University of Southampton

Faculty of Environmental and Life Sciences

School of Geography and Environmental Science

Domestic Drinking Water Availability in sub-Saharan Africa:

Investigating Drivers and Indicators

by

Mair Lucy Heath Thomas-Possee, BA, MSc

ORCID ID: 0000-0003-1899-2434

Thesis for the degree of Doctor of Philosophy

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Abstract

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Domestic drinking water supplies prone to interruptions and low per capita domestic water availability have been frequently reported among sub-Saharan African (SSA) households. Despite expanded international monitoring of drinking water availability through the sixth Sustainable Development Goal (SDG), little is known about the reality households face in receiving the water they require to meet their needs, nor how service availability has been measured to date. Using a 'three-paper format', this thesis aims to provide an insight into the complexities and inequalities in drinking water availability across SSA, whilst shedding light on the metrics used to assess service availability and the data currently available for monitoring progress towards SDG 6.

Through a systematic literature review, the first paper examines the methods used to date to measure drinking water availability, whilst synthesising existing evidence on African domestic drinking water availability. Findings indicate households across Africa are consistently faced with inadequate quantities of water. Only 9% of the 42 included studies reported household drinking water availability that meets the World Health Organisation's minimum benchmark of 100 litres per capita per day that is required to meet basic needs. Research has used a multitude of diverse study methods and metrics to quantify service availability which restricts the ability to compare availability between studies.

Building on these findings, a cross-sectional, multi-level regression analysis was conducted in the second paper, drawing on georeferenced Demographic and Health Surveys. This explores the determinants of household-reported interruptions to drinking water services via improved sources in Ethiopia, Gambia, Malawi, Nigeria, Sierra Leone, South Africa, Tanzania, Uganda, Zambia and Zimbabwe. Evidence shows inequalities in service availability across the study countries, which in

the highest instance, in Tanzania, sees 55% of households reporting an interruption. Similarities across countries in the household and community factors associated with interruptions are evident. Households living in urban areas, under water-scarce conditions or using a piped source are most likely to report an interruption to their supply.

The third paper assesses the consistency of data from water providers, a government water regulator and household water service users, when reporting on piped drinking water service availability in urban and peri-urban Zambia. A novel methodology involving multi-level modelling and spatial linkage of a household survey with water sector databases was successfully developed to integrate the three data perspectives. The three data streams are found to correlate with one another in their reporting of service availability. Direct comparison is limited however by the variations in metrics used, with a reliance from providers and regulators on yearly mean service hours, whilst household user data uses the more specific measure of availability in the last two weeks. The paper argues that whilst regulator and service providers can generate timely sub-national indicators of water availability, the annual metrics in these reports may fail to capture local-level inequalities or seasonal water interruptions.

Overall, this thesis highlights the inequalities that households experience in drinking water service availability across SSA, and the multitude of contextual and compositional factors that are associated with service interruptions. It also shows the breadth of empirical approaches used to measure availability and the complexities of the metrics used for quantification. The study develops insights by applying public health concepts, notably composition and context, to household water availability, whilst providing methodological contributions which advance understanding using geospatial and data integration techniques. The work concludes by emphasising the importance of improving domestic drinking water availability across SSA in order that standards of living are improved, and adverse health effects reduced. Recommendations are also provided for advancing and streamlining data collection to more effectively monitor progress towards SDG 6, thus ensuring that no one is left behind.

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Research Thesis: Declaration of Authorship

Print name: Mair Lucy Heath Thomas-Possee

Title of thesis: Domestic Drinking Water Availability in sub-Saharan Africa: Investigating Drivers and Indicators

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
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Thomas, M.L.H., Channon, A.A., Bain, R.E.S., Nyamai, M., and Wright, J.A., 2020. Household-Reported Availability of Drinking Water in Africa: A Systematic Review. *Water*, 12 (9), 2603.

Signature: Date:

COVID-19 Impact Statement

A significant proportion of my doctoral research has been conducted during the COVID-19 pandemic and the following year when a 'new normal' has been evolving. With the pandemic occurring early on during the second year of my PhD, the original planned thesis had to significantly change in its scope and direction in order to ensure successful completion.

The thesis presented is therefore a result of adapted plans, and the use of already-available data sources. Originally, the main analytical chapter(s) would have included primary data collection. Two plans for fieldwork existed, including:

(a) Primary data collection in Ghana to explore the availability of drinking water in healthcare facilities (HCFs) across the Eastern Region. This analysis aimed to explore whether HCFs have the capacity to secure more reliable water services than surrounding households or whether local environmental, social and economic barriers to services are common to both households and HCFs. Harmonised data on WASH in HCFs is not widely available (Chatterley *et al*. 2018), hence the reliance on primary data collection. Surveys, which included questions similar to the JMPs core and expanded question sets (WHO and UNICEF 2018a), would have been used. This would have allowed for comparison between the healthcare and household contexts, whilst exploring synergies between Sustainable Development Goal (SDG) 3 and SDG 6. This analysis would have replaced the secondary data multi-country analysis in Chapter 5 and resulted in a thesis with a completely different angle on drinking water availability in sub-Saharan Africa.

(b) Visits to government water regulators in three research countries, in order to identify additional reports and data that are not available internationally. This fieldwork also aimed to develop an understanding of both the national policy context around water services and of related data systems. The fieldwork would have supported and developed the analysis undertaken in Chapter 6 which would likely have been a country comparison between South Africa, Kenya and Zambia. As a result of COVID-19 and the analysis that was possible without fieldwork, Chapter 6 subsequently focuses solely on the situation in Zambia.

Whilst extensive measures were taken to minimise the impact of the pandemic on this thesis, it was never possible to completely mitigate the unprecedented times experienced.

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A few special thanks to those that have made my PhD journey a success and who inspired me from the get-go, to…

Jim, who kickstarted my journey into academia through supervising my undergraduate dissertation. Thank you for immersing me in the world of WASH from the get-go, for your ongoing support over the last 8 years and for considering me for numerous opportunities along the way.

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List of Abbreviations

BWS......................................Blue Water Scarcity

DHS......................................Demographic and Health Survey

EA ....Enumeration Area

ERGO .... Ethics Research and Governance Online

ESRI .... Environmental Systems Research Institute, Inc.

GADM.................................. Database of Global Administrative Areas

GCS .... Geographic Coordinate System

GDP .... Gross Domestic Product

GIS .... Geographical Information Systems

GPS .... Global Positioning System

HWIAS .... Household Water Insecurity Access Scale

HWISE.................................. Household Water Insecurity Experience Scale

IPCC .... Intergovernmental Panel on Climate Change

JMP...................................... Joint Monitoring Programme

LMICS .... Low- and Middle-income Countries

LPCD .... Litres per Capita per Day

LPHHD .... Litres per Household per Day

MICS .... Multiple Indicator Cluster Surveys

MDGs................................... Millennium Development Goals

PPP .... Purchasing Power Parity

PPS .... Probability Proportional to Size

PRISMA................................ Preferred Reporting Items for Systematic Reviews and Meta-Analysis

PSU .... Primary Sampling Unit

SDGs .... Sustainable Development Goals

SSA .... Sub-Saharan Africa

UN .... United Nations

UNDP................................... United Nations Development Programme

UNICEF .... United Nations Children's Fund

WASH ....Water, Sanitation and Hygiene

WHO....................................World Health Organisation

WFN .... Water Footprint Network

WGS..................................... World Geodetic System

WRI......................................World Resources Institute

Chapter 1

Introduction

1.1. Overview

For millions of households in sub-Saharan Africa (SSA) having a drinking water service that is fully functioning, safe and accessible remains a pipe dream. The effects of inadequate services are widespread. For individuals, ill-health such as diarrhoea can quickly ensue when the water required for normal day to day life is lacking and simple tasks become challenging. On a societal level, basic industrial and agricultural practices, that enable a productive economy and support livelihoods, are impossible (Rudra *et al*. 2018).

As of 2010, water was officially recognised as a human right (Hutton and Chase 2016). In its consideration of the availability and quality of services, the human right to water states it must be: *'available continuously and in a sufficient quantity to meet the requirements of drinking and personal hygiene, as well as of further personal and domestic uses, such as cooking and food preparation, dish and laundry washing and cleaning. […] Supply needs to be continuous enough to allow for the collection of sufficient amounts to satisfy all needs, without compromising the quality of water'* (United Nations 2010a, p. 6). This human right is not 'optional, voluntary or something that can wilfully be ignored by governments' (Smiley 2016, p. 1321), it is a binding obligation which requires responsibilities that must be accepted and acted upon. This in particular is critical as the right to water is a precondition to multiple other rights including food, education and health (Chipeta 2009).

