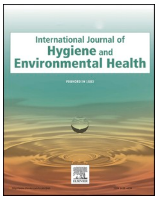
International Journal of Hygiene and Environmental Health 231 (2021) 113632

Contents lists available at ScienceDirect

International Journal of Hygiene and Environmental Health

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



Daily changes in household water access and quality in urban slums undermine global safe water monitoring programmes

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ARTICLE INFO

Keywords:
Drinking water
Slums
Water access
Microbial pollution
SDG6
Malawi

ABSTRACT

Global drinking water monitoring programmes and studies on water quality in urban slums often overlook short-term temporal changes in water quality and health risks. The aim of this study was to quantify daily changes in household water access and quality in an urban slum in Malawi using a mixed-method approach. Household drinking water samples ($n = 371$) were collected and monitored for *E. coli* in tandem with a water access questionnaire ($n = 481$). *E. coli* concentrations in household drinking water changed daily, and no household had drinking water that was completely safe to drink every day. Seasonal changes in drinking water availability, intermittent supply, limited opening hours, and frequent breakdown of public water points contributed to poor access. Households relied on multiple water sources and regularly switched between sources to meet daily water needs. There were generally similar *E. coli* levels in water samples considered safe and unsafe by residents. This study provides the first empirical evidence that water quality, water access, and related health risks in urban slums change at much finer (daily) temporal scales than is conventionally monitored and reported globally. Our findings underscore that to advance progress towards Sustainable Development Goal (SDG) Target 6.1, it is necessary for global water monitoring initiatives to consider short-term changes in access and quality.

1. Introduction

Globally, 785 million people lack access to even the most basic drinking water services (UNICEF and WHO, 2019), which can significantly affect their health and wellbeing. For example, in 2016, there were an estimated 485,000 deaths from diarrhea attributable to inadequate water access (Prüss-Ustün et al., 2019). On a global scale, access to safely managed drinking water services has improved over recent years (Fuller et al., 2016). However, the burden of unsafe water is still disproportionately higher in low and middle-income countries, particularly countries in sub-Saharan Africa (SSA) where, in 2015, the number of deaths attributable to water pollution was higher than any other region in the world (Forouzanfar et al., 2016; Landrigan et al., 2018).

In SSA and elsewhere in the Global South, population growth and rapid urbanization have created ‘slums’ where most of the urban population lives. While we acknowledge the negative connotations of the term ‘slum,’ we use it here broadly to capture a diversity of settlements that lack access to basic services, while recognising that other terms (e.g. informal settlement) have their own drawbacks (Ezeh et al., 2017; Gilbert, 2007). An estimated 881 million people lived in slums in 2014 (UN-Habitat, 2016), and this number is predicted to grow to at least 3 billion by 2030 (UN-Habitat, 2014). Most residents in slums are poor, water insecure, and regularly deal with overcrowded and risky environmental conditions (Adams et al., 2020). There are often pervasive deficiencies in the water supply (and issues of access) within slums because they lie outside of centralised urban water infrastructure (Ezeh et al., 2017). Many slum dwellers do not own private taps, so they depend on costly but often unsafe water from private water vendors (Adams and Vasquez, 2019).

Target 6.1 of the SDGs calls for “universal and equitable access to safe and affordable drinking water for all” by 2030 (UN General Assembly, 2015). Achieving this target requires improved monitoring of safe water over both short and long time scales, particularly in slums where access to safe water may vary with multiple

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https://doi.org/10.1016/j.ijheh.2020.113632
Received 7 April 2020; Received in revised form 8 August 2020; Accepted 11 September 2020
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temporally-dependent factors, including income, season, and availability, as well as being shaped by social relations and poverty (Adams et al., 2020; Price et al., 2019). In order to measure progress towards Target 6.1, a 'drinking water ladder' was developed and has become an integral part of the WHO & UNICEF's Joint Monitoring Programme (JMP) (WHO and UNICEF, 2017). The JMP drinking water ladder benchmarks service levels across countries and provides an aspirational global target of a 'top rung,' which in practice means that everyone in that country has access to *safely managed water*; i.e., "drinking water from an improved water source which is located on premises, available when needed, and free from faecal and priority contamination". This definition represents a significant step forward from the Millennium Development Goals (2000–2015), where water quality was often inferred from the water source (Bain et al., 2014).

