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The difference a day can make: the temporal dynamics of drinking water access and quality in urban slums

Abstract

In urban slums – home to approximately 1 billion people worldwide - access to clean drinking water is woefully inadequate despite the United Nations' declaration that access to safe water is a fundamental human right. Households in slums are frequently forced to rely on multiple drinking water sources to meet their needs. Numerous factors influence choice of water source, including water quality, availability, reliability, and affordability. These factors are not temporally static, but rather will vary over multiple timescales (from sub-daily changes to annual changes and beyond) in response to changes in the water source itself and changes in the household's ability to use that source. For example, the cost of water can change over time in response to water availability (e.g. rainy season versus dry season) and a slum household's ability to pay for water will often change over time in response to changes in household income. However, existing national and global monitoring of safe water access, including Sustainable Development Goal 6, overlook these temporal dynamics of water access, quality and health risk in slums. This paper proposes a research agenda for exploring temporal changes in drinking water access and quality in urban slums and their potential influence on health risk. It argues that in the design of research studies, policy interventions, and drinking water monitoring aimed at improving access and health in urban slums, temporal dynamics

should be considered over at least three interlinked time scales: short-term (from sub-daily to week-to-week), medium-term (from month-to-month to season-to-season) and long-term (from year-to-year). The paper concludes with recommendations for future research on temporal dynamics of drinking water and health in slums.

Keywords: water access; temporal and spatial water quality; informal settlements; health risks; temporal change; sustainable development goals

1. Introduction

This paper argues for the need to incorporate temporal changes in water access into research agendas, policy interventions, and monitoring of water and health in urban slums. We define slums in line with UN-Habitat (2003) as settlements that lack one or more of the following conditions: access to improved water, access to improved sanitation, sufficient living space, durability of housing and secure tenure. Slums are heterogeneous places and living conditions (e.g. population densities, housing tenure, economic and social make up, service provision) vary both between and within slums (Ezeh et al. 2017).

In urban slums access to drinking water varies over both short and long timescales due to source availability, location, water quality, reliability, affordability, and a range of social and cultural factors; however, such temporal dynamics are largely ignored by the research, policy, and monitoring communities. We argue that temporal changes in accessing sufficient safe water impact water-related health risks over three interlinked time periods (*short-term*, from sub-daily to week-to-week;

medium-term, from month-to-month to season-to-season; and *long-term*, year-to-year) (Figure 1), and it is critically important that these changes in health risk over time are captured in water monitoring initiatives.

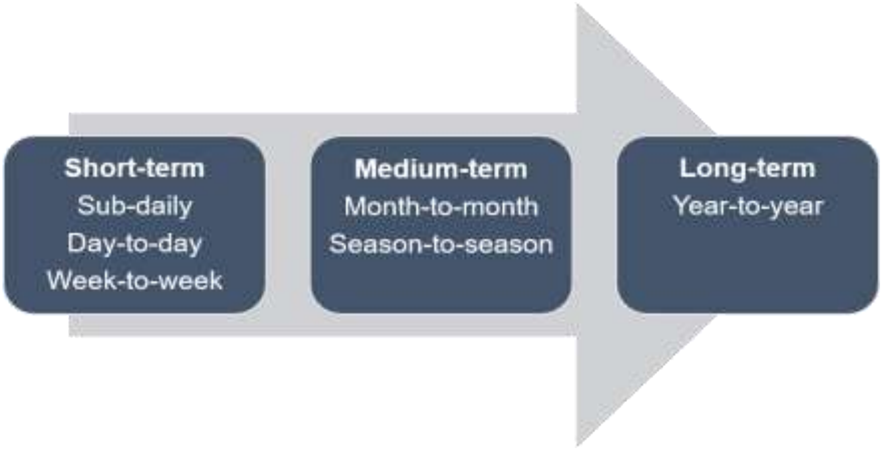

Figure 1: Temporal changes in drinking water access and quality can be considered over three interconnected time periods.

The paper begins by summarising the global context of safe water access before critiquing the global water monitoring initiatives that measure progress in water access. We go on to describe water access in urban slums with a focus on the factors which affect drinking water decision making in slums and how these factors change over time. We conclude with recommendations for future research to explore the temporal dynamics of drinking water in slums.