At present, only 30% of the population in SSA have a safely managed drinking water source classified as being available when needed, free from faecal and priority contamination and easily accessible (WHO and UNICEF 2021). 74 million people in SSA are dependent on surface water such as lakes, rivers and streams (WHO and UNICEF 2021). They are unable to attain the basic human right of water and subsequently struggle to go about basic household and domestic activities (OHCHR 2010; Oageng and Power Mmopelwa 2014). The impacts are multifaceted, ranging from premature death due to consumption of contaminated water, to increased absenteeism from schools (Jasper *et al*. 2012) and women's impaired capacity to engage in economic activities as hours are spent collecting water as a priority (Stevenson *et al*. 2012).

The availability of domestic drinking water, defined as that which households use for consumption, cooking, sanitation and hygiene (JMP 2022a), is significantly reduced due to a range of factors. Services that are 'available when needed' are those which provide *sufficient* water or water which is available *most of the time,* for example, continuously (24 hours a day, 7 days a week) or for at least 12 hours per day or four days per week (WHO and UNICEF 2021). Following this definition, for the remainder of this thesis, the term 'water availability' refers to *sufficient water for household consumption, which is available most of the time*. Crucially, ongoing social-demographic pressures such as population growth and urbanisation, coupled with increasing variability and water scarcity are serving to undermine the availability of services at the household level (Whaley and Cleaver 2017).

In northern and southern Africa prolonged and extreme droughts, seasonal variations in rainfall and the degradation of water resources are all resulting in extended and extreme periods of water stress where demand is exceeding supply (EEA 2019; World Resources Institute 2019a). As a result, sharp geographic, sociocultural and economic inequalities persist; not only on a global scale between developed and less developed countries, but between rural and urban areas, and within towns and cities where low-income, informal settlements (World Health Organization 2019). Rapid population growth and urbanisation have seen existing water utilities outpaced by demand (Purshouse *et al*. 2017). Subsequently, local authorities and governments struggle to develop infrastructure at the necessary rate (Rimi Abubakar 2018). This is further impacted by limited funds and poor domestic investment, coupled with a reliance on international aid and NGO support in order to expand existing water services, all of which can hamper local involvement and advancement of knowledge (Ioris 2016).

1.2. The Bigger Picture: Drivers of Domestic Water Availability

Planetary health, “the health of human civilisation and the state of the natural systems on which it depends” (Whitmee *et al*. 2015, p. 1978), recognises the emerging chronic and acute threats from unsustainable and inequitable processes to natural and human-made systems, which are essential to humanity’s survival (French *et al*. 2021). Human exploitation of the natural environment has outstripped natural resources, including water, and their availability, resulting in the unprecedented changes faced over the past decades (Ramirez-Rubio *et al*. 2019). As such, we are faced with increasingly complex social structures, global health problems and inequities in resources such as water within and across nations (Myers 2017). These are perfectly illustrated in the complexities of drinking water and its availability across societies.

The effects of water insecurity on populations, and individuals, are multifaceted, not least because of how interrelated they can be. Availability of, and access to, water underpins all aspects of modern society, namely equitable, stable and productive ecosystems and societies (Gain *et al*. 2016). It is intrinsically linked to other sustainability issues ranging from poverty, hunger, health, gender equality and education, to disasters, climate change and ecosystem integrity (Bernhardt 2015; Daramola and Olawuni 2019). The social and economic demand for water is further impacted by the spatial and temporal variations of water availability (Mekonnen and Hoekstra 2011). The following sections discuss the importance of water within society and thus the effects that water insecurity has on national, regional, local and household level.

Industrial processes and manufacturing have been criticised for their negative impacts on water availability and quality (Tundisi et al. 2015; Brisman et al. 2018). In low- and middle-income countries (LMICs) in particular, successful and productive industry, and thus adequate water service, is critical to the development of society and economies (Christiaensen and Martin 2018). As of 2017, 91 of 135 LMICs' economies were reported to be reliant on commodity exports, especially agricultural and mining products (UNCTAD 2017), and in 2016, $1.511 trillion was contributed to the economies of 25 top African countries reliant on mining (ICMM 2018). Therefore, despite its impacts on local water resources, supporting this industry is arguably a crucial investment for countries striving to improve their economy and achieve multiple development goals (Bebbington and Williams 2008; Li 2018). To date, it has been reported that 69% of the world's freshwater withdrawals are dedicated to agriculture and are subsequently unavailable for human consumption, a relationship illustrated in the water-energy-food (WEF) nexus (AQUASTAT 2016). However, the agricultural, forestry and fishing sector plays a pivotal role in economic growth, contributing 15.8% of SSA's GDP in 2017 (World Bank 2017). Therefore, supporting irrigation schemes, which are necessary for agriculture in arid environments, is critical to development. On a more local scale, the capacity for smallholders to maintain their livelihood through subsistence crops and livestock production is also critical to development, especially considering that they contribute up to 53% of the world's food (Graeub *et al*. 2016).

On a regional scale, adequate water sources are critical to maintaining suitable healthcare services and achieving development goals which focus on reducing mortality levels. Historically, the international development agenda has primarily focused on water, sanitation and hygiene (WASH) at the household level (WHO and UNICEF 2017a), and has only more recently included a significant focus on WASH in healthcare facilities. Sufficient availability of WASH is a prerequisite for quality care in healthcare facilities (Rajasingham *et al*. 2018), especially in enabling hand hygiene, showering and bathing, cleaning and washing equipment and for a variety of general and specialised medical treatments (Cronk and Bartram 2018). Recent figures show that 74% of health care facilities globally have basic water services, meaning water was available from an improved source on premises, however this equates to an estimated 896 million people using inadequate health care facilities with no water service (WHO and UNICEF 2019a). Given these conditions, premature mortality is often exacerbated by unsanitary conditions which result in infection. Globally, the prevalence of healthcare-acquired infection stands at 16% (Allegranzi *et al*. 2011). High risk medical procedures are especially vulnerable to infection and in LMICs childbirth may be a particularly risky procedure which can result in infant and maternal mortality. One third of maternal deaths globally that occur in healthcare facilities can be attributed to poor WASH (Mills *et al*. 2016).

The global recognition of the role that WASH in schools plays in improving access to education and learning outcomes, especially for girls, has been instrumental in improving school attainment rates (UNESCO 2017). Ensuring that attainment is not affected by a lack of running water is vital in also achieving SDG 4 which aims *'to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all'* (United Nations 2022a). The challenges remain substantial however, with an estimated 19% of schools globally, or 570 million children, lacking basic water provisions and services required for handwashing, sanitation and menstrual sanitation (Jasper et al. 2012; WHO and UNICEF 2018b). Improvements of the latter are especially important for preventing gender-based disparities in educational attainment and for increasing gender equality. SDG 5 aims to '*achieve gender equality and empower all women and girls'* (United Nations 2022b), given the effect of poor WASH in schools on attendance, improvements to the availability of water services is critical in meeting SDG 5. A recent systematic review found WASH interventions which promoted hand-washing and point-of-use water treatment reduced the odds of student absenteeism in girls by 58% (McMichael 2019). The health effects of poor water availability correlate with school attendance and improvements can help to reduce the 443 million school days missed every year across the world with 272 million as a result of diarrhoea (Wagner and Pramling Samuelsson 2019; Yizengaw et al. 2022).

More locally, poor water availability substantially affects individual health. SDG 3 aims to '*ensure healthy lives and promote wellbeing for all at all ages'* (United Nations 2022c), however in Africa it is estimated that 115 people die every hour from diseases linked to a range of WASH related exposures (UNDESA 2014; Prüss-Ustün et al. 2019). Where water is insufficient individuals must prioritise its use, in which case handwashing tends to be reduced, thus increasing the risk of diarrhoea (Kanda *et al*. 2017). Reducing the incidence of diarrhoea is critical in reducing global child mortality rates: however its incidence remains inextricably high with diarrhoea being the second biggest cause of under-five child mortality and accounting for an estimated 525,000 child deaths a year (World Health Organization 2017a). The burden of ill-health created by poor water availability can also result in economic losses at the household level. It is estimated that for every dollar invested in WASH services, a US$4.3 return occurs due to lower healthcare costs for individuals and society, and greater productivity and involvement in the workplace (UN Water *et al*. 2014). Use of poor quality and unavailable resources mean people spend more time and effort physically collecting water and less time being productive in other ways, such as working.

The majority of cultures have different roles and responsibilities for men and women in the use and management of water (Chipeta 2009), thus the burden of collecting water tends to fall to women or children. In some rural areas, women spend up to 6 hours a day collecting water (Stockholm International Water Institute 2007). When water services are not available on premises, children as young as 3 years old are valuable assets in fetching water. By the age of 13, children can carry the same amount as adults (Sugita 2006). While research into the gender-specifics of water-related activities is limited (Sorenson *et al*. 2011), women and girls are responsible for water collection in 80% of households using water sources located off premises (WHO and UNICEF 2017b). The role that children play in collecting water markedly reduces their instructional time spent in schools and as a result absenteeism becomes inherent (Alhassan and Kwakwa 2014). Most notably, Hunter *et al*. (2014) found that absenteeism substantially decreased during the rainy season when water resources are more readily available to households.