Currently, the WHO (World Health Organisation) recommends the enumeration of *Escherichia coli* (*E. coli*) in drinking water as the best faecal indicator organism for monitoring recent faecal contamination (Kostyla et al., 2015; UNICEF and WHO, 2019). The majority of drinking water quality studies measuring *E. coli* in slums have been cross-sectional (e.g., Blanton et al., 2015; Debela et al., 2018) or seasonal (e.g., Kostyla et al., 2015) in design. A major limitation of these studies is that they overlook the potential for household drinking water quality to change over much shorter timescales (e.g., day-to-day) in response to changes in source contamination, availability, reliability, and affordability (Price et al., 2019). For example, in SSA residents often have a secondary (or 'back up') drinking water source for when their preferred source is unavailable (Okotto et al., 2015; Tutu and Stoler, 2016), e.g. due to breakdown of the source or limited supply.

Understanding short-term changes in water quality and access is vitally important for rapid progress towards target SDG6.1 since one-off measurements by month or season can mask other temporal changes in access, quality, and associated health risks experienced by residents of slums. However, monitoring changes in drinking water quality at such high temporal resolution is challenging because of the increased resource requirements of such monitoring and the lack of standardised study designs that take this approach. Therefore, our aim was to assess how the key factors that underpin access to water in slums (i.e., accessibility, reliability, affordability) change over time and to quantify whether access to safe drinking water changes from day-to-day. To achieve this aim, we undertook daily water quality (*E. coli*) monitoring of drinking water at the household level in parallel with a community-wide questionnaire and examined issues of drinking water access in Bangwe, an urban slum in Blantyre, Malawi.

2. Methods

2.1. Study area

This study was undertaken in Bangwe, a slum to the east of Blantyre, Malawi's second-largest city and commercial capital (Fig. 1). Between 2008 and 2018, Blantyre City's population grew by 2% per annum, and its population in 2018 was 800,264, with nearly 65% of the population living in urban low-income, informal, and unplanned settlements (Malawi Government, 2019). Bangwe was chosen as the study area because of its high population density and the low-income status of its residents. It has a particularly hilly topography, which means that there is a reliance on a variety of tap, ground, and surface water sources, and many residents use communal water points rather than relying on household taps (Magoya, 2018).

Blantyre's geographic location, in the Shire-Zambezi river basin, means that freshwater is relatively abundant in comparison to some parts of southern Africa (Tchuwa, 2018). In Blantyre City, tap water is abstracted, treated, and distributed by the local water board (Kalulu and Hoko, 2010). However, the city faces many water management challenges, including a lack of tap water infrastructure into low-income communities, water losses through the piped system, the poor water supply and quality, and lack of reliable electricity supply (Adams and Zulu, 2015).

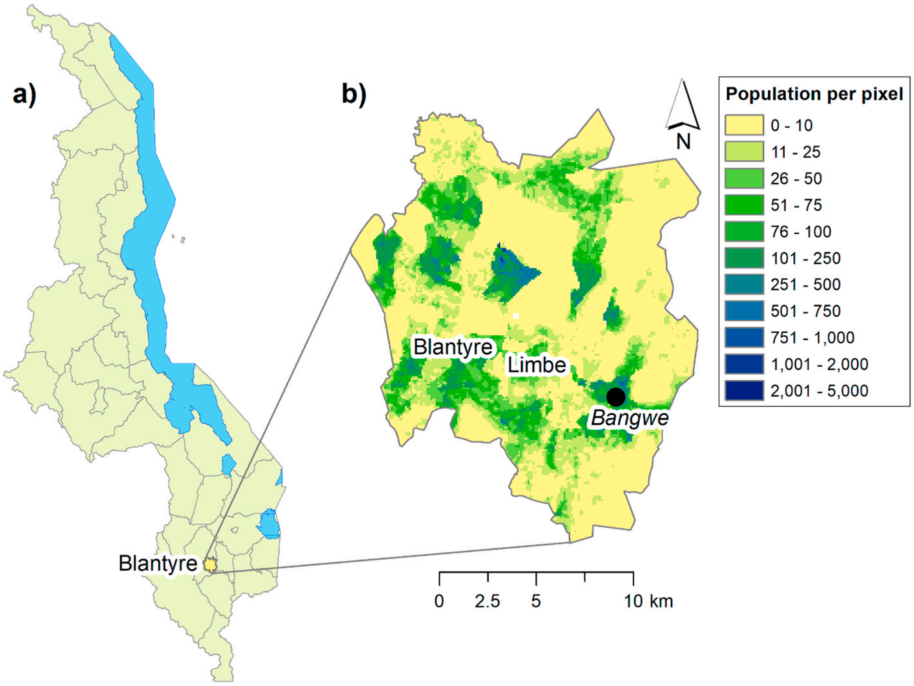


Fig. 1. Study site locations: (a) Malawi and (b) the Blantyre district, including the study site Bangwe. Blantyre district has been shaded by population numbers per pixel (WorldPop, 2017).

