

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

3
4 **Abstract**

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

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

28

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

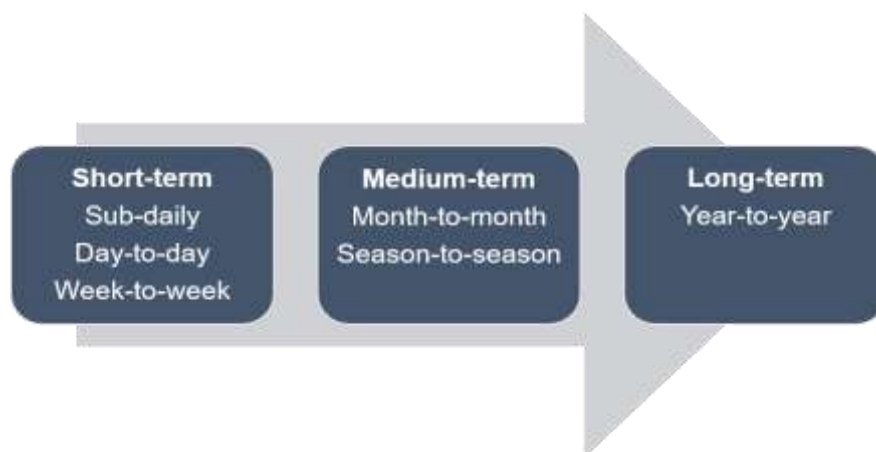
31

32 **1. Introduction**

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

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

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



50

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

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

59

60 **1.1. Global context of safe water access**

61 In 2010, the United Nations (UN) stated that access to safe water was a basic
62 human right, and that clean drinking water was fundamental to the realisation of all
63 human rights (UN General Assembly 2010). Yet globally, an estimated 663 million
64 people still rely on unimproved water sources (including unprotected wells and

65 surface water) for their drinking water (WHO and UNICEF, 2015a). The majority of
66 people without access to improved drinking water sources live in low- and middle-
67 income countries in sub-Saharan Africa (319 million), South Asia (134 million), East
68 Asia (65 million) and South East Asia (61 million) (WHO and UNICEF, 2015a). Water
69 access within individual countries is not equitable, with poor and marginalised
70 groups, such as those living in crowded urban slums, experiencing worse access
71 and bearing the highest pollution (and related poor health) burden (Landrigan et al.
72 2018; Penrose et al. 2010).

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

79 While the successful achievement of MDG target 7c ("to reduce by half the
80 number of people without access to safe water") five years ahead of schedule in
81 2010 (WHO and UNICEF 2012), many argue that the improvements are
82 exaggerated due to poor indicators for monitoring (e.g. Smiley, 2017). For example,
83 the MDGs focused on physical access to improved water sources without
84 consideration for whether the source was safe, affordable, or reliable. More
85 importantly, the MDG target assumed that all improved sources are safe.

86
87 The Sustainable Development Goals (SDGs) replaced the MDGs in 2015 and
88 included a specific goal that calls for clean water and sanitation for all people (SDG6,
89 which includes eight individual targets). Safely managed drinking water is defined as

90 'drinking water from an improved water source which is located on premises,
91 available when needed and free from faecal and priority contamination' (WHO and
92 UNICEF, 2017a). The aim of target 6.1 is to "achieve universal and equitable access
93 to safe and affordable drinking water for all" by 2030 (UN General Assembly 2015).
94 This target demonstrates that water-related health is a product of challenges
95 affecting both water access (including availability, reliability and affordability) and
96 water quality (Subbaraman et al. 2015). This highlights the progression from the
97 MDGs to the SDGs, with a shift in focus from solely monitoring water access to the
98 safe and sustainable management of water.

