temporal resolution capturing of water use behaviors and reduce recall bias. However, longitudinal studies are both resource and labor intensive to conduct. One potentially more feasible strategy to collect this information from households is recruiting households to log their own water decisions and behavior for a period of time using water diaries. Hoque & Hope (2018) effectively used water diaries to capture the use of multiple water sources (among other findings) over a 4-week period in Kenya, with an average of five water sources per household being reportedly used over that period. In a longer 18-week study in Bangladesh, they also found households reporting using multiple sources using the water diary method (Hoque & Hope 2020). During their cross-sectional survey, approximately 80 and 55% of households reported using improved water sources as their main source for drinking and cooking, respectively. However, the water diary results reveal that the use of sources fluctuates over time, and that numerous other sources, including unimproved sources, are regularly used throughout the study period. Specifically, a small minority of households reported in the cross-sectional survey using unimproved vended water as their main source for drinking (<10%) and cooking (<5%); however, the water diaries revealed that, on certain days, over 60% of households are using vended water for consumptive purposes. Additionally, deep tube wells were cited as the most common main source for drinking (~55%) and for cooking (~35%) during the cross-sectional survey; however, the water diaries indicate that they were actually the least commonly used source in the community, with less than 10% of households on average using deep tube wells on a daily basis (Hoque & Hope 2020). This illustrates the temporal variation in water source selection and use, highlighting limitations of cross-sectional surveys only capturing the household's primary water source at the time of surveying. If regular, repeated visits are not possible to collect data on water source selection, we recommend that water diary strategies be considered for capturing MWSU. If a cross-sectional survey must be used, we recommend capturing both primary and supplemental water sources used by the household for drinking, with separate questions for different seasons.

As new technologies emerge, there are additional options for assessing water access. Technology, such as Landsat imaging, could be used to remotely analyze the conditions of surface water and coastal water areas and potentially observe if water access points are online or damaged (Andres *et al.* 2018). Alternatively, the current methods of surveys and interviews can be supplemented with sensor technology. There is evidence that reported behavior and actual behavior vary (Vedachalam *et al.* 2017; Kirby *et al.* 2019); Kirby *et al.* (2019) found significant reductions between reported water filter use and water filter use measured with a covert sensor. Physical sensors attached to provided storage containers, household filter systems, and/or water sources themselves (Turman-Bryant *et al.* 2019) could allow for tracking the volumetric use of different sources, revealing potential bias in survey responses or underreporting in unimproved water source usage. At the very least, using computer-assisted (MacDonald *et al.* 2016) survey techniques can reduce costs and expand the capabilities of a survey compared to traditional methods, such as paper-and-pencil enumeration. Digital methods can be further extended by using mobile phone surveys and/or interviews, commonly used in the mobile health field (mHealth), for data collection.

Capturing the quantity of water that a household obtains or drinks from each source is also a critical gap of knowledge in understanding the implications of this behavior. Cook *et al.* (2016) conducted household surveys in rural Kenya, evaluating household primary and supplemental water source behaviors, as well as estimating the quantity of water obtained from each source by households. Guzmán & Stoler (2018) also estimated the volume of water collected by a household from each source during their survey in rural Ghana. This was an uncommon addition to a survey and a more comprehensive estimation of the full scope of household water collection behaviors (Cook *et al.* 2016). Collecting data regarding the quantity of water collected from each source (i.e., via surveys/questionnaires, structured observations, water utility data, or volumetric sensors), combined with the microbial quality of source water, would allow for the estimation of the health risk or exposure to pathogens due to MWSU. From this analysis, the different risk thresholds associated with different MWSU and SUSU behaviors could be characterized. Risk assessment could also provide insight into how reliable a water source needs to be in order to prevent negative health outcomes associated with SUSU. This is critical information to gather and should be prioritized in order to understand how best to manage water systems in order to avoid unsafe or risky water use behaviors. This will also help determine the best data collection methods for capturing the level of 'availability' or 'sufficiency' for water sources that households' access, and reflect the actual health risks to users. It is critical to adopt these types of practices and study designs in order to accurately report global safe water access and identify important pathways of exposure to contaminated water.

CONCLUSIONS

This review presents evidence that the use of multiple sources for drinking water is a common phenomenon in LMICs. Furthermore, the practice of supplementing primary improved water sources with an unimproved source, or SUSU, occurs in many populations across multiple regions. SUSU remains undocumented in global monitoring efforts, raising concerns about the accuracy of safe drinking water estimates. The unmonitored use of unimproved water sources, its impact on water intervention effectiveness, and the potential for building climate resilience in the realm of water access as a result of the MWSU and SUSU behaviors have varied but important implications for human health. Further research and continued understanding of the drivers of MWSU are needed in order to capture the full scope of this important behavior and to inform future planning and intervention efforts. Improved data collection methods, such as expanding survey questions to capture a household's full profile of sources used annually and prioritizing longitudinal season-specific studies, are crucial in achieving the goals outlined in SDG 6 for global safe drinking water access.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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