1.1. Global context of safe water access

In 2010, the United Nations (UN) stated that access to safe water was a basic human right, and that clean drinking water was fundamental to the realisation of all human rights (UN General Assembly 2010). Yet globally, an estimated 663 million people still rely on unimproved water sources (including unprotected wells and surface water) for their drinking water (WHO and UNICEF, 2015a). The majority of people without access to improved drinking water sources live in low- and middle-income countries in sub-Saharan Africa (319 million), South Asia (134 million), East Asia (65 million) and South East Asia (61 million) (WHO and UNICEF, 2015a). Water access within individual countries is not equitable, with poor and marginalised groups, such as those living in crowded urban slums, experiencing worse access and bearing the highest pollution (and related poor health) burden (Landrigan et al. 2018; Penrose et al. 2010).

Almost a quarter of all deaths globally in 2012 were attributed to preventable environmental causes including pollution of drinking water (Prüss-Ustün et al., 2016). More specifically, the 'Global Burden of Disease' study estimated that 1.8 million global deaths were caused by water pollution in 2015 (Forouzanfar et al. 2016). These adverse health impacts continue to occur despite improvements in household access to water during the lifetime of the Millennium Development Goals (MDGs).

While the successful achievement of MDG target 7c ("to reduce by half the number of people without access to safe water") five years ahead of schedule in 2010 (WHO and UNICEF 2012), many argue that the improvements are exaggerated due to poor indicators for monitoring (e.g. Smiley, 2017). For example, the MDGs focused on physical access to improved water sources without consideration for whether the source was safe, affordable, or reliable. More importantly, the MDG target assumed that all improved sources are safe.

The Sustainable Development Goals (SDGs) replaced the MDGs in 2015 and included a specific goal that calls for clean water and sanitation for all people (SDG6, which includes eight individual targets). Safely managed drinking water is defined as ‘drinking water from an improved water source which is located on premises, available when needed and free from faecal and priority contamination’ (WHO and UNICEF, 2017a). The aim of target 6.1 is to “achieve universal and equitable access to safe and affordable drinking water for all” by 2030 (UN General Assembly 2015). This target demonstrates that water-related health is a product of challenges affecting both water access (including availability, reliability and affordability) and water quality (Subbaraman et al. 2015). This highlights the progression from the MDGs to the SDGs, with a shift in focus from solely monitoring water access to the safe and sustainable management of water.

1.2. Global drinking water monitoring programmes

The success of SDG6.1 will be determined from global water monitoring statistics. Since 1990, the WHO and UNICEF have been responsible for monitoring global access to drinking water through the Joint Monitoring Programme (JMP) for water supply and sanitation (WHO and UNICEF 2014). Up until 2000, the JMP relied upon national governments to produce water access estimates; however, this approach frequently resulted in incomplete datasets that produced vastly different annual estimates of water access (Bartram et al. 2014). Since 2000 (the start of the MDG monitoring period), the JMP has instead relied on population and housing censuses, together with other nationally representative household surveys, administrative data and service provider data. This has enabled progress in drinking water access to be tracked for 232 countries, areas and territories (WHO and UNICEF, 2017b). The comprehensive approach of the JMP was a major factor in its adoption by the UN for monitoring progress towards the MDGs and SDGs (Pérez-Foguet, Giné-Garriga, and Ortego 2017).

The accuracy of this monitoring depends heavily on the quality of the national data collected, and milestones such as the release of harmonised question sets (WHO and UNICEF 2006) have been vital in improving the monitoring accuracy. However, some argue that a lack of harmonisation and standardisation in census questions and categorisation systems persist and further refinement is still needed (Yu et al. 2016). National estimates of safe water access are made by the JMP using linear regression between dates when survey data are available (WHO and UNICEF, 2017c). Critiques of the methodological approach of the JMP, and particularly its use of linear regression, is available in Bartram *et al.* (2014) and Fuller *et al.* (2016).

The JMP uses a water ladder (Figure 2) to track a population's access to drinking water over space and time, where each 'rung' of the ladder represents a different level of access. These ladders are powerful tools that can be used by decision makers to support planning and policy decisions (Pérez-Foguet, Giné-Garriga, and Ortego 2017). Until 2017, an improved (e.g. piped water onto premises, protected dug well) versus unimproved (e.g. unprotected dug well, surface water) classification of water access was used by the JMP to track progress in water access (Figure 2a). However, this approach was subject to criticism, because it was based entirely on the type of facility used and did not consider factors that might affect the use of that facility at the household level, for example, the ease of access, affordability or availability (M. Langford and Winkler 2014; Martínez-Santos 2017; Yu et al. 2016). Importantly, an 'improved water source' does not necessarily provide water that is safe to drink (Bain *et al.,* 2014). In the context of urban areas and slums, temporally dynamic challenges that undermine water availability, such as intermittent supply, water rationing, high rates of non-functional water points, and areas with low water pressure are not captured by the JMP's monitoring strategies (Smiley 2016, Adams 2017). The JMP service ladder was therefore not fit for purpose as it did not address the 'sustainable access' and 'safe drinking water' aspects of MDG Target 7c (e.g. Bartram *et al.*, 2014).