2.2. Data collection and analysis

To determine the temporal dynamics of water access and water quality, a multi-level mixed methods approach was used. In-depth questionnaires (section 2.2.1) were used to explore community-level views on the temporal dynamics of water access and quality. A subsample of these households were also recruited for a household drinking water quality study, which combined daily monitoring of their household water quality with a daily water practices questionnaire designed to explore factors that could temporally affect household water quality (section 2.2.2).

2.2.1. In-depth water access questionnaires

Questionnaires were used to gather information about household residents' socio-economic status, water access and use, water consumption, storage and treatment practices, sanitation facilities, hygiene practices, and future community water recommendations from adult residents. The questionnaire generated both quantitative (from multiple choice and yes/no questions) and qualitative (from open-ended questions) data. Questionnaires were designed by the research team, with some questions building on standard question designs (e.g., those used in the WHO & UNICEF JMP (UNICEF and WHO, 2018)) and others developed *de novo*. The study protocol was approved by the University of Stirling General University Ethics Panel (reference: GUEP169). The questionnaires were piloted by the research team and adapted as necessary.

A stratified random sampling approach was used during the two field missions in July/August 2017 (the dry season) and January 2018 (the rainy season). In brief, communities were geographically split into near-equal sized parcels using Google Maps satellite imagery, and each parcel was targeted for questionnaire sampling on a different day with the aim of covering the whole of Bangwe between the two sampling campaigns. In this way, each household included in the sample participated only once. Within each parcel, a research assistant (RA) was allocated a walking transect, designed to ensure that coverage within the parcel was maximised. Along each walking transect, RAs stopped at every n house (where n was determined by rolling a dice) to ask if they would participate. The number of households that declined to participate was not systematically recorded by RAs, but anecdotally was below approximately 10%. The household head or, if the household head was unavailable, another adult (over 18 years of age) in the household was recruited. Community members were asked to read an information sheet (or have this read to them) before giving their consent to participate. The survey questions were asked in the local language, Chichewa, and the responses ($n = 481$ [314 in July/August 2017 and 167 in January 2018]) recorded in English on paper questionnaires. Data was subsequently input to SPSS (version 23) by an independent researcher, and quality assurance and quality control checks were undertaken to reduce data input errors.

2.2.2. Daily drinking water quality testing study

A subset of 30 households that had participated in the in-depth questionnaire (section 2.2.1) were selected to participate in the second phase of the study. The 30 participating households were selected based upon their geographic location, their primary source of water, and their willingness to participate in both the baseline and the follow-up sampling campaign. During the two sampling campaigns, these households were visited every day for seven consecutive days, and an RA collected a sample of their household drinking water, which was linked to a daily questionnaire exploring some of the key water practices that may affect household drinking water quality. The decision to focus on daily drinking water monitoring (rather than weekly or hourly, for example) represented a balance between being able to capture the variation in *E. coli* that we theorised in (Price et al., 2019) (resulting from changes in factors including water access and water practices) and the practicality of collecting and analysing the drinking water samples.

A total of 371 drinking water samples were collected from the 30 households during the maximum of seven consecutive days in both July 2017 and January 2018 by trained RAs. Concurrently, a daily water quality practices questionnaire was undertaken with residents. The questionnaire was purposefully short and was used to collect information on the source of the water, perceptions of safety, transport and storage, water treatment, and household cases of diarrhea in the previous 24 h.

For some households, it was not possible to collect a drinking water sample every day because there was no one at home, e.g., residents were at work or had gone to church, while some residents moved house between the two sampling campaigns. The transiency of slum populations over short and long timescales is a major challenge in undertaking this type of research, and this needs to be fully considered in future research designs.