As is evident, poor WASH has wide-ranging effects on households, communities and national economies. These effects are further exacerbated by a range of broader drivers, namely water scarcity and the resultant water insecurity, and the pressures of rapid population growth and urbanisation that is occurring in LMICs. These ongoing and diverse challenges, which continue to affect global, regional and local availability of drinking water, are complex to say the least. The following sections discuss the impacts of these issues on water services across Africa.

1.2.1. Water Insecurity and Stress

Water insecurity is conceptualised as a consequence of inadequate and unsafe availability and access to services and the *'inability to benefit from affordable, adequate, reliable and safe water for wellbeing and a healthy life'* (Tsai et al. 2016; Young, Collins, et al. 2019, p. 1). It remains a real and prevalent issue, especially in LMICs. Despite longstanding attention on improving access and availability of drinking water through policies and agendas (United Nations 1977), drinking water shortages are estimated to impact at least four billion people, nearly two thirds of the global population, for at least one month a year (Mekonnen and Hoekstra 2011).

Worsening water security and rising water stress, defined as when human and ecological demands are not being met, has been particularly pertinent across the continent of Africa where it affects one in three people (World Health Organization Regional Office for Africa 2019). Most notable are the disparities that have emerged in recent years between northern Africa and SSA. In the year of expiry of the Millennium Development Goals (MDGs) in 2015, 92% of north Africa's population had an improved water service compared to 61% in SSA (UNDESA 2014). SSA is also home to the highest number of water-stressed countries in the world; by 2030, it is anticipated that between 75 million and 250 million people will be living in areas of high water stress (Bureau and Strobl 2012). While the causes of water stress are complex and exacerbated by growing water demand, these visible geographical differences in water availability can largely be attributed to variations in annual rainfall and temperatures and increased vulnerability and unpredictability of weather patterns as a result of climate change (Masson-Delmotte *et al*. 2021). 66% of Africa is arid or semi-arid, thus regions such as the Sahel, Sahara and Southern Africa are often the worst affected because of their environmental conditions (UNDP 2006); more than 300 of the 800 million people in SSA live in environments where less than 1,000m^3 of renewable water is available per capita per year (UNDESA 2014).

The ongoing impacts of climate change, including a reported 10% decline in annual rainfall in some areas of SSA, is also amplified by water lost as a result of rising temperatures and a resultant increase in evapotranspiration (Masson-Delmotte *et al*. 2021). Droughts and increased pressures from climate change have been particularly prominent in countries in northern and southern Africa (Ward 2015). 2005 saw more than 20 million people affected by drought across the Horn of Africa (UNDP 2006), while in 2019 45 million across 14 countries of eastern and southern Africa and the Horn of Africa were impacted by severe drought. The consequences of periodic drought were further worsened by El Nino events which for the second time in three years disrupted weather patterns and resulted in rainfall that was significantly below average: in some areas of southern Africa the annual rainfall fell by 50% (Anyadike 2019). Not only do changes in rainfall patterns and the occurrence of drought directly implicate water services and inhibit basic WASH related activities, but they also significantly impact agriculture and more than often result in food scarcity and famine (UNDP 2006).

1.2.2. Social-demographic Pressures on Water Services

In addition to the environmental causes discussed, population growth, urbanisation and increases in household and industrial uses further impact water stress (World Health Organization Regional Office for Africa 2019). Population growth in particular is accelerating the deterioration of water services, with old and inadequate infrastructure often being outstripped by urban development and growth (Rouse 2014; Padowski et al. 2016). Economic water insecurity is becoming all too familiar across Africa, with insufficient domestic financing and limitations in human, economic and institutional capacities due to endemic poverty. Underdeveloped economies are affecting capacities to not only develop, but manage water resources in a sustainable manner (UNDESA 2014). This is particularly the case in regions where populations do not have the financial means to make use of sufficient water sources on their own; over half the population of SSA live on less than US$1 a day (*ibid*.). Therefore, while deep and widespread poverty makes addressing water issues challenging, it is further impacted by the additional economic losses that poor quality water services incur. SSA loses about 5% of its GDP, or some $28.4 billion annually, as a result of ill-health due to inadequate drinking water services, time spent out of work to collect water and other similar WASH-related impacts (World Health Organization n.d.).

These causes are resulting in variations between both rural and urban, and richer and poorer, populations. For example, in urban, richer areas of Africa over 90% of the population have access to a piped water source, whereas in rural poorer regions 40% of households do not have water sources on premise and less than 50% of the population use any form of improved water source (UNDESA 2014). Rural water insecurity is especially acute in SSA where the number of people without a safely managed supply increased by 38 million during the MDG period of 1990-2015 (Hope *et al.* 2012). That said, new trends have begun to emerge which suggest that access in urban areas has deteriorated with urban water systems threatened by ageing infrastructure, climate related effects and rapid population growth leading to the development of informal settlements in major cities (Purshouse et al. 2017; Ferguson and Charles 2021). For instance, drinking water access in urban Kenya reduced from 92% to 82% from 1990 to 2015 (World Health Organization 2016). As Adams (2018) notes, the pressures of these informal urban settlements are posing a challenge to national and municipal governments, who are seeking to achieve universal access and availability to good quality water in the face of growing demands. Progress by such governments is also being hindered by a lack of coordination between authorities and harmonisation of laws and policies, and they are further challenged by shortages of skilled staff and stretched resources (Adams and Zulu 2015).

Pressures have also intensified as a result of conflict, industrialisation and increased inequalities in resource distribution (Bisung and Elliott 2018). Over the last 30 years in particular, conflicts over water have been especially evident (Nelson 2010). Domestic-industrial competition for scarce water resource has been known to limit water availability, particularly for the most vulnerable of populations. During the 2018 drought in Cape Town, South Africa, where the city fought to avoid ‘Day Zero’, the day when taps would stop flowing, Coca-Cola’s use of local water sources came under scrutiny as the poor and working-class struggled to afford alternative water sources whilst Coca-Cola used millions of litres of municipal water in its production processes (Robins 2019). Similarly, underperformance of state agencies have seen the development and semi-privatisation of some water resources, resulting in unaffordable price rises, such as in urban Ghana (Twum and Abubakari 2020). International disputes as a result of dam projects and their influence on countries downstream are not uncommon; conflicts over the development of the Grand Ethiopian Renaissance Dam are ongoing between Ethiopia, Sudan and Egypt (Basheer *et al*. 2021). Where civil unrest and conflict are rife, for example in Syria and northern Nigeria, the demolition of water infrastructure is common and has resulted in large populations being totally cut off from drinking water services for extended periods of time (King 2015).

1.3. Policy Context

Despite the complexities of providing drinking water services that are available when needed, improvements have been, and continue to, be made. In the last 5 years, the proportion of the SSA population using safely managed services rose from 27% to 30%, and those using a basic service, one which is classified as improved and includes a 30 minute round trip to collect (JMP 2022a), rose from 33% to 35% (WHO and UNICEF 2021). While global development agendas and international bodies such as the United Nations (UN) and the World Health Organisation (WHO) have considered, but not officially recognised, access to drinking water as a basic human right since 1977 (United Nations 1977), it has only been acted upon more recently. At the national and international level, the role of monitoring drinking water services falls to the WHO and United Nations Children's Fund (UNICEF) Joint Monitoring Program (JMP). Prior to the JMP's monitoring of water services, numerous policies and UN agendas existed, thus creating a fragmented monitoring landscape.

The recognition of drinking water as a development issue was established by the League of Nations Health during the 1930s, when it was addressed alongside sanitation in their rural hygiene programme (Bartram *et al*. 2014). Since then, the UN has accepted the importance of WASH and as a result during the 1960s began their international monitoring activities (Figure 1-1). In the years preceding the development of the MDGs, the UN declared the 1970s as the Second UN Development Decade. Similarly, the 1980s was declared as the International Drinking Water Supply and Sanitation Decade (United Nations General Assembly 2003), and the predominant focus was on providing water for domestic purposes (Hall *et al*. 2014). 1990 marked a pivotal year in the recognition of drinking water within international agendas, particularly the MDGs, which included a specific water-related target. This aimed to halve the proportion of global population without sustainable access to safe water (United Nations 2015a). In an effort to fulfil the international MDG commitments made on water and water-related issues, the period 2005-2015 was declared as International Decade for Action 'Water for Life' (United Nations 2015b).