a) Pre-2017 water ladder

Piped water on premises	Piped household water connection located insider the user's dwelling, plot or yard
Other improved	Public taps or standpipes, tube wells or boreholes, protected dug wells, protected springs, protected springs, rainwater collection
Unimproved	Unprotected dug well, unprotected spring, cart with small tank/ drum, tanker truck, bottled water
Surface water	River, dam, lake, pond, stream, canal, irrigation channels

b) Current water ladder

Safely managed	Drinking water from an improved water source which is located on premises, available when needed and free from faecal and priority chemical contamination
Basic	Drinking water from an improved source, provided collection time is not more than 30 minutes for a roundtrip including queuing
Limited	Drinking water from an improved source for which collection time exceeds 30 minutes for a roundtrip including queuing
Unimproved	Drinking water from an unprotected dug well or unprotected spring
Surface water	Drinking water directly from a river, dam, lake, pond, stream, canal or irrigation canal

Figure 2: A comparison of, (a) pre-2017 (improved/unimproved classification) and (b) current (service-based) water ladders used by the JMP. Redrawn from WHO and UNICEF (2015b) and WHO and UNICEF (2017a).

In 2017, the JMP introduced a new water ladder to try and address some of the limitations associated with the improved-unimproved water access categories. In the updated JMP ladder (Figure 2b), the key components of 'safely managed' water are accessibility, availability and quality (WHO and UNICEF, 2017a). The 'basic' and 'limited' rungs still require access to an improved water source, but have more lenient access requirements, for example, the collection time for 'limited' water access can be over thirty minutes. The ‘safely managed’, ‘basic’ and ‘limited’ categories combined are analogous with the improved categories in pre-2017 monitoring but aim to provide a more detailed understanding of access in the SDG monitoring period (important when moving from *improvements* in safe access (MDGs) to *universal safe access* (SDGs). The achievement of universal access (SDG6.1) will not happen unless there are significant improvements in clean water access in low income urban areas (slums).

1.3. Safe drinking water access in urban slums

In 2014 there were an estimated 881 million people living in slums (UN-Habitat 2016) and this is predicted to rise to approximately 2 billion by 2030 (UN-Habitat, 2003). Slums often develop in the hazardous or undesirable parts of a city, and due to the high density of housing (Pierce 2017), formal water supply infrastructure is often not extended into slum areas. Some slums lack legal status and are therefore not recognised by the local government, who have a significant impact on people’s access to piped water (Agarwal and Taneja 2005; Subbaraman et al. 2012). Even where formal infrastructure is extended into slums, the quality of water residents receive can be poorer than the high-income residents. For example, in Lilongwe, Malawi, a statistically significant difference in water contamination levels was noted between high-income and low-income parts of the network and this was attributed to prioritisation of high-income areas for maintenance works, the use of higher quality pipes in high income areas and prioritising high income areas in times of shortage (Boakye-Ansah et al. 2016). Even within slums, there can be substantial variations in living conditions between households (Jahan et al. 2015; Ezeh et al. 2017; S. Smiley et al. 2017) including in people's access to adequate safe water.

In addition to spatial variations, there are also temporal changes in water quality, availability, reliability, and affordability that impact people's abilities to obtain sufficient safe drinking water. The JMP asks, "What is the main source of drinking-water for members of the household?" (WHO and UNICEF 2006). This assumes that the water source used by a household is fixed and does not change over time. The JMP ignores the complex realities of daily life in slums (Nganyanyuka et al. 2014; E. A. Adams 2017) where daily decisions need to be made about how best to meet the household's basic needs (including access to food, energy and water). Drinking water decision making is not static, but instead changes over time. For example, household decision making over what source to use at different times may be shaped by changes in the availability of rain water between seasons, increased contamination of a well following heavy rainfall, and changes in a household's circumstance (e.g. seasonally-changing household income levels affecting people's ability to pay for water or short-term informal work impacting time available for collecting water). Further, when water is not available as-needed, it will commonly be stored to buffer against times when water is unavailable (Majuru, Suhrcke, and Hunter 2016), and this can be an entry point for contamination (Wright, Gundry, and Conroy 2004). Temporal changes in drinking water sources (e.g. changing contamination levels), together with household level decision-making about where to collect water from (e.g. seasonal changes in people's abilities to pay for water), are likely to have significant health consequences for slum residents.