All drinking water samples were collected in sterile Whirl-Pak bags (Whirl-Pak®, Nasco, USA), stored in a coolbox, and processed within 6 h of collection. Each water sample was briefly shaken and 100 mL vacuum-filtrated through a 0.45 μm cellulose acetate membrane (Sartorius Stedim Biotech., Gottingen, Germany). The membrane was aseptically transferred to the surface of a plate containing *E. coli* selective membrane lactose glucuronide agar (MLGA) (CM1031, Oxoid, Basingstoke, UK). The plate was inverted, incubated at 37 °C, and enumerated 18–24 h later. Based on the concentration of *E. coli* 100 ml^{-1}, each water sample was classified into a health risk category, i.e., safe (zero *E. coli* 100 ml^{-1}), low risk (1–10 *E. coli* 100 ml^{-1}), medium risk (11–100 *E. coli* 100 ml^{-1}) and high risk (>100 *E. coli* 100 ml^{-1}) (Rocha-Melogno et al., 2019).

Statistical testing was undertaken to explore whether the two samples (the households for which drinking water quality data was collected ($n = 30$) and those for which we did questionnaires ($n = 451$) were from the same population. This included the Mann Whitney U test for the age of the respondent and the number of people living in the household and Fisher's exact test for gender, education, employment status, house ownership status, and main water source. For Fisher's exact test, where multinomial probability distributions between those households for which we collected water quality data and those for which we did not were statistically significantly different, we undertook a post hoc analysis involving pairwise comparisons using multiple Fisher's exact tests (2×2) with a Bonferroni correction. Statistical significance was accepted at $p < 0.01$. For all other statistical testing, the significance level was set at 0.05.

3. Results

A total of 481 residents from 481 individual Bangwe households completed the in-depth water access questionnaire (Table 1), of which 30 households also took part in the daily drinking water quality testing study (Table 2). The mean household size and age of respondents were 5 and 34, respectively. The households for which drinking water quality data were collected were not significantly different from other households in the community in terms of the age of the respondent and household size (Mann Whitney U test), and the gender, education level, employment status and household ownership (Fisher's exact test) (Table 2). Furthermore, there was no difference in the choice of the main water source of those households where water samples were collected and other households (Fisher's exact test where post hoc testing identified that all pairwise comparisons were not statistically significant). Therefore, households for which we collected water quality data were broadly similar to those for which we did not collect water quality data, suggesting that our sampling was representative of the general population.

3.1. Daily household drinking water quality

Based on *E. coli* concentrations, none of the 30 households had water

Table 1

Summary data for all the households that took part in the in-depth water access questionnaire study ($n = 481$).

Variable		
	Mean	
Number of people in the household	5.0	
Age of respondent	34	
	n	**%**
Gender of respondent	389	80.9
Female	92	19.1
Male		
Completed education level of respondent	21	4.4
No education	207	43.0
Primary	229	47.6
Secondary	24	5.0
College or higher		
Employment status of respondent	65	13.5
Employed for wages	196	40.7
Self-employed	177	36.8
Unemployed	26	5.4
Student	11	2.3
Retired	6	1.2
Other		
Ownership status of home	122	25.4
Owners (with property title)	100	20.8
Owners (without property title)	251	52.2
Renters	8	1.6
Other		
Main water source used	94	19.5
Improved sources	201	41.8
Piped to dwelling, yard, plot or/neighbour	85	17.7
Piped to public tap	47	9.8
Borehole	38	7.9
Protected well	4	0.8
Protected spring	5	1.0
Unimproved sources	7	1.5
Unprotected well		
Surface water		
Other		

Table 2

Summary data for the households that took part in the in-depth water access questionnaire study and the daily drinking water quality study ($n = 30$).

Variable		
	Mean	
Number of people in the household	4.5	
Age of respondent*	33	
	n	**%**
Gender of respondent	25	83.3
Female	5	16.7
Male		
Completed education level of respondent	1	3.3
No education	14	46.7
Primary	15	50.0
Secondary	0	0.0
College or higher		
Employment status of respondent	2	6.7
Employed for wages	17	56.7
Self-employed	9	30.0
Unemployed	1	3.3
Student	1	3.3
Retired	0	0.0
Other		
Ownership status of home	7	23.3
Owners (with property title)	6	20.0
Owners (without property title)	16	53.3
Renters	1	3.3
Other		
Main water source used	0	0.0
Improved sources	13	43.3
Piped to dwelling, yard, plot or/neighbour	11	36.7
Piped to public tap	5	16.7
Borehole	1	3.3
Protected well	0	0.0
Protected spring	0	0.0
Unimproved sources	0	0.0
Unprotected well		
Surface water		
Other		

that was safe to drink every day (Fig. 2), although there were no obvious trends in *E. coli* concentrations related to specific days of the week. Out of the matched households between the two sampling seasons ($n = 23$), 52% had water in the 'high risk' category (>100 *E. coli* 100 ml^{-1}) on at least one day of the week. A slightly higher proportion of all drinking water samples ($n = 371$) were in the 'high risk' category in the rainy season (11% of 187 samples) compared to the dry season (8% of 184 samples), although slightly more drinking water samples were classified as 'safe' in the rainy season (46%) compared to the dry season (44%).