99

100 **1.2. Global drinking water monitoring programmes**

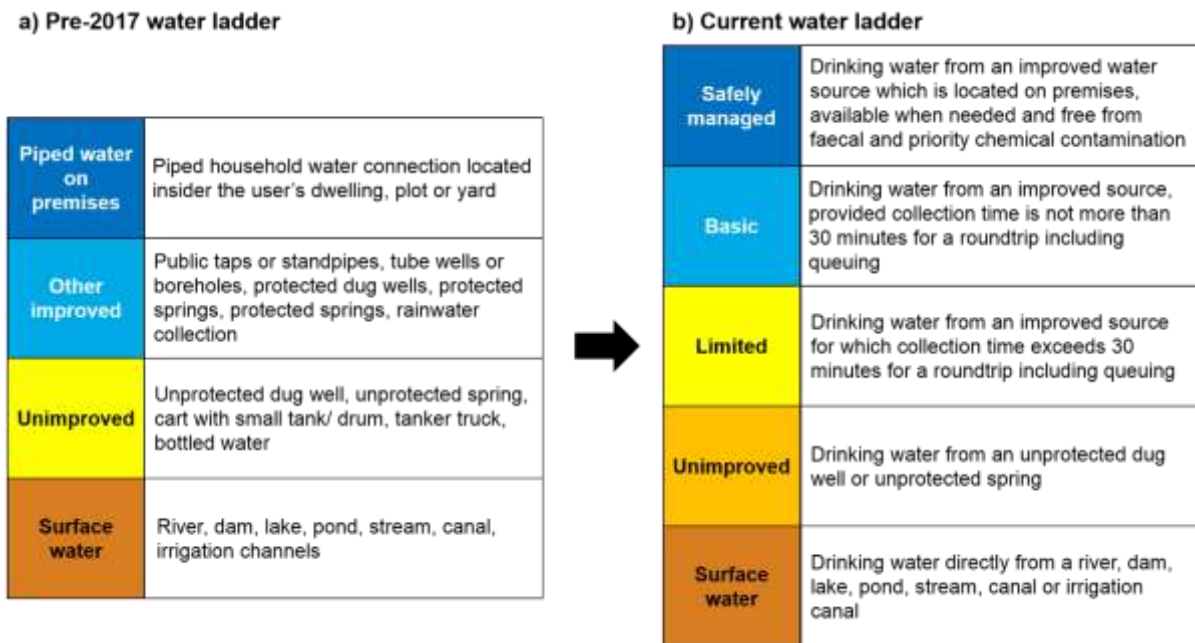
101 The success of SDG6.1 will be determined from global water monitoring
102 statistics. Since 1990, the WHO and UNICEF have been responsible for monitoring
103 global access to drinking water through the Joint Monitoring Programme (JMP) for
104 water supply and sanitation (WHO and UNICEF 2014). Up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

113 adoption by the UN for monitoring progress towards the MDGs and SDGs (Pérez-
114 Foguet, Giné-Garriga, and Ortego 2017).

115 The accuracy of this monitoring depends heavily on the quality of the national
116 data collected, and milestones such as the release of harmonised question sets
117 (WHO and UNICEF 2006) have been vital in improving the monitoring accuracy.
118 However, some argue that a lack of harmonisation and standardisation in census
119 questions and categorisation systems persist and further refinement is still needed
120 (Yu et al. 2016). National estimates of safe water access are made by the JMP using
121 linear regression between dates when survey data are available (WHO and UNICEF,
122 2017c). Critiques of the methodological approach of the JMP, and particularly its use
123 of linear regression, is available in Bartram *et al.* (2014) and Fuller *et al.* (2016).

124 The JMP uses a water ladder (Figure 2) to track a population's access to drinking
125 water over space and time, where each 'rung' of the ladder represents a different
126 level of access. These ladders are powerful tools that can be used by decision
127 makers to support planning and policy decisions (Pérez-Foguet, Giné-Garriga, and
128 Ortego 2017). Until 2017, an improved (e.g. piped water onto premises, protected
129 dug well) versus unimproved (e.g. unprotected dug well, surface water) classification
130 of water access was used by the JMP to track progress in water access (Figure 2a).
131 However, this approach was subject to criticism, because it was based entirely on
132 the type of facility used and did not consider factors that might affect the use of that
133 facility at the household level, for example, the ease of access, affordability or
134 availability (M. Langford and Winkler 2014; Martínez-Santos 2017; Yu et al. 2016).
135 Importantly, an 'improved water source' does not necessarily provide water that is
136 safe to drink (Bain *et al.*, 2014). In the context of urban areas and slums, temporally
137 dynamic challenges that undermine water availability, such as intermittent supply,

138 water rationing, high rates of non-functional water points, and areas with low water
 139 pressure are not captured by the JMP's monitoring strategies (Smiley 2016, Adams
 140 2017). The JMP service ladder was therefore not fit for purpose as it did not address
 141 the 'sustainable access' and 'safe drinking water' aspects of MDG Target 7c (e.g.
 142 Bartram *et al.*, 2014).



143
 144 **Figure 2:** A comparison of, (a) pre-2017 (improved/unimproved classification) and
 145 (b) current (service-based) water ladders used by the JMP. Redrawn from WHO and
 146 UNICEF (2015b) and WHO and UNICEF (2017a).