We argue that because of this, water access and quality monitoring needs to go beyond the timescales of existing monitoring programmes, e.g. modelling annual changes using few data points as in the WHO and UNICEF JMP or the standard cross-sectional or seasonal research study designs. Importantly, the challenges of accessing sufficient clean water for slum residents vary over multiple timescales, and this needs to be considered in the design of future research agendas, drinking water monitoring programmes, health interventions and drinking water policies. Here, we propose a research agenda that can advance our understanding of temporal changes in water access and quality over multiple time periods (Figure 1) including: short-term (from sub-daily to week-to-week), medium-term (from month-to-month to season-to-season) and long-term (year-to-year).

2. Factors affecting temporal water access and quality in urban slums

Due to the high density of housing and associated basic services in slums, individual households will often have multiple drinking water sources in proximity to their residence (Howard et al., 2002). However, people’s ability to access these different sources of water, together with how a particular water source is chosen will be mediated by many factors (Figure 3). The framework in Figure 3 implies that individual collectors of water have the autonomy to make decisions about the water that their household consumes, though we acknowledge this may not always be the case. Frequently, the women of the household are responsible for collecting drinking water (Crow and Mcpike 2009), although the decision of where and when to collect that water may be influenced by the spouse or adult male in the household (Fisher and Naidoo 2016).

Household drinking water decision making will depend firstly on the sources available to that household (central ring in Figure 3). There are then a series of factors (middle ring in Figure 3) related specifically to the source (e.g. cost of water, presence of contamination, reliability of the source) and the household (e.g. ability of household to afford water, perceptions of contamination, socio-cultural factors) that will shape people's decision making about which drinking water source to access (S. L. Smiley 2013; Wasonga, Okowa, and Kioli 2016). In the outermost ring of Figure 3, we highlight that household decision making about drinking water competes with the multiple demands on people's time and energy, which includes the collection of other essentials to support life (for example energy or food), money generation, providing childcare, completing household chores, socialising and other demands. Together, these factors combine to make the decision-making process of collecting drinking water both complex and multidimensional.

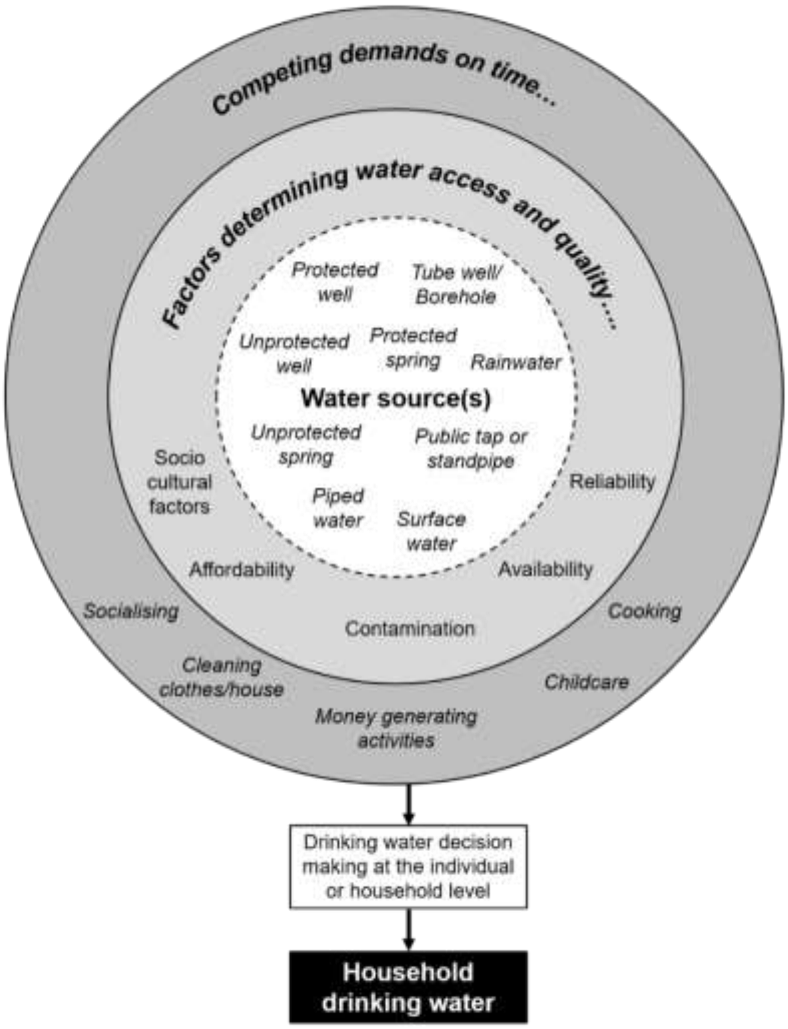

Figure 3: Household drinking water decision framework for people living in slums highlighting some of the key factors affecting drinking water decision making in urban slums.