Although it was rare for respondents in the 30 sample households to consider their drinking water unsafe for drinking (only 5% of drinking water samples, $n = 17$), a comparison of drinking water samples considered "safe" and "unsafe" by residents showed generally similar *E. coli* levels (Fig. 2). The majority (97%) of water samples were from covered household storage containers; however, the quality of the cover varied and included plastic or metal lids, plastic or metal plates and dishes, plastic buckets, and weaved baskets. Drinking water was more likely to be stored in the household for over 24 h during the dry season (29%) than in the rainy season (25%). There was no obvious difference in *E. coli* concentrations in water samples stored for under 24 h and more than 24 h.

Considering only matched households between the July 2017 and January 2018 sampling campaigns, 43% of households switched their drinking water from one source category to another (e.g., tap to borehole) for one day or more (Fig. 2). While household drinking water samples from tap water (public and private taps) were more likely to be perceived by households as 'safe' compared to other sources, the water they provided was often found to be unsafe for consumption; 8% ($n = 153$) of drinking water samples from public taps and 12% ($n = 25$) of drinking water samples from private taps were in the 'high risk' category for *E. coli* (Fig. 3).

3.2. Household water access

Most residents (85%) utilised a secondary source of water when their main source of water was unavailable (Fig. 4), with only 18% of people switching to an alternate water point within the same source category (e.g., borehole to borehole). Those using improved drinking water sources generally transferred to another improved drinking water source (e.g., public tap to borehole), rather than switching to an unimproved source. Nearly all respondents (90%) considered their main drinking water source to be safer than their secondary drinking water source, while 59% considered their secondary source safe.

Most drinking water sources were not available for 24 h per day (Table 3). On average, public taps, boreholes, and protected springs were only available for 12 h per day, with the most common reasons for restricted availability being limited opening hours and irregular supply. There was a clear difference in availability for piped water from different sources; drinking water from public taps was available for 12 h per day and drinking water from a private tap (i.e., located in the dwelling, yard, plot, or at neighbour's house) was available for 21 h per day, on average.

From the sample population of 481 residents, 81% were frustrated with some aspect of safe drinking water access in their community (Table 4). Key frustrations included intermittent supply (including seasonal changes in the quantity of water available, fixed or limited water point opening hours, or breakdown (25%)), affordability concerns related to the cost of water per bucket or the billing system (20%), and the lack of water points (20%).