147
 148 In 2017, the JMP introduced a new water ladder to try and address some of the
 149 limitations associated with the improved-unimproved water access categories. In the
 150 updated JMP ladder (Figure 2b), the key components of 'safely managed' water are
 151 accessibility, availability and quality (WHO and UNICEF, 2017a). The 'basic' and
 152 'limited' rungs still require access to an improved water source, but have more
 153 lenient access requirements, for example, the collection time for 'limited' water

154 access can be over thirty minutes. The ‘safely managed’, ‘basic’ and ‘limited’
155 categories combined are analogous with the improved categories in pre-2017
156 monitoring but aim to provide a more detailed understanding of access in the SDG
157 monitoring period (important when moving from *improvements* in safe access
158 (MDGs) to *universal safe access* (SDGs). The achievement of universal access
159 (SDG6.1) will not happen unless there are significant improvements in clean water
160 access in low income urban areas (slums).

161

162 **1.3. Safe drinking water access in urban slums**

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

177 variations in living conditions between households (Jahan et al. 2015; Ezeh et al.
178 2017; S. Smiley et al. 2017) including in people's access to adequate safe water.

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

200 We argue that because of this, water access and quality monitoring needs to
201 go beyond the timescales of existing monitoring programmes, e.g. modelling annual

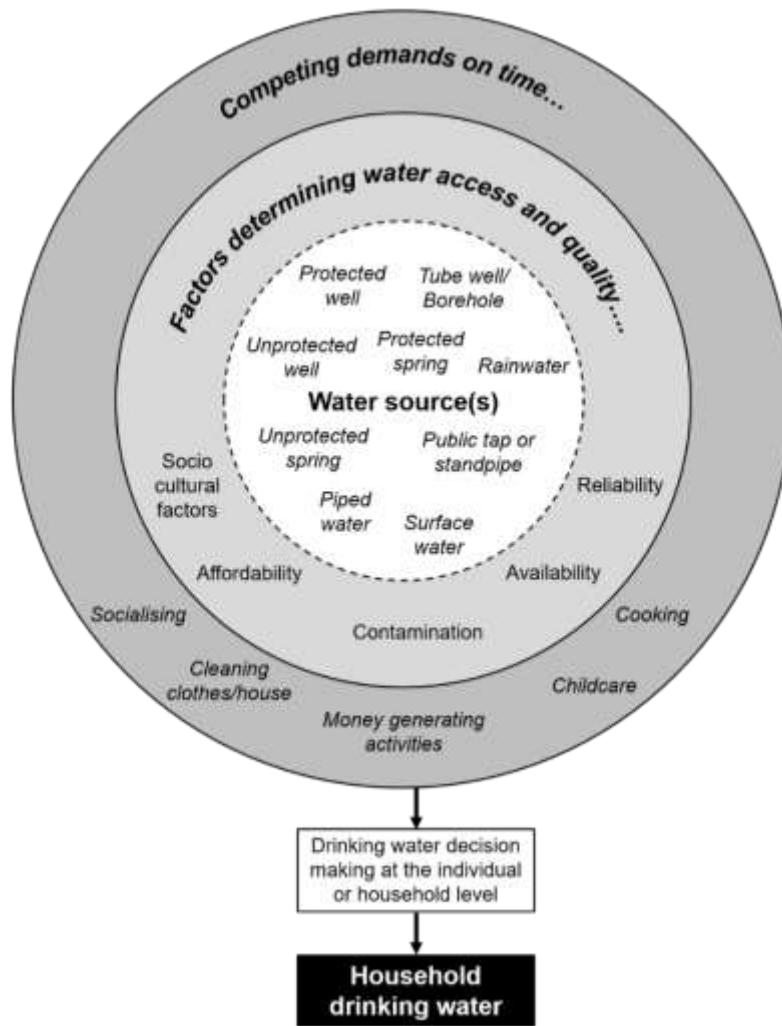
202 changes using few data points as in the WHO and UNICEF JMP or the standard
203 cross-sectional or seasonal research study designs. Importantly, the challenges of
204 accessing sufficient clean water for slum residents vary over multiple timescales, and
205 this needs to be considered in the design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

211

212 **2. Factors affecting temporal water access and quality in urban** 213 **slums**