The current 2030 Agenda, which has been developed as the post-2015 international development agenda and is more widely known as the Sustainable Development Goals (SDGs), goes beyond the MDGs and includes a dedicated water goal, which specifically includes the addition of availability. SDG 6 aims to 'ensure availability and sustainable management of water and sanitation for all' by 2030 (United Nations General Assembly 2014). Crucially, the development of the MDGs from 1990-

2015 and their successors, the 2015 SDGs, have been critical in effecting change through specific sub-targets and goals which aim to improve drinking water services (Daramola and Olawuni 2019).

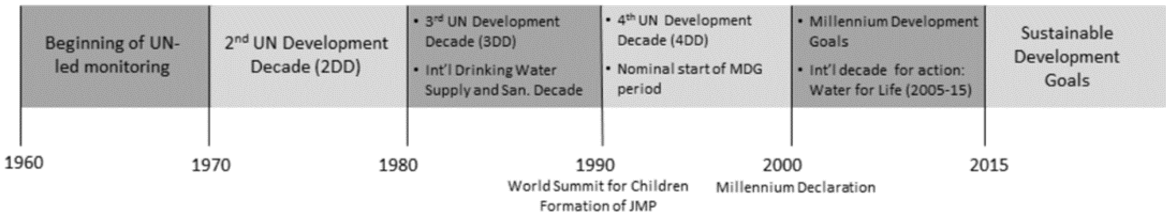


Figure 1-1: Timeline of international targets and actions relating to WASH (Source: Bartram *et al*. 2014)

1.4. Thesis Rationale

This thesis focuses solely on the availability of drinking water in the context of SSA. It does so for several reasons. Firstly, SSA is consistently one of the regions with the worst drinking water provision, having fallen short of meeting the 2015 MDG target 7c (United Nations 2015a). Secondly, availability has only been included as a measure of a safely-managed drinking water service since the development of the SDGs (Majuru *et al*. 2018). It is therefore a relatively new concept within international development agendas and related literature, and global measurement standards of availability were only facilitated following the development of the SDGs. Subsequently, systematic knowledge of the measures used to date to quantify service availability is lacking.

The addition of availability to the definition of a safely managed drinking water source has also resulted in new pressures and demands on data sources for monitoring (Yu *et al*. 2016). Whilst there are multiple data streams available for international monitoring, namely from the perspective of users, water providers and government regulators, at present the JMP predominantly use that available from users through household surveys and censuses (Bartram *et al*. 2014). The JMP require data which represent at least half the population in question in order to make its estimates (WHO and UNICEF 2017b). Given this and the new pressures on data sources, methods which help to meet this criterion threshold are needed. As such, an understanding of whether data from users, providers and regulators are consistent with one another, and could subsequently be used in conjunction, is of great value.

Alongside the need to address knowledge gaps relating to measuring drinking water availability and meeting new data pressures, a comprehensive understanding of the factors that affect availability in households and communities across SSA is lacking. Such factors are multifaceted and complex. Improving understanding is critical in ensuring the availability of services is increased and interruptions that households face are reduced, especially if SDG 6 is to be achieved. At present, achieving SDG 6 will require a quadrupling of current rates of progress (WHO and UNICEF 2021). The recently published 2021 Intergovernmental Panel on Climate Change (IPCC) report highlights that climate change is likely to increase variability in rainfall and the intensity of droughts. As such water scarcity, and subsequently water stress, are likely to influence the amount of drinking water available to households (Masson-Delmotte *et al*. 2021). Additionally, ongoing population change, urbanisation and the increasing demands on water service infrastructure are also proving detrimental to drinking water availability in urban areas (Hutton and Chase 2016). Understanding the threat these factors pose to supplying households across SSA with their required drinking water is vital, particularly in ensuring inequalities are minimised and no one is 'left behind' following the 2030 agenda (WHO and UNICEF 2019b; He et al. 2021).

1.5. Thesis Aim and Objectives

Based on the rationale given, this thesis aims to quantify factors that affect drinking water availability across SSA and associated geographic and socio-economic inequalities. It also aims to evaluate the metrics used to assess service availability and the data currently available for monitoring progress towards SDG 6.

The primary objectives of this PhD thesis therefore are:

1. *To assess how research has measured the availability of drinking water in SSA to date and examined its consequences.*

2. *To evaluate whether different data perspectives correlate and can subsequently be used in conjunction with one another in monitoring progress towards SDG 6.*

3. *To assess the environmental effect of water scarcity/stress on drinking water availability across SSA.*

4. *To explore variations and inequalities in drinking water availability across SSA and common contextual and compositional factors associated with user-reported service availability.*

Chapter 2

Contextualising the Problem: International Monitoring of Water Service Levels

2.1. Overview

This chapter and the subsequent review aim to give context to this PhD thesis, its research aims and the three empirical chapters. In the first section an overview of how drinking water services are and have been monitored by the JMP is provided, with specific focus given to inequalities and how they are accounted for. This is followed by a discussion of the available data used to measure household water access and how the JMP has used a range of sources. A specific focus on household surveys and censuses is given, as well as data available from utility companies and regulatory databases. The section concludes with a comparative evaluation of available data streams.

The second section of this chapter examines how the JMP define a 'safely managed drinking water source', noting the elements of service quality and accessibility, before focusing in greater detail on the availability of sources and different concepts, including service continuity, functionality and intermittency. Discussion of different water sources used in LMICs and SSA and their characteristics is then undertaken, with specific emphasis given to how each source's availability can be affected.

To conclude this chapter, in the final section focus is given to the role that contextual and compositional factors play on service availability. In three sub-sections, household-level factors that affect the availability of drinking water are explored, these household factors are then contextualised by considering the role of service providers and their economics on service availability before discussing the broader drivers of water availability, such as WEF, urbanisation, climate change and political instability. In doing so, a conceptual framework is presented and discussed throughout.

2.2. International Monitoring of Drinking Water Services

As discussed in Chapter 1, the journey to recognise water as both a human right, and on an international plane as a development issue, has been complex (Bartram *et al*. 2014). As the importance of the role of safe drinking water on quality of life has been recognised and prioritised over the last thirty years, monitoring of water services has been enhanced (WHO and UNICEF 2013). As a result, SDG 6 includes six targets, each with their own indicators, which are used to monitor progress towards its achievement (United Nations 2021). Of particular interest for this thesis is target 6.1 which aims by 2030 to achieve *'universal and equitable access to safe and affordable drinking water for all'* (ibid.). Indicator 6.1.1 is used to monitor progress towards this target by using the proportion of the population using safely managed drinking water services. Safely managed drinking water services are defined in detail in the proceeding section (2.4).

The JMP's main mission is 'to produce reliable estimates of national, regional and global progress on WASH to inform decision making by government, donor and civil society organisations' (WHO and UNICEF 2019c). As part of the JMP's monitoring of progress towards SDG 6, estimates are generated for specific types of drinking water sources, namely piped versus non-piped sources (Bain *et al*. 2018). Successful monitoring, and the collection of required data, is critical in tracking progress and achieving local, regional and international goals, especially those relating to SDG 6 (Yu *et al*. 2016).

2.2.1. Past and Current International Monitoring of Household Drinking Water Services

The existence of key milestones for monitoring household drinking water services started with the establishment of the MDGs, which resulted in the JMP creating a standardised set of drinking water and sanitation categories. MDG target 7c aimed to halve the proportion of the population without sustainable access to safe drinking water and sanitation, between 1990 and 2015 (United Nations 2014). Progress towards the target was measured using *'the proportion of the population using an improved drinking water source*' (United Nations 2008). Historically, the JMP have classified drinking water services based on a binary system of improved/unimproved services, whereby 'improved' concerns sources whose nature of design and construction mean that they have the potential to deliver safe water (JMP 2022a). In contrast, an unimproved service tends to provide unsafe and poor-quality water (Shaheed *et al*. 2014).

A common critique of the monitoring approach used during the MDGs has included criticism of the use of the binary improved/unimproved classification and its inability to reflect the breadth of service level people actually received (Bartram 2008; Bain et al. 2018). Given this, from 2008 these binary categories were expanded to develop the 'Drinking Water Ladder' which aims to better understand the disparities in access beyond the typical improved-unimproved categories (Bisung and Elliott 2018). Critically, it highlighted the highest and most desirable level of service attainable as 'piped water on premises' (a category that was specifically designed to be distinguishable from other, more general improved sources (WHO and UNICEF 2011)), as well as the lowest service level, surface water (Moriarty *et al*. 2011). This method of measuring household water access was subsequently used throughout the MDGs, with the JMP's classification of an 'improved source' reflecting the MDG targets definition of 'safe water' (WHO and UNICEF 2012).