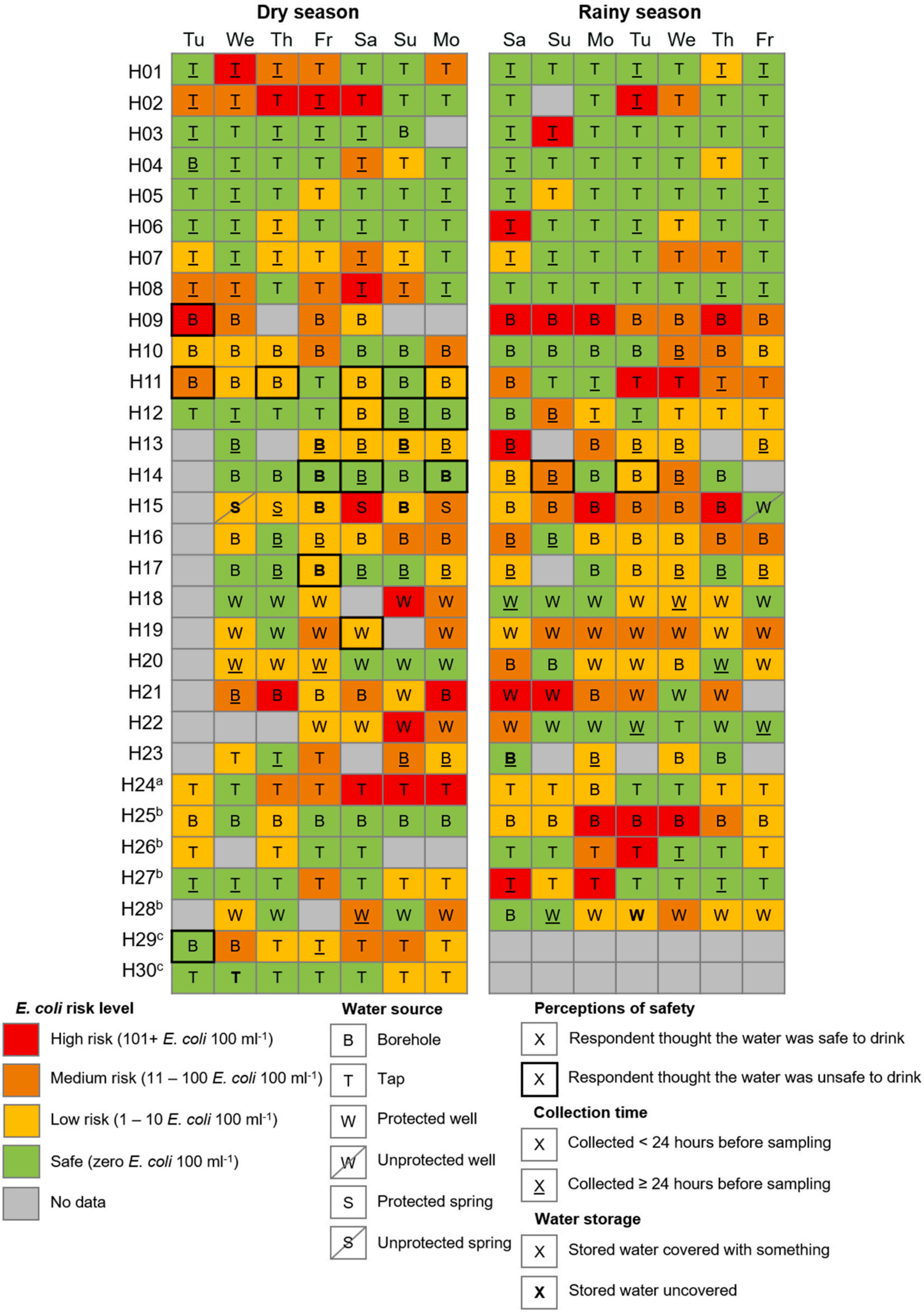


Fig. 2. Daily *E. coli* concentrations for the 30 households (H01 – H30) across two seasons. Households were matched between the two seasons, except for households H*n*[a] (where the residents moved out of the house after the first sampling campaign into a neighbouring house where they then participated in the study), H*n*[b] (where residents moved out of the house after the first sampling campaign and replacement respondents in the same household were identified for inclusion), and H*n*[c] (where residents moved out of the house after the first sampling campaign and no replacements were identifiable).

4. Discussion

4.1. Daily changes in household drinking water quality

This study is the first to demonstrate empirically that water access and quality in slums vary over shorter timescales than traditionally measured in global monitoring programmes. All 30 of the households in this study used drinking water with evidence of faecal contamination on at least one day during the sampling periods. These daily changes in water quality underpin changing waterborne disease risks that are not captured by the standard "one-off" or "seasonal" approaches to monitoring drinking water quality in research studies and national

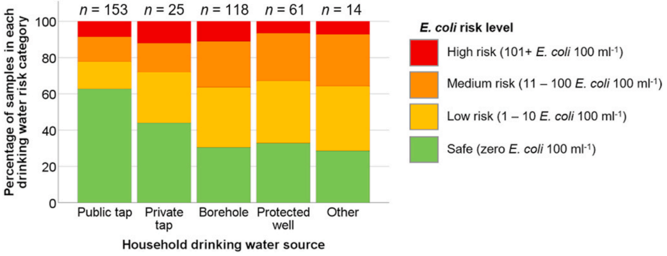
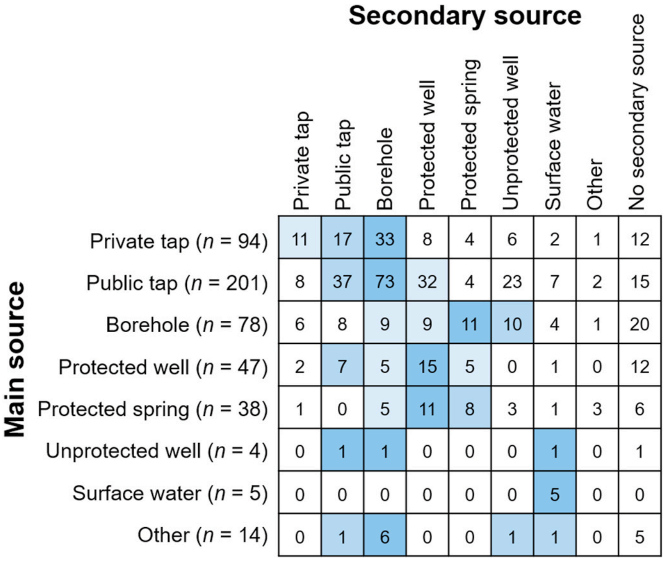