This complexity is further increased because the factors highlighted in Figure 3, and particularly those highlighted as determining water access and water quality (i.e. socio-cultural factors, affordability, contamination, availability and reliability), are temporally dynamic over multiple timescales (e.g. changing from day-to-day). Importantly however, this temporal complexity is not yet considered in global water monitoring programmes aimed at achieving SDG6 nor embedded in research designs. We therefore discuss in more detail in the following sections these temporal dynamics and how they feed into drinking water decision making. We do not discuss here socio-cultural factors (such as caste, ethnic, racial, or religious identity, gender and power relations (E. A. Adams, Juran, and Ajibade 2018; Pierce 2017)) and how these affect safe water access, because changes over time for these factors (and their impacts on water access) are less well understood. Instead, we recommend further research in this area (see section 3.2).

2.1. Availability

Urban households frequently use multiple sources (and source types) to meet their household drinking water needs (Thompson et al. 2000; Tutu and Stoler 2016; Okotto et al. 2015). While many sources are common to all low-income urban areas (e.g. boreholes, shallow wells, public taps), their distribution, availability, and reliability differ across countries, between different urban areas in the same country and within urban areas. A study in the slums of Kenya found that within the same slum, different water sources had different levels of coliform bacteria (Kimani-Murage and Ngindu 2007), suggesting that even within the same urban area or slum, water quality varies.

Distance to a water source is an important determinant of the quantity of water used in the household, since water is frequently carried on the head or back of the collector and requires a significant physical effort (Hunter, MacDonald, and Carter 2010; Magala, Kabonesa, and Staines 2015). Urban water collectors commonly visit water points multiple times throughout the day, and sometimes travel long distances (Mutisya and Yarime 2011; Crow and Mcpike 2009), which places a burden on people’s time due to queuing and long waiting times at popular water sources

(Rashid 2009; E. A. Adams 2017; Thompson et al. 2000). People's choice of water source may also depend on how 'risky' the walking route is, for example people might avoid uneven terrain, flooding etc. (S. Smiley et al. 2017).

Competing demands on water collectors (including paid work, childcare, cooking) can affect people's ability to queue, which may encourage people to use sources where they can access water more quickly even if they know the water is of a lower quality (Crow and Mcpike 2009). These competing demands are unlikely to be static, but rather fluctuate over time; in the short-term (e.g. due to the changing availability of informal paid work), the medium-term (e.g. due to seasonal patterns of work, school terms, flooding) and the long-term (e.g. children becoming more independent as they get older).

2.2. Reliability

The effects of climate change are already impacting the reliability of water supplies in slums (Dos Santos et al. 2017), for example, through changing rainfall patterns that affect freshwater availability. In many urban slums of developing countries, intermittent supply of water is common due to low water pressure from out-dated water infrastructure, coupled with growing demand and subsequent water rationing by public water utilities (Stoler et al., 2012; Adams 2017). Intermittent water supply can be defined as water that is not available for 24 hours every day (Martínez-Santos 2017), and it can be highly unpredictable on very short (i.e. hourly) timescales (Crow and Mcpike 2009). Intermittent water supply, while common, is a multi-dimensional problem that goes beyond water scarcity (Galaitsi et al. 2016). Intermittency can be subdivided into predictable intermittency (e.g. Borehole A has specified opening hours), irregular intermittency (e.g. the owner of Borehole B has left home but will be back at some point soon) and unreliable intermittency (e.g. the owner of Borehole C has left home for an unknown length of time) (Galaitsi et al. 2016). In large urban centres where small-scale water enterprises such as water vending by the gallon or by the bucket is common, households using such services may find it hard to predict vendor delivery schedules and are forced to alter their daily schedules (McGranahan et al. 2006; S. L. Smiley 2016).