The JMP's drinking water ladder has undergone several transitions (Figure 2-1) and developments of the JMP classifications occurred from 2010. Most notably, this involved the addition of a fourth category: 'surface water from other general unimproved services', which became the classification of the least desirable drinking water sources (WHO and UNICEF 2012). Bottled water was added into the improved classification, however it was only considered improved so long as households had other improved water services available for domestic uses beyond drinking (Moriarty *et al*. 2011). Finally, MDG target 7c was also designed to address improvements in overall coverage with its framing of 'reduced by half', as such, it failed to consider inequalities in coverage between different populations (Bain *et al*. 2018).

Figure 2-1: Evolution of the JMP drinking water ladder for global reporting of progress on drinking water (Source: Yu, 2018)

The JMP's service ladder has continued to develop in order to reflect additional policy-based changes and the shift in accepting water as a human right in 2010 resulted in significant changes in monitoring and measuring household water access (UNDESA 2010). Most notably, the key elements of affordability, accessibility and equality were acknowledged as being critical to the monitoring of water services. The International Water and Sanitation Centre subsequently developed indicators which corresponded with these elements, namely quality, quantity and the reliability of services (Moriarty *et al*. 2011).

The diligence of the JMP in monitoring WASH during the MDGs were applauded by some, especially given the early completion in 2012 of the drinking water component of target 7c (Kayser *et al*. 2013). An estimated 89% of the global population had access to safe water in 2012 and the MDG target had seemingly been met (WHO and UNICEF 2012). However, more recently, debate has emerged about the overestimation of MDG results (Clasen 2012; Bain, Cronk, Wright, et al. 2014). Arguments regarding the overestimation of 'basic services' are ongoing, with Bain, Cronk, Wright, *et al.* (2014) criticising the MDG indicator for failing to account for measurements of water quality by not including microbial water safety. Supporting this, Clasen (2012) also argue the MDG target did not fully address elements of water quantity or access, nor was any clear guidance given about what the MDG specifically means by 'access', 'safe' or 'sustainable'. Progress towards universal access likely overestimates the use of basic services as the indicators used to classify an 'improved source' insufficiently addressing key aspects of water safety and access (Majuru *et al*. 2018). It has also been recognised that drinking water sources were often classified as 'improved' despite potentially being of poor quality and containing faecal contamination (Bain, Cronk, Hossain, *et al*. 2014). Majuru *et al*. (2012) report that despite the Department of Water Affairs (DWA) in South Africa reporting that 97% of the population had access to an improved water service, this figure only considered the infrastructure provided and it did not consider the quality of service provisions (DWA 2010).

Following the expiry of the MDGs, the development of the new 2030 agenda and resultant SDGs saw the inclusion of a dedicated water and sanitation goal (United Nations 2021). The WHO and UNICEF, through the JMP, were named the monitoring agencies of the SDG targets for WASH, and the JMP developed a five year strategy to focus on enhancing the global monitoring of WASH in the context of the SDG Agenda (WHO and UNICEF 2019c). The subsequent monitoring framework developed sought to refine the service ladder used throughout the MDGs, while taking into consideration accessibility to basic services, water quality, sustainability, affordability, reductions in inequality, levels of service and settings beyond the household, such as healthcare facilities and schools (Bisung and Elliott 2018).

Changes were also made to the binary improved-unimproved classification of water sources, in order to reflect SDG 6's eight targets (Table 2-1). The JMP have enhanced their monitoring framework to include more specific elements of accessibility, availability and quality of drinking water, in order to respond to the monitoring needs required in order to track progress towards SDG 6 (United Nations General Assembly 2014). These changes were in part informed by the five normative criteria of the Human Right to Water and Sanitation: accessibility, acceptability, availability, affordability, and quality(Human Rights Council 2011). Thus, the drinking water service ladder includes five categories, 'safely managed', 'basic services', 'limited sources', 'unimproved sources' and 'surface water' (Figure 2-1).

Table 2-1: Targets and indicators of SDG 6 (Source: United Nations, 2022d)

Target		Indicator	
6.1	By 2030, achieve universal and equitable access to safe and affordable drinking water for all.	6.1.1	Proportion of population using safely managed drinking water services.
6.2	By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.	6.2.1	Proportion of population using safely managed sanitation services, including a hand-washing facility with soap and water.
6.3	By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally.	6.3.1	Proportion of domestic and industrial wastewater flows safely treated.
		6.3.2	Proportion of bodies of water with good ambient water quality.
6.4	By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity.	6.4.1	Change in water-use efficiency over time.
		6.4.2	Level of water stress: freshwater withdrawal as a proportion of available freshwater resources.
6.5	By 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate.	6.5.1	Degree of integrated water resources management implementation (0-100).
		6.5.2	Proportion of transboundary basin area with an operational arrangement for water cooperation.
6.6	By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.	6.6.1	Change in the extent of water-related ecosystems over time.
6.a	By 2030, expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies.	6.a.1	Amount of water- and sanitation-related official development assistance that is part of a government-coordinated spending plan.
6.b	Support and strengthen the participation of local communities in improving water and sanitation management.	6.b.1	Proportion of local administrative units with established and operational policies and procedures for participation of local communities in water and sanitation management.

Based on this new service ladder, for a drinking water source to meet the criteria required of the SDG and therefore be classified as an improved and 'safely managed' source, it must be available when needed, located on premises and compliant with faecal and priority chemical standards (JMP 2022a). A 'basic service' considers an improved drinking water service from which the roundtrip for water collection takes less than 30 minutes. Where access to a source takes longer than this, it is considered an unimproved water source and is classified as 'limited drinking water' (JMP 2022a). Most recently, the JMP has begun to further develop their monitoring and the drinking water service ladder by replicating it for additional contexts such as healthcare facilities and schools. Other advances include specifically focusing on inequalities between population sub-groups such as rural/urban and rich/poor (UN Water 2019a).

2.2.2. Accounting for Inequalities

The SDGs commit UN member states to take bold and transformative steps to ensure 'no one is left behind' – this includes focusing on closing gaps in services between disadvantaged groups and the rest of a country's population (WHO and UNICEF 2019b). SDG 6 includes a specific focus on achieving *equitable* drinking water which implies the progressive reduction and elimination of inequalities between sub-groups (UN Water 2015)**.** Inequalities, whereby different populations have variations in living standards and health (McKay 2002), may include: spatial inequality, social inequality between different population groups living in the same region, gender inequality, or generational inequality (Yang *et al*. 2013).

Inequalities in water services tend to focus on three main dimensions: (1) geographic location, (2) socio-economic groups and (3) individual characteristics (WHO and UNICEF 2019b). Differences based on geographic location include rural versus urban areas, as well as peri-urban areas and informal settlements. Whilst research has historically shown that households in rural areas fare worse in their reliance on non-piped and public services than urban areas (Bain, Wright, et al. 2014; Adams and Smiley 2018), more recently, focus has shifted towards including analysis of variations and inequalities in drinking water in unplanned and illegal settlements (Maingey *et al*. 2022) and the effect of population growth and urbanisation on reduced urban uptake of piped services (Stoler *et al*. 2013, Adams 2018). Geographical inequalities also concern differences in coverage between subnational areal units and regions within countries (Yu 2018).

Socio-economic inequalities are often found based on differing levels of wealth, level of education of heads of households, ethnicity, religion, language and migratory status (WHO and UNICEF 2019b). Inequalities in water services relating to ethnicity, religion and migratory status all tend to favour majority groups. Typically, wealthier households have greater access to improved drinking water sources (Mulenga *et al*. 2017) and Nnaji *et al*. (2018) comment that rainwater is often perceived as a drinking water source used by the poor. The availability of sources is also significantly higher among the richest than in other wealth quintiles (WHO and UNICEF 2019b). Finally, inequalities relating to individual characteristics are often associated with age and sex, the latter of which primarily concerns the gender of the person responsible for collecting water. Women and children typically bear this burden and subsequently deal with the consequences of the lost time spent travelling and collecting water. For example, reduced capacity and ability to work and attend school (Geere and Cortobius 2017).

Given the emphasis of the SDGs and 2030 Agenda on addressing these inequalities, data must be disaggregated by income, gender, age, race, ethnicity, migratory status, disability, geographic location and other nationally relevant characteristics (UN Water 2015). During the MDGs however, estimates were disaggregated only by urban and rural populations, and in some countries by socio-economic status (Bain *et al*. 2018). It was only during the 2017 update from the JMP that socio-economic and spatial inequalities were more systematically reported. As such, calls have been made for the global expansion of water service data, and more effective use of data, that is disaggregated and includes the stratification of inequalities that account for informal settlements, disadvantaged groups and sex (Schwemlein et al. 2016; Bain et al. 2018)**.** This is especially critical given that SDG 6 will only be deemed achieved once it has been met for all sub-groups within the population (WHO and UNICEF 2019b).