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

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



238

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

242 This complexity is further increased because the factors highlighted in Figure
 243 3, and particularly those highlighted as determining water access and water quality
 244 (i.e. socio-cultural factors, affordability, contamination, availability and reliability), are
 245 temporally dynamic over multiple timescales (e.g. changing from day-to-day).
 246 Importantly however, this temporal complexity is not yet considered in global water
 247 monitoring programmes aimed at achieving SDG6 nor embedded in research
 248 designs. We therefore discuss in more detail in the following sections these temporal

249 dynamics and how they feed into drinking water decision making. We do not discuss
250 here socio-cultural factors (such as caste, ethnic, racial, or religious identity, gender
251 and power relations (E. A. Adams, Juran, and Ajibade 2018; Pierce 2017)) and how
252 these affect safe water access, because changes over time for these factors (and
253 their impacts on water access) are less well understood. Instead, we recommend
254 further research in this area (see section 3.2).

255

256 **2.1. Availability**

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

266

267 Distance to a water source is an important determinant of the quantity of water
268 used in the household, since water is frequently carried on the head or back of the
269 collector and requires a significant physical effort (Hunter, MacDonald, and Carter
270 2010; Magala, Kabonesa, and Staines 2015). Urban water collectors commonly visit
271 water points multiple times throughout the day, and sometimes travel long distances
272 (Mutisya and Yarime 2011; Crow and Mcpike 2009), which places a burden on
273 people's time due to queuing and long waiting times at popular water sources

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

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

285

286 **2.2. Reliability**

287 The effects of climate change are already impacting the reliability of water
288 supplies in slums (Dos Santos et al. 2017), for example, through changing rainfall
289 patterns that affect freshwater availability. In many urban slums of developing
290 countries, intermittent supply of water is common due to low water pressure from
291 out-dated water infrastructure, coupled with growing demand and subsequent water
292 rationing by public water utilities (Stoler et al., 2012; Adams 2017). Intermittent water
293 supply can be defined as water that is not available for 24 hours every day
294 (Martínez-Santos 2017), and it can be highly unpredictable on very short (i.e. hourly)
295 timescales (Crow and Mcpike 2009). Intermittent water supply, while common, is a
296 multi-dimensional problem that goes beyond water scarcity (Galaitzi et al. 2016).
297 Intermittency can be subdivided into predictable intermittency (e.g. Borehole A has

298 specified opening hours), irregular intermittency (e.g. the owner of Borehole B has
299 left home but will be back at some point soon) and unreliable intermittency (e.g. the
300 owner of Borehole C has left home for an unknown length of time) (Galaitisi et al.
301 2016). In large urban centres where small-scale water enterprises such as water
302 vending by the gallon or by the bucket is common, households using such services
303 may find it hard to predict vendor delivery schedules and are forced to alter their
304 daily schedules (McGranahan et al. 2006; S. L. Smiley 2016).

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

319

320 **2.3. Affordability**

321 The cost of water is an important part of the decision-making process for slum
322 dwellers (WHO 2008). Those households without piped connections frequently pay

323 more for their water than those with a household connection (Banerjee and Morella
324 2011; Pierce 2017; S. L. Smiley 2017). Further, slum households which are not
325 recognised by the government pay significantly more for their water than those that
326 are legally recognised (Subbaraman et al. 2013). However, the affordability of water
327 does not remain constant, with fluctuations in price resulting from the availability of
328 water, or the household's ability to pay changing over time.

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

342

343 **2.4. Quality**

344 Perceived or actual water quality is a key driver of a collector's decision-making
345 about drinking water (e.g. Okotto *et al.*, 2015). As already discussed, drinking water
346 sources can be divided into "improved" (e.g. public tap, borehole, protected well) and

347 “unimproved” (e.g. an unprotected well, an unprotected spring), however water
348 sources within the “improved” category may still become contaminated (Bain *et al.*,
349 2014). Within individual water source categories some sources may be more prone
350 to contamination than others depending upon the design, quality of construction and
351 maintenance.