Intermittent water supply can drive water collectors to seek a more reliable supply of water, even if that water comes from a lower quality source (Asaba, Fagan and Kabonesa, 2015; Okotto *et al.*, 2015; Smiley, 2017). When water is limited, people adopt a variety of coping strategies including storing water or drilling new wells (Majuru, Suhrcke, and Hunter 2016). In households where it is essential to store water when the supply is intermittent, the chances of that water becoming contaminated increases (Wright, Gundry, and Conroy 2004). Reduced access to water due to intermittent supply can lead to prioritisation of the available water for drinking and less water available for other important tasks, like washing hands, that will have important hygiene and public health implications (Crow and Odaba 2010; WHO 2008). For piped water, intermittent flow increases the risk of recontamination (Kumpel and Nelson 2014, 2016; Satapathy 2014; WHO 2008) and can increase *E. coli* concentrations and the incidence of acute diarrhoea (Adane et al. 2017; Kumpel and Nelson 2013).

2.3. Affordability

The cost of water is an important part of the decision-making process for slum dwellers (WHO 2008). Those households without piped connections frequently pay more for their water than those with a household connection (Banerjee and Morella 2011; Pierce 2017; S. L. Smiley 2017). Further, slum households which are not recognised by the government pay significantly more for their water than those that are legally recognised (Subbaraman et al. 2013). However, the affordability of water does not remain constant, with fluctuations in price resulting from the availability of water, or the household's ability to pay changing over time.

Constantly changing water prices, which are often unpredictable, and the high cost of water from vendors mean that households may not consume as much safe water as they need (Dana 2011; Nzengya 2015). In the Drawers of Water II study, Thompson *et al.* (2000) found that long-term (1967 – 1997) changes in un-piped water cost varied for different locations across Africa; in some urban locations the costs reduced over time, while in others the cost of water increased by a significant amount (US $0.5 – 1 per cubic metre). Some sources, including surface water and rainwater, may only be available in the rainy season (Lapworth et al. 2017), and this change in availability through the seasons can subsequently affect the cost of water (Crow and Odaba 2010). The cost of water to the household can change over shorter timescales in response to varying source availability, i.e. when a source stops being available, the source that consumers switch to may be more or less costly.

2.4. Quality

Perceived or actual water quality is a key driver of a collector's decision-making about drinking water (e.g. Okotto *et al.*, 2015). As already discussed, drinking water sources can be divided into "improved" (e.g. public tap, borehole, protected well) and “unimproved” (e.g. an unprotected well, an unprotected spring), however water sources within the “improved” category may still become contaminated (Bain *et al.,* 2014). Within individual water source categories some sources may be more prone to contamination than others depending upon the design, quality of construction and maintenance.

Water may be contaminated at source, at the distribution point (e.g. kiosk), and during transport or storage (E. Adams, Price, and Stoler 2019; Rufener et al. 2010; Satapathy 2014). In slums, water is commonly transported between the source and the home, and then stored in containers within the household. Household contamination of stored water is common, particularly in settings with young children or shared access to a single water container; in these situations clean drinking water can still become contaminated despite being collected from an “improved” source (e.g. Wright, Gundry and Conroy, 2004; Boateng *et al.,* 2013; Blanton *et al.*, 2015; Shields *et al.*, 2015; Alarcon Falconi *et al.*, 2017). Although many studies have demonstrated that drinking water in slums is often contaminated, most of these studies are cross-sectional (e.g. Chemuliti *et al.*, 2002; Kimani-Murage and Ngindu, 2007; Muoki, Tumuti and Rombo, 2008; Opisa *et al.*, 2012; Subbaraman *et al.*, 2013; Blanton *et al.*, 2015; K’oreje *et al.*, 2016; Debela *et al.*, 2018), which provide only a “snapshot” of water quality that does not reflect the temporal dynamics of risk resulting from the numerous factors shaping access, use, and decision making in urban slums (Figure 3). Our higher temporal resolution water access and quality monitoring approach proposed here will help us better understand the complex relationship between drinking water and health in slums, which will enable the design of more effective health interventions.

The quality of water consumed by a household can change over time because of internal factors (e.g. a change in the contamination level of the water) or external factors (e.g. changes in access or water practices).