2.3. Measuring Drinking Water Services and Perspectives of Availability

Following the transition from the MDGs to the SDGs and the change in emphasis of policy to include all elements of water services, new pressures and demands were placed on data sources needed for sufficient monitoring (Yu *et al*. 2016). In addition to monitoring progress towards SDG 6, where data on each element of a safely managed drinking water source is required, monitoring data is needed to inform policy development, track progress and inform national resource investment (Schwemlein *et al*. 2016). As such, to effectively implement policies and make evidence-based decisions, data that are accurate, reliable, routinely collected, disseminated and updated is required (Gine Garriga et al. 2013; Charles and Greggio 2021). This may be available from household surveys and censuses and government regulators, as well as from water service providers. Each offer a different perspective on drinking water and have their own merits and limitations.

Where possible, the JMP use data based on household responses that are available through national censuses and household surveys for their estimates (WHO and UNICEF 2017c). However, regional and global estimates for basic drinking water services are only made when data are available for at least 50% of the relevant population. In order to meet this data threshold, systematic searches using websites from administrative data sources such as national statistical offices, key sector institutions such as ministries of water and sanitation and regulators of drinking water services, are also undertaken (WHO and UNICEF 2021). As such, in 2021 the JMP drew on 6,743 global data sources, 4,426 of these were used to produce their estimates of which 3,283 were used for monitoring drinking water services (JMP 2022b). 339 censuses were used, 1,697 household surveys and 1,114 sources of administrative data (*ibid.).*

The following sections explore in greater detail the different data sources mentioned, including household surveys and censuses which offer the perspective of the user, administrative data from water regulators and additional sources from water providers. Attention is also given to how details of service availability are collated, as well as the advantages and limitations of each data source. In doing so, particular consideration is given to the role of gender in data collection and the effect on subsequent data and results. This is particularly pertinent given the gendered nature of water in SSA and the inequities faced due to the reliance and role women play in household water provisioning (Pouramin et al. 2020).

2.3.1. Provider Data from Utility Companies

Piped drinking water sources are supplied by private and public (owned by the state) utility companies (hereafter referred to as ‘providers’). These may be municipal, regional or national companies, all of which are responsible for system operations and management, the development of supply infrastructure, tariffs and billing, performance monitoring and governance of piped sources (Rimi Abubakar 2018). The performance of providers in SSA is diverse and has been criticised as generally being weak, especially due to increased pressures from population and growth and urbanisation (van den Berg and Danilenko 2017). Given this, monitoring is critical in ensuring providers supply users with the highest standards possible. As part of their efforts, most providers routinely collect data based on their performance.

The International Benchmarking Network (IBNET), originally developed by the World Bank, provides a database of systematically collected provider performance data. Since 1997 IBNET has been involved in the monitoring of the water sector and has been applauded for having the most systematic collection of data on drinking water source continuity (Rawas *et al*. 2020). As an initiative, it aims to encourage water providers to compile and share data and has subsequently been instrumental in producing its own global standard performance assessment (Danilenko *et al*. 2014). In 2015, data from 2,518 providers across the world, who collectively supply piped water to 636 million people, were available in IBNET (IBNET 2021a). Data is available for 41 African countries, dating back to 1995 in the cases of Burkina Faso and Niger. Since then, there has been a decline in the number of providers reporting to IBNET, though this has coincided with IBNET's redesign. Acting on recommendations following consultations with stakeholders, IBNET is currently transitioning from a survey to a data service (IBNET 2021a), with the aim to have broader coverage and a more collaborative approach by including data from providers and other service providers, regulators and researchers (NEW IBNET 2022). Of particular value is its collection of data including metrics of availability such as continuity of service as average hours of supply per day and residential consumption, measured using the average amount of water consumed, in litres, per person per day.

Despite the merits of IBNET, the quality of the data is solely reliant on the quality of data supplied by each provider which can be highly varied (Danilenko *et al*. 2014). Bartram *et al*. (2014) illustrate the variations in reporting undertaken by providers compared to user data from 1980-2000. They find that data from providers has large fluctuations in water coverage estimates, whereas user data from household surveys and censuses is more consistent over time. The overall standard of data from providers has subsequently been criticised as being limited in its scope as it does not include services that are constructed by NGOs or other non-governmental parties (Yu 2018), nor those that have been spontaneously created by household or community initiatives. Similarly, providers are often ill-informed on services delivered or managed by local governments in smaller towns or cities, and have been known for failing to consider the functionality of facilities (Bartram *et al*. 2014). It is for these reasons that the JMP transitioned away from the use of provider data in 2000 when previously it had been heavily relied upon for monitoring efforts (WHO *et al*. 2004).

2.3.2. Data from Water Users

In the early 1990s, analyses showed that provider reporting of populations with water services generally exceeded those reported by consumers. Consequently, a historical shift in the late 1990s saw a movement by the WHO and JMP towards analysing water systems using consumer-reported data from nationally representative government census and household surveys, rather than 'sector' information from service providers or line ministries. This sought to provide more accurate coverage estimates of national, regional and global progress on access to drinking water, which considered the users of facilities and had increased accuracy and credibility (WHO *et al*. 2004). Of value is the capacity of user data to enable the perspective of households and individuals to be heard. Experiences and functionality of water services are available from those who actually use them and therefore have the greatest knowledge and insight (Bartram *et al*. 2014). Secondly, compared to providers, users have increased willingness to provide such information.

Conducted approximately every 10 years, national censuses include the collection of data at the individual level for the whole of a country's population. Typically, all household members are either interviewed or fill out a questionnaire which includes a range of questions, often including some that specifically focus on water services (Bartram *et al*. 2014). By comparison, household surveys are undertaken periodically by over 100 countries globally. National statistical agencies, in conjunction with foreign or international agencies such as the World Bank, UNICEF or USAID, undertake surveys using a nationally representative sub-sample of the population (Bartram *et al*. 2014). Examples include Demographic and Health Surveys (DHS), Multiple Indicator Cluster Surveys (MICS), Living Standards Measurement Surveys (LSMS). Yu (2018) reports that the most frequently used household surveys for water service-related research include DHS, MICS, LMS, and World Health Surveys (WHS). Additional surveys such as the Performance Monitoring for Action (PMA) surveys have also emerged in recent years. In all cases, to ensure that results are representative, multi-stage cluster surveys are used whereby enumeration areas are randomly selected using probability proportional to size (PPS) sampling (Yu 2018). Within each of these primary sampling units (PSU), between 10 and 35 households are randomly selected and where possible the head of household surveyed. These samples are stratified based on variables such as geographic location (rural/urban) and sometimes sociodemographic characteristics in order to increase homogeneity (Bartram *et al*. 2014). As with censuses, a limited number of questions relating to water services are included.

Compared to household surveys, censuses provide full population coverage that can be spatially disaggregated to a greater extent than survey data (Yu *et al*. 2014). Given household survey data are not collected on the individual level, it is difficult to disaggregate data for lower administrative units or smaller population sub-groups (Bain *et al*. 2018). Thus, with census data, water service indicators can be quantified for the smallest of minority populations. There is however limited public availability of the small area statistics that are produced through censuses (Yu 2018). Censuses are also only undertaken every decade, whereas household surveys are undertaken much more frequently – generally every 2-4 years. In the Democratic Republic of Congo for example, the last census was in 1984 (GRID3 2020). That said, household surveys are becoming less realistic on a financial basis as their regularity and the requirement of larger sample sizes makes them expensive to undertake (Yu *et al*. 2016). Censuses have also been criticised as having low reliability in some countries due to over-inflation of head counts and implausible statistics due to political interference (Okolo 1999).

Despite the strengths in having a comprehensive source of data, disparities and a lack of uniformity and harmonisation have been inherent issues in the questions used within censuses and household surveys, namely their failure in some instances to specifically address service availability and continuity (Yu *et al*. 2016). Therefore, while data systems that are standardised, consider availability and continuity of water services and specifically focus on individual users are optimal, the reality of achieving this has thus far been difficult. Censuses for example are limited in their use, as inconsistent terminology between countries means that comparison is limited. This subsequently undermines the utility of census data for international monitoring (Yu *et al*. 2016).

To address the shortfalls of water service data that is available from household survey and census data, and streamline data collection between countries, during the MDGs the JMP partnered with major international survey programmes to develop and standardise core questions which could be used (WHO and UNICEF 2006). Critically, while these sought to maintain similarities with previous questions by building on the JMP's improved/unimproved classifications used throughout the MDGs, they introduce new criteria derived from the Human Right to Water and Sanitation (*ibid*.). These core questions include similar response categories between countries in order that data is harmonised to efficiently elicit a large amount of usable and comparable data. (Bartram *et al*. 2014). Following their release in 2006, the JMP has managed to streamline international survey programmes such as the DHS and MICS through the inclusion of these core questions, a step that has been critical in monitoring progress towards SDG 6 (WHO and UNICEF 2018a) (WHO *et al*. 2020a).