Fig. 3. *E. coli* containimation in household drinking water samples collected from various water sources. The 'other' category includes water collected from protected or unprotected springs, unprotected wells, and surface water.



Main source \ Secondary source	Private tap	Public tap	Borehole	Protected well	Protected spring	Unprotected well	Surface water	Other	No secondary source
Private tap (*n* = 94)	11	17	33	8	4	6	2	1	12
Public tap (*n* = 201)	8	37	73	32	4	23	7	2	15
Borehole (*n* = 78)	6	8	9	9	11	10	4	1	20
Protected well (*n* = 47)	2	7	5	15	5	0	1	0	12
Protected spring (*n* = 38)	1	0	5	11	8	3	1	3	6
Unprotected well (*n* = 4)	0	1	1	0	0	0	1	0	1
Surface water (*n* = 5)	0	0	0	0	0	0	5	0	0
Other (*n* = 14)	0	1	6	0	0	1	1	0	5

Fig. 4. Cross-tabulation comparing the main drinking water source of 481 residents with the source they switch to if their main water source is unavailable (e.g., due to season, breakdown, or opening hours). The most popular switches from each main source are highlighted in blue (darker colours = a greater number of people switching). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Availability of drinking water from most common sources.

Drinking water source	*n*	Average availability per day (hrs)	% water points available < 24 h/day	Most common reason(s) for availability < 24 h/day*
Piped to dwelling	94	21	24	A, B
Piped to public tap	201	12	95	A, B
Borehole	85	12	94	A
Protected well	47	15	74	A, B
Protected spring	38	12	97	A
Unprotected well	4	24	0	n/a
Other	7	20	43	A
Missing data	5	n/a	n/a	n/a

interventions (Debela et al., 2018; K'oreje et al., 2016; Okotto-Okotto et al., 2015).

Table 4
Summary of people's frustrations in accessing drinking water in Bangwe (*n* = 481).

Frustration with drinking water	*n*	%	Typical comments
Affordability	98	20	*Water is very expensive to access; Billing system is not good*
Distance/terrain	35	7	*Long distances to fetch water; Terrain is bad and situation becomes worse when it rains; We cross the main road to get water so it is dangerous*
Impact on people's time and energy	17	4	*A lot of energy needed to fetch water; Very long queue at source; Quarrelling at water source*
Lack of water points	73	15	*Very few water sources; We are always trying to find water; Few boreholes and public taps*
Intermittency of supply	119	25	*When water stops we find it difficult to source alternative water; During dry season most water sources dry up; Pipeline breaks disturb daily life*
Water quality and health	20	4	*Salty water; Insects found in water*
Other reason	27	6	*Misuse of water; Not enough storage containers*
No frustrations	92	19	*We have no problem with the water supply*

While the WHO & UNICEF JMP highlight that water quality testing should ideally be undertaken regularly across the year, they also include in their calculations one-off water quality measurements, although they do acknowledge that this only provides a "snapshot" of reality (WHO and UNICEF, 2018). That drinking water is "free from faecal and priority contamination" is a key requirement for *safely managed water* on the JMP drinking water ladder (UNICEF and WHO, 2019). Therefore, such water quality measurements feed into calculations of what percentage of the population resides on each "rung" of the water ladder and ultimately assesses a country's progress towards SDG6.1. However, our findings provide evidence that the approach currently used by the JMP fails to capture the changing waterborne disease risk to urban slum residents from short-term temporal changes in water quality.