Over long timescales, increased population density caused by rural to urban migration and population growth puts increased pressure on any existing water supply infrastructure (Dana 2011; Kimani-Murage and Ngindu 2007). Maintenance of infrastructure is vital to ensure continued clean water supply to household and public taps (Makris, Andra, and Botsaris 2014; Lee and Schwab 2005), however, population densities are increasing, and further investment in water infrastructure is required to ensure demand for water is met. If demand cannot be met by existing water infrastructure, consumption will likely decrease (Dana 2011) and alternative supplies will be sought to meet the household need (Thompson et al. 2000; Okotto et al. 2015). This can have a large impact on the quantity and quality of water consumed in the household (Dagdeviren and Robertson 2011). Long-term changes in sanitation, waste disposal and other water contamination hazards will impact contamination levels of water from groundwater and surface sources (Okotto-Okotto et al. 2015). Predicted climate changes, most notably the increased intensity of rainfall in many parts of the World (IPCC 2014, 2018), will impact the mobilisation of pollutants above and below the ground surface (Sadik et al. 2017). Changing water practices, e.g. WASH (water, sanitation and hygiene) interventions that promote water treatment may reduce water-related health risks over longer timescales (Fewtrell and Colford 2005; R. Langford, Lunn, and Brick 2011). Slum upgrading, including improvements in water and sanitation, may also impact water-related health risks over longer timescales (Turley et al. 2013); although there is currently limited evidence of any associated improvements in health outcomes from slum upgrading (Lilford et al. 2017). There are very few studies that have investigated long-term (e.g. year to year) change in water quality in slums either at source or within households (Thompson et al. 2000; Okotto-Okotto et al. 2015).

Studies exploring seasonal changes in water quality are more common. For slum dwellers that rely on surface water and groundwater to meet their drinking water needs, different rainfall levels between seasons could have significant impacts on the quality of the water they consume due to mobilisation of contaminants (Howard et al. 2003; Lapworth et al. 2017). Changing rainfall levels across the seasons could also influence exposure to water contaminants as households change their main water source between dry and rainy seasons based on the availability of the source at particular times of the year (Mason 2015; Shaheed et al. 2014).

Over shorter timescales (e.g. from day to day), the amount and intensity of rainfall can be an important predictor of drinking water quality (Lapworth et al. 2017), meaning water that is safe to drink one day may not be safe to drink on another day. Individuals may decide to change their water source based on sensory observations, such as taste or smell (Subbaraman et al. 2015). The treatment of water prior to consumption can significantly improve water quality and reduce associated health impacts; importantly however, treatment (e.g. chlorine) may not be applied consistently from day-to-day due to cost or availability (Clasen et al. 2007).

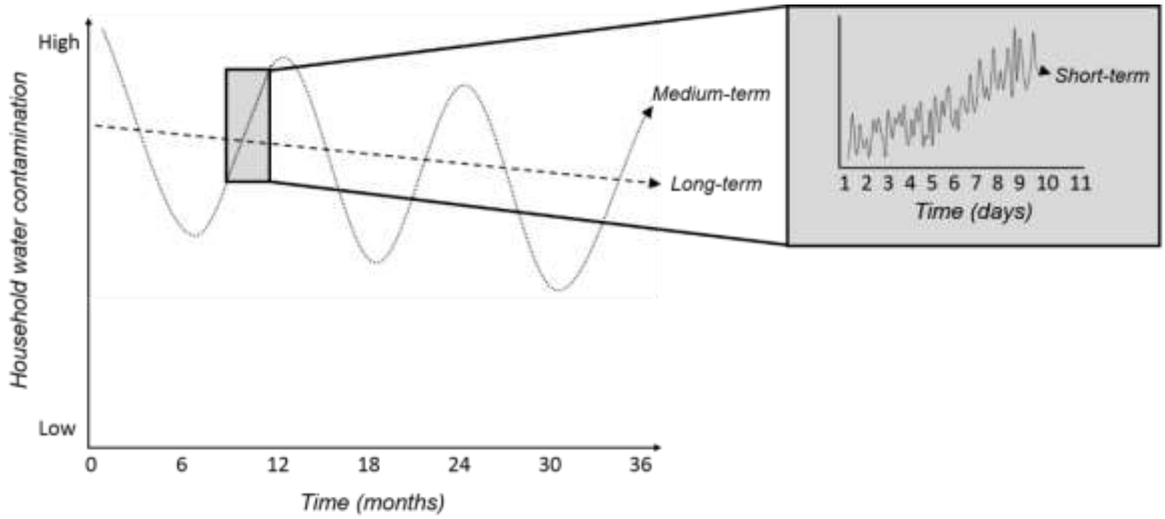

Figure 4: A theoretical example (for slum household 'X') of the temporal dynamics of the risk of exposure to contaminants in drinking water in urban slums as a function of both water access and water quality. The theoretical risk of exposure to drinking water contaminants for slum household 'X' varies over multiple timescales in response to changes in water access and water quality.

In this section we have given the theoretical basis for short-, medium- and long-term changes in safe water access for slum dwellers. This temporal complexity is explored further in the theoretical model in Figure 4, where for theoretical slum household 'X', the long-term decreasing level of drinking water contamination (in response to changes in either source contamination or the choice of source [itself a function of factors including availability, affordability and reliability], or both), masks the shorter-term (daily and seasonal) fluctuations in drinking water contamination, arising from, for example, changing the water source used. These short-term changes in contamination may cause acute adverse health impacts, e.g. diarrhoea (Hunter, MacDonald, and Carter 2010). These acute health risks are masked by one-off or infrequent water quality sampling. This highlights that more temporally-refined water quality monitoring is needed in urban slums to capture temporal changes in water-related health risks.