Since 2012 the JMP has been further developing these core questions in order that they address the SDG criteria for drinking water service levels. The JMPs 2017 thematic report comments that huge variations exist in the questions used by household surveys to measure and quantify service availability (see for example Table 2, of WHO and UNICEF, 2017b, p. 36). However, this has been minimised with the development of the JMP's core question on availability which asks *'in the last month, has there been any time when your household did not have sufficient quantities of drinking water when needed?'* (WHO and UNICEF 2018a). An additional update was made to the core questions in 2018 and they now correspond with the JMP's drinking water service ladder (see section 2.2.1). In addition to the core questions, the JMP released a set of expanded questions to be used where resources allow. Critically, these include elements of service continuity and reasons water is not available when needed (WHO and UNICEF 2018a).

The merits of the JMPs core question on availability and its role out has seen a significant increase in data that allows for comparison across countries. However, in order that the question is easily adopted and is not restricted by the logistical and financial constraints of conducting national household surveys, it is limited in its scope. Subsequently there are several limitations that must be recognised. For instance, it has significant temporal limitations as it does not account for the number of full day interruptions a household experiences within the specified 2-week window. This means that short- and longer-term interruptions are not captured, scheduled rationing as a result of intermittent services, nor are interruptions that are recurring or a result of seasonal variations. The questions temporal specificity may also lead to telescoping or errors of omission as respondents misclassify interruptions that were *'around 2 weeks ago'* (Gaskell *et al*. 2000). Additionally, the narrow scope of the question prevents more complex water use behaviour from being captured, for instance, multiple source use, water storage practices and the use of tanks.

The survey question is also prone to recall and response biases, especially as respondents may think answering in a particular way could result in a positive outcome. Issues could arise due to a reliance on verbal responses to the survey question rather than enumerators observing the sources; this allows the respondent to provide a response that misrepresents the truth (Wright *et al.* 2004) resulting in issues of misreporting. Finally, the question is restricted to only drinking-water availability, whereas water is required for numerous additional domestic purposes. As a result, households may report having sufficient availability, whilst in reality their standard of living is significantly affected by a lack of available water for other purposes such as cooking, cleaning and sanitation. The survey question therefore does not reflect the Human Right to Water (Human Rights Council 2011).

2.3.3. Government Regulator Data

When data is not available from household surveys or censuses, the JMP use information from national government agencies, such as water regulators (Bartram *et al*. 2014) (WHO and UNICEF 2017c). In doing so, the size of the JMP database considerably increases (Bain *et al*. 2018). Government water regulators (hereafter referred to as 'regulators') benchmark levels of service from different providers within a country. Regulators consist of professionals who are tasked with setting and enforcing appropriate regulations and standards, as well as undertaking national and sub-national surveillance of water services (WHO 2022). The existence of regulators is often seen as a tool to ensure better governance within the sector, which in LMICs results in better customer performance and protection (van den Berg and Danilenko 2017). Critically, it means that providers are held accountable and supported in providing efficient, affordable, reliable and quality services (ESAWAS Regulators Association 2021).

In working with regulators, the JMP collaborate with regulator networks such as the International Network of Drinking Water Regulators (RegNet) and the Eastern and Southern Africa Water and Sanitation (ESAWAS) Regulators Association (JMP 2022b). RegNet is a global forum developed by the WHO which aims to share and promote good practice in the regulation of water services (WHO 2022). ESAWAS is an association which includes regulators from Kenya, Rwanda, Burundi, Zanzibar, Zambia, Mozambique, Lesotho, Uganda and Malawi and aims to be a leading forum for promoting effective regulation of water services in eastern and southern Africa (ESAWAS Regulators Association 2022).

Typically, data from regulators are available in the form of annual reports which provide benchmarks of services for utility company coverage areas. For example, in South Africa the Department of Water and Sanitation has a series of Blue Drop Reports which report on the performance of national water utilities, whilst data can be requested, it is only accessible in pdf format however (DWS 2022). As with provider data, the quality of regulator data is dependent on that reported by the utility company. Data also only concern piped water services and within countries, there is not necessarily uniformity in the thresholds used by different types of utilities which are then reported in regulatory data. For example, when reporting service continuity data to regulators in Kenya, larger providers use a threshold of 20hrs service a day, whereas smaller providers use a threshold of 12 hours per day (WASREB 2021). Finally, between countries uniformity of metrics used is varied, especially with regards to service availability (Thomas *et al*. 2020).

2.3.4. Summary of Data Sources and Limitations

Current empirical approaches to assessing service availability using data from users, regulators and providers is shown in the model depicted in Figure 2-2. The underlying *true level* of drinking water availability may vary on a variety of domains such as the contextual and compositional characteristics outlined in section 2.6. This true level of availability may be reflected in data from the provider, regulator or user, all of which measure service availability in different ways as discussed in the preceding sections. Providers often *test* service availability using an annual average of a) the litres per capita provided per day or b) the hours of service provided in a day. This is then reported by the provider in their benchmarking data. The provider also reports their data to the regulator, who tend not to collect their own data, meaning that data is often similar.

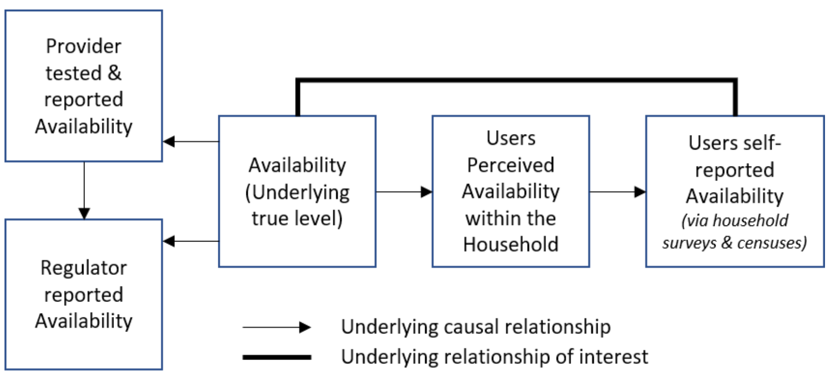


Figure 2-2: Empirical model for the assessment of the availability of drinking water services (Adapted from Sadana *et al.*, (2002))

The users *perceived* availability of drinking water is based on their knowledge and beliefs, whereas their *self-reported* availability is what the user, often the head of household, reports within a household survey or census to a lay interviewer. Crucially, this may differ to what the user perceives, especially because of limitations in the survey question used, or specific incentives or sanctions that may exist and subsequently influence reporting behaviour. Perceptions may also differ from the true availability of services as a result of different definitions of availability, different expectations of services and different behaviours within the household. As such, what is observed, tested or reported by users is not always consistent given the variations in perceptions of availability.

Inevitably each data source has its own limitations which must be taken into consideration. For example, provider and regulator data focuses solely on piped sources, whereas user data includes all drinking water sources. When considering availability of sources, this does however vary depending on the type of user data. For example DHS only collect data on source availability for households using a piped service, tubewell or borehole for drinking water, or households using bottled water for drinking and piped, tubewells or boreholes for cooking and handwashing (Croft *et al*. 2018).

In all cases there are biases within the data. Household survey and census data have biases as certain populations, such as those living in marginal or informal settlements, are excluded or under-represented due to the sampling frameworks used. This is especially the case if the sampling framework is based on outdated census information (Yu 2018). Whereas the collective use of data from providers and regulators can present challenges as few are randomised or nationally representative, as such care must be taken to avoid bias (Bartram *et al*. 2014).

User data are available at a much higher spatial resolution, whereas regulator and provider data are at the coverage area of utility companies. As such, regulator and provider data consist of averages of differences across a network rather than providing household level data, hence why the JMP currently favours use of the latter (WHO and UNICEF 2017c). An additional benefit of household survey data being at the household level is that it enables and facilitates analysis of inequalities across populations (WHO and UNICEF 2017c), whilst census data have full population coverage and can be disaggregated to an even greater extent (Yu 2018). Significant proportions of the population are also missing from provider and regulator data as municipal water services can serve few households in LMICs, with the poor, rural, and those in minority groups who are less likely to have a piped service subsequently underrepresented (Rimi Abubakar 2018). This has also been exacerbated as providers have struggled to keep up with the pressures of urbanisation and population growth, resulting in a decline in piped water services as primary water sources in SSA.

This shortfall in provisions of piped sources means that even greater proportions of the population are not represented in provider data (van den Berg and Danilenko 2017).