352 Water may be contaminated at source, at the distribution point (e.g. kiosk), and
353 during transport or storage (E. Adams, Price, and Stoler 2019; Rufener *et al.* 2010;
354 Satapathy 2014). In slums, water is commonly transported between the source and
355 the home, and then stored in containers within the household. Household
356 contamination of stored water is common, particularly in settings with young children
357 or shared access to a single water container; in these situations clean drinking water
358 can still become contaminated despite being collected from an “improved” source
359 (e.g. Wright, Gundry and Conroy, 2004; Boateng *et al.*, 2013; Blanton *et al.*, 2015;
360 Shields *et al.*, 2015; Alarcon Falconi *et al.*, 2017). Although many studies have
361 demonstrated that drinking water in slums is often contaminated, most of these
362 studies are cross-sectional (e.g. Chemuliti *et al.*, 2002; Kimani-Murage and Ngindu,
363 2007; Muoki, Tumuti and Rombo, 2008; Opisa *et al.*, 2012; Subbaraman *et al.*, 2013;
364 Blanton *et al.*, 2015; K’oreje *et al.*, 2016; Debela *et al.*, 2018), which provide only a
365 “snapshot” of water quality that does not reflect the temporal dynamics of risk
366 resulting from the numerous factors shaping access, use, and decision making in
367 urban slums (Figure 3). Our higher temporal resolution water access and quality
368 monitoring approach proposed here will help us better understand the complex
369 relationship between drinking water and health in slums, which will enable the design
370 of more effective health interventions.

371

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

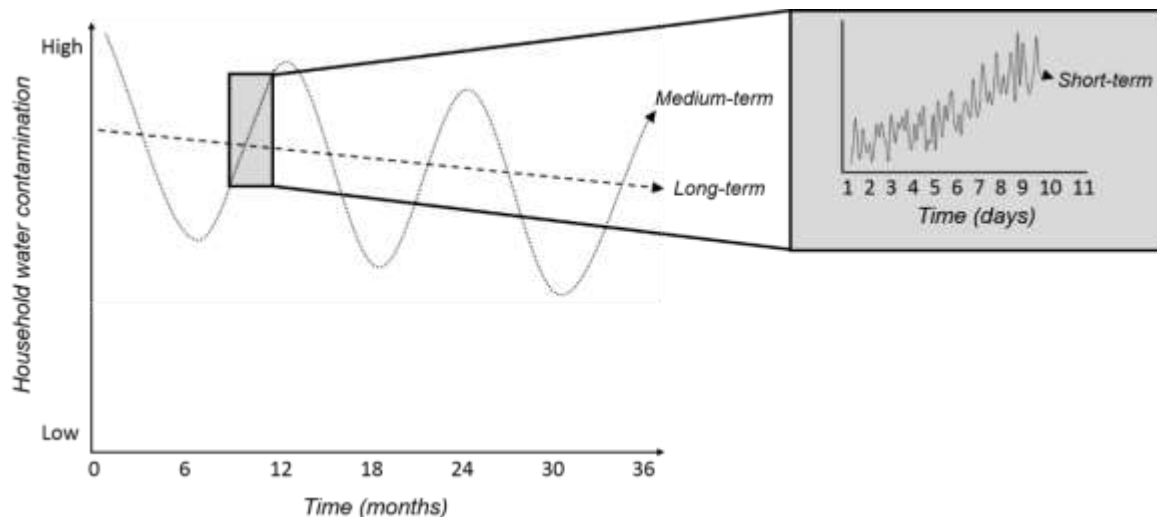
375 Over long timescales, increased population density caused by rural to urban
376 migration and population growth puts increased pressure on any existing water
377 supply infrastructure (Dana 2011; Kimani-Murage and Ngindu 2007). Maintenance of
378 infrastructure is vital to ensure continued clean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

397 upgrading (Lilford et al. 2017). There are very few studies that have investigated
398 long-term (e.g. year to year) change in water quality in slums either at source or
399 within households (Thompson et al. 2000; Okotto-Okotto et al. 2015).

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

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

416



417

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

423

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

435 water quality monitoring is needed in urban slums to capture temporal changes in
436 water-related health risks.

437

438 **3. Recommendations for future research**

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

442

443 **3.1. Short-term water access and quality monitoring**

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

456 As we have shown, there is a theoretical basis for understanding short-term
457 changes in accessing sufficient safe water for slum dwellers, although no studies

458 have been identified that directly address this key issue. We therefore recommend
459 that further work is undertaken to better understand changes in temporal access to
460 safe water, over short (i.e. within a day, day to day, and days to weeks) timescales.
461 While we acknowledge the challenges of incorporating short-term access and risk
462 metrics into both global and national monitoring, particularly in terms of time and
463 resource requirements, there are methods and approaches that could be used to
464 help tackle this. For example, the number of environmental monitoring studies
465 utilising citizen scientists, i.e. recruiting members of the public to assist in the project
466 (Bonney et al. 2009), has increased significantly in recent years (Jollymore et al.
467 2017).

468

469 **3.2. The role of socio-cultural factors in shaping temporal dynamics of safe** 470 **water access**

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

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

491

492

493 **4. Conclusion**

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

505

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

517

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520

521

522

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