There were no clear differences in *E. coli* concentrations in drinking water samples collected in the dry season compared to the rainy season (based on visual inspection of the data in Fig. 2). The lack of seasonal differences in *E. coli* concentrations may reflect the fact that the majority of the population uses publicly shared rather than household taps, and therefore transportation, storage, and handling may be more important determinants of *E. coli* contamination than season. Water collection, transport, handling, and household storage are key entry points for contamination even for water sources that may be clean at source (Wright et al., 2004; Rufener et al., 2010; Boateng et al., 2013). Household observations indicated several contamination risk factors from water collection and handling. For example, drinking water was commonly transported uncovered, and it was routinely carried on the head with fingers resting in the water during transport. Some residents complained that they found dead insects and other foreign objects in their stored water. Storage covers for drinking water were often not designed for that purpose. For example, dishes, other buckets, and baskets were frequently used as ad hoc covers. This practice, combined with other household drinking water management practices, e.g., unclean storage containers (Meierhofer et al., 2019), the method of extracting drinking water from storage containers (Harris et al., 2013), and the extent of mixing of water from different sources (Adams et al., 2020), can compromise the quality of stored drinking water.

4.2. Daily changes in household drinking water access

Our findings reaffirm our recent proposition that a household's ability to access sufficient, safe drinking water changes over time in response to multiple factors, including availability, reliability, and perceptions of water safety (Price et al., 2019). We have shown that most drinking water sources were not available for 24 h per day. Intermittent supply, whether that be predictable (e.g., opening hours), irregular, or unreliable, is a common problem in developing countries (Galaitsi et al., 2016). Even within the 'tap water' category, there was a large difference in terms of the mean number of hours per day the source was available between public taps/public water kiosks (12 h per day) and private taps (21 h per day) since community water sources are generally closed at night (Adams, 2018). Given the same level of reliability between publicly shared sources and privately owned or onsite household taps, the latter offers more guarantee of availability compared to publicly shared taps that are limited by many factors. Most residents (85%) relied on a secondary drinking water source when their main source was unavailable, consistent with previous studies (e.g. Kumpel and Nelson, 2015; Adams, 2018). This was a vital coping strategy for water insecurity as it buffered against water shortages from intermittent supply or limited opening hours at the primary source. In addition, access to water was constrained by its high cost (20% noted that water was too expensive). Recent work shows that households with higher water expenditures are more likely to be water insecure than those with lower expenditures (Stoler et al., 2019). Decision making about choice of water source is largely influenced by cost, availability, and intermittency, all of which can ultimately influence daily variations in household exposure to *E. coli*.

A residents' perception about the safety of their drinking water may pose additional risks for water contamination. Although most residents were confident in the quality of their drinking water and considered it safe to drink, only 45% of the drinking water samples we monitored met the requirements for safe drinking water as determined by *E. coli* contamination (WHO, 2017). No household included in the drinking water quality study perceived their water to be unsafe to drink on every day that a drinking water sample was collected. Instead, perceptions changed on a day-to-day basis based on the source of the water and sensory observations of water quality (e.g., taste and smell) (Subbaraman et al., 2015). However, residents overwhelmingly put their faith in the safety of piped water (both piped onto premises and public taps or kiosks), by responding that water that was unsafe to drink never came from a tap.

5. Conclusion

In this paper, we provide the first empirical evidence that the quantities of the indicator bacteria *E. coli* (a proxy for the presence of hazardous faecal contamination) changed from day-to-day in household drinking water in a Malawian slum. This day-to-day variability in contamination needs to be considered by policy makers when pursuing 'universal and equitable access to safe and affordable drinking water for all' (SDG6.1). These findings also have important implications for monitoring progress towards SDG6.1 and suggest that one-off or infrequent monitoring will not capture the changing contamination risk that people experience especially in urban households. Further work to determine the most appropriate sampling interval (e.g. sub-daily or weekly) to fully characterise the changing contamination risk needs to be undertaken as well as an exploration of how these day-to-day changes in contamination impact public health. While water quality testing at finer temporal resolution will take significant time and resources, our findings highlight that alternative, low-cost approaches to regular water quality testing at the household level are necessary to better characterise changing levels of contamination. This could include utilising citizen science approaches to data collection and analysis in slum contexts, although careful consideration needs to be given to this to ensure that the research benefits both the researchers and the citizens and the time and energy burden placed upon vulnerable populations is not too high. In addition to the monitoring of drinking water within the household, further research should also explore the temporal dynamics of drinking water contamination risk at the source and during transit to help inform intervention design aimed at reducing contamination risk, e.g. whether to pursue interventions based on improving water infrastructure or hygiene-based interventions.

Acknowledgements

This work was financially supported by the Royal Geographical Society, UK [grant number ESRG02/17]. We thank our five local research assistants who carried out the surveys, and all the residents of Bangwe who took part in the survey (particularly those who allowed us to sample their drinking water every day).

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