2.3.4.1. The Role of Gender on Data

Gender is intrinsically linked to WASH and drinking-water availability (Pouramin *et al*. 2020). Socio-cultural norms and expectations in LMICs across SSA, mean women are more often than not responsible for household water and its collection (Harris *et al*. 2017). As a result, recognising the role that gender plays within WASH and how this translates within data is crucial. The gender data gap – *'a gap in our knowledge that is at the root of perpetual, systemic discrimination against women and that has created a pervasive but invisible bias with a profound effect on women's lives'* (Caroline Criado Perez 2019) – continues to impede understanding of women and girls lives, and this is perpetuated by their role in WASH and a lack of recognition. From gender related biases in primary data, to the effect of failing to account for gender within secondary datasets, acknowledging the consequences that the gender of both the interviewer and interviewee can have on data collection, and the subsequent quantitative data, is paramount (Pullum *et al.* 2018).

The construction and development of survey questions and questionnaires can lead to gender related biases (Weber *et al.* 2021). Structural and institutional drivers of gender bias exist in data, for example, the gender composition of technical committees that set and decide on survey questions, including the JMPs core and expanded questions, is often unknown. However, it has the capacity to significantly affect the ways in which questions are worded or who they are targeted at. For instance, until recently there has been a systemic blind spot in the monitoring of WASH as a result of the failure to collect information on who is responsible for water and water collection within the household. This overwhelmingly affects women, who typically bear the burden of the responsibility for household water in LMICs (Pouramin *et al*. 2020), meaning women and their perspectives are excluded from WASH data. Only in the most recent phase (8) of the DHS has a question been included which asks for the name of the person who 'usually goes to the water source to collect water for the household' (The DHS Program 2020a). Whilst this is a positive step, the gender of the person responsible is only recorded if they are included in the surveys household roster, meaning such details will otherwise be missing. Evidence from analysis using MIC surveys, which has a long-standing survey question that collects information on who collects water and their sex, has shown the value in accounting for women's roles in WASH. See for instance Graham *et al*. (2016) whose use of MICs data has enabled the quantification of women's roles as water collectors to be accounted for in 24 SSA countries.

The quality of user data from household survey and census data is prone to vary as a result of social interactions between interviewer and interviewee (Di Maio and Fiala 2020), an issue that is limited with provider and regulator data. Typically household surveys and censuses interview the head of the household, however there is much debate surrounding who should be selected as the respondent to household surveys and whether the head of household is most appropriate (Nkolo et al. n.d.; Bookwalter *et al*. 2006; Demombynes 2013). This is particularly pertinent given the role of water and water collection often falling to women and children within a household (Pouramin *et al. 2020)*. As a result, responses to survey questions may not be reflective of the realities of the household water situation due to heads of households lacking knowledge or experience. Surveying the head of household can therefore lead to measurement error and item nonresponse.

Question phrasing and the interview process can also lead to gender biases in user data. Known as the enumerator-effect, survey responses may be influenced by interviewer characteristics, including their gender (West and Blom 2017). Sociodemographic similarities between the respondent and interviewer can increase cooperation rates, whilst being of the same gender can create trust between the respondent and the enumerator (West and Blom 2017). Some evidence suggests that female interviewers may be perceived as 'less frightening' and have a tendency to collect higher quality responses than males, especially in relation to gender-sensitive questions (Di Maio and Fiala 2020). The genders of the interviewer and interviewee will also affect certain feelings and subsequently behaviours when being interviewed. For example, feelings of embarrassment around certain behaviours and practices can affect respondents willingness to be truthful. Wright *et al*., (2004) found during fieldwork that households using unprotected drinking-water sources were often reluctant to admit this was the case because of the known hazards to health, as such, in some instances they reported using safer protected sources.

The effect of gender is limited in provider and regulator data since data collection does not require social interaction, rather it is reliant on effective monitoring of water services. However, both data sources are only available at provincial level or provider coverage area, meaning they fail to acknowledge characteristics of households and how these link to water services (Weber *et al.* 2021). To effectively account for gender, data needs to be representative and collected at the individual level in order that it be sex-disaggregated (Dooley *et al*. 2020). Allowing for robust and reliable analysis which explores gender differentials in WASH is especially important with provider and regulator data given it feeds into national policy and guides the allocation of government resources and investments.

2.4. Safely Managed Drinking Water

Progress towards SDG 6 is measured using indicator 6.1.1 which quantifies the proportion of the population using a safely managed drinking water source (WHO and UNICEF 2018a). As previously mentioned, in order that an improved water source is classified as the highest level of service and safely managed, it must meet three key criteria: availability, quantity and accessibility. The availability of services is inherently affected by the quality of water available to the user, and whether it is physically and economically accessible. The following sections explore each of these criteria, how they are measured and their importance in relation to global development agendas.

2.4.1. Quality

785 million people do not have clean water close to home (UN Water 2019a): rather they rely on using water that is poor quality and contains a range of contaminants. Living in an area where safe water is lacking comes with a range of consequences, most notably the reliance on water sources that are harmful to the consumer (Alhassan and Kwakwa 2014). Contamination of water services can occur at the source, as well as whilst being transported and stored (Sobsey *et al*. 2002). In addition to unsafe water that is consumed from surface sources such as rivers and lakes, piped water from distribution systems may also be contaminated due to system inadequacies and as a result of the practice of intermittent services (see section 2.2.3.2) (Lee and Schwab 2005; Onda et al. 2012).

Faecal contamination, from both humans and animals, is of the highest concern to water quality because of its impacts on the health of individuals (Bain, Cronk, Hossain, *et al*. 2014). Sharing of water services with animals, proximity to latrines, as well as contamination due to poor infrastructure and open defecation all result in the greatest microbial risk (World Health Organization 2017b). Additional contaminants can range from chemicals, fertilisers and waste products from agriculture and industry which enter catchment systems, to hazards from naturally occurring radioactive substances and geogenic contaminants that are derived from underlying bedrock and their sediments (i.e. arsenic and fluorides) (Rickert *et al*. 2016). Advanced and nature-based technologies such as reverse osmosis, UV treatment, settlement ponds and chlorination are used by providers to treat water supplies and remove these contaminants (Castellar *et al*. 2022). Household treatment of water can also be undertaken to improve its quality, for example by using methods such as cloth filtering, boiling, the use of chemicals such as chlorine, solar disinfection, and ceramic filters (Sobsey et al. 2002; Alhassan and Kwakwa 2014). In addition to using these treatment methods, the safety of water can also be significantly increased if multiple measures and barriers are in place. In essence, these management approaches aim to prevent pathogens from entering water systems and services from the offset (WHO, 2017). For example, sufficient management of water services involves the protection of water resources, proper selection and operation of treatment steps and management of distribution systems.

Water quality is particularly critical to the development agenda because of its contributions to ill-health. Without good quality water, a household cannot be protected from water-borne and water-related diseases; as such water quality is an important indicator of household water security (Alhassan and Kwakwa 2014). In particular, the inadequacy of rural water services and coverage has been recognised as a major contributor to human disease and malnutrition in many developing countries. Despite global improvements in rural water quality (between 2000 and 2017 water quality in rural areas improved from 42% to 53% free from contamination (WHO and UNICEF 2019b)), diseases such as cholera, typhoid, river blindness, hepatitis, shigellosis and malaria continue to be widespread (Asare 2004). Washing hands following defecation and before preparing and cooking food is a simple yet crucial measure that can be undertaken in order to reduce disease transmission, however. Without an adequate water service, however, this becomes impossible (Aderibigbe *et al*. 2008). Therefore, interventions to improve the quality of drinking water are vital in order to ensure significant health benefits can be achieved (World Health Organization 2017b).

The JMP states that water must be 'free from faecal and priority contamination' in order that it be deemed safely managed (WHO and UNICEF 2017c). Expanding on this, Alhassan and Kwakwa (2014) note this means it must be safe to drink and free from pathogenic bacteria, viruses and parasites, faecal, chemical and radiological contaminants and hazards, and acceptable to consumers. However, the use of an improved source as an indicator of safe water use and water quality has been questioned by Wright *et al.* (2004) and Godfrey *et al.* (2011). Both argue that it is likely to overestimate the population using safe water since some improved sources may provide water that is microbiologically or chemically contaminated (Onda *et al*. 2012). More widely accepted methods are outlined by the WHO and include two main elements: health and acceptability. The latter concerns parameters which may not have any direct health effects but result in objectionable taste, appearance, or odour in the water, whereas the health guidelines take into account chemical and radiological constituents that have the potential to directly cause ill-health (Onda *et al*. 2012).

Numerous water quality measures and indicators exist. While *E. coli,* faecal coliform bacteria and enterococci have been argued to be the most appropriate indicators of waterborne disease risk (Moe et al. 1991; Onda et al. 2012), additional chemical parameters that are often used include ammonia, pH, chloride, iron, lead, arsenic and copper content (Rickwood and Carr 2007). Monitoring of water quality has recently included the use of household surveys which have integrated direct testing of contaminants into their protocols. Critically, whilst this enables the collection of data that is representative of populations (WHO and UNICEF 2019b), data is only collected through a single measurement of water quality and therefore is not a substitute for routine