3. Recommendations for future research

Based on the findings from this review, we recommend two key areas for further research; short-term water access and quality monitoring and exploration of the role of socio-cultural factors in shaping temporal dynamics of safe water access.

3.1. Short-term water access and quality monitoring

We've shown that numerous factors shape everyday water use in slums, including availability, affordability, intermittent supply and daily decisions embedded in socio-cultural traditions. Therefore, future work needs to systematically examine the linkages and pathways between water access and health risks and variations over different temporal scales. Water quality has recently been added as a criterion for measuring 'safely managed water' within the JMP (WHO and UNICEF, 2017a ; Figure 2). As part of this, a water quality testing module has been designed for inclusion in national household surveys (WHO and UNICEF, 2015b). This aims to provide data on water quality (through cost effective field tests) at the water source and/or point of use, which will feed in to calculations of sub-national (urban, rural) and national access to safely managed water. Going forward, this will improve understanding of long-term sub-national and national trends in access to safe water.

As we have shown, there is a theoretical basis for understanding short-term changes in accessing sufficient safe water for slum dwellers, although no studies have been identified that directly address this key issue. We therefore recommend that further work is undertaken to better understand changes in temporal access to safe water, over short (i.e. within a day, day to day, and days to weeks) timescales. While we acknowledge the challenges of incorporating short-term access and risk metrics into both global and national monitoring, particularly in terms of time and resource requirements, there are methods and approaches that could be used to help tackle this. For example, the number of environmental monitoring studies utilising citizen scientists, i.e. recruiting members of the public to assist in the project (Bonney et al. 2009), has increased significantly in recent years (Jollymore et al. 2017).

3.2. The role of socio-cultural factors in shaping temporal dynamics of safe water access

The role of socio-cultural factors in shaping temporal dynamics of water and health in slums is also poorly understood. However, it is well documented that access to water is commonly influenced by socio-cultural factors, such as caste, ethnic, racial, or religious identity, gender and power relations (Adams et al., 2018; Pierce, 2017). Work by Sultana (2011) in Bangladesh revealed how social norms, gendered power relations, social ties and networks mediated the use of different water sources by creating conflicts. A study in Sri Lanka found that caste influenced both the choice of water source used and the cost of water (Lall 2015). In an Indian slum, a study found that people would sometimes stay up all night so that they did not miss the times that water was flowing (Subbaraman et al. 2014).

While some of the socio-cultural factors that influence water source use are fixed or slow to change (e.g. racial discrimination), other social factors are dynamic over shorter timescales. Water points are spaces of social interaction (Chandola 2013), although long queues at communal water sources can often lead to fights over water access, compounding the stress and conflict associated with routine chores, and ultimately influencing the use of particular water sources (Bapat and Agarwal 2003; Chant 2014; Crow and Mcpike 2009). However, there is no definitive evidence as to whether these phenomena and their interactions with water access over different time scales underlie health vulnerabilities and risks in urban slums and there is the need for more systematic studies to investigate these pathways.

4. Conclusion

This paper has described the importance of temporal changes in securing sufficient safe drinking water to meet the needs of slum dwellers. We have shown that the key factors that determine whether a slum household has sufficient clean water (source availability, reliability, affordability, contamination and social factors) may change over long (year-to-year), medium (month-to-month to season-to-season) and short (sub-daily to week-to-week) timescales. These temporal changes in water access can influence the volume of water used per person and the quality of that water, with important implications for people’s water-related health. These temporal changes in water use (particularly short-term changes) in slums have so far been broadly overlooked in water monitoring initiatives including the WHO and UNICEF JMP which monitors progress towards the SDGs.

Based on this, we have made a series of recommendations for future water access and water quality research, highlighting that the changes in health risk faced by slum dwellers over different time scales reflect everyday water access challenges. In particular, we highlight the need for better understanding of the short-term temporal changes in water contamination (and associated health risk) for slum residents. This is a key area where researchers and non-governmental organisations can build on the JMP approach and supplement existing knowledge with focused water monitoring campaigns in slums. Ultimately, knowing more about the struggles slum dwellers face in accessing water provides more robust evidence of the problem and helps us to create better strategies to improve people’s access to water and consequently improve their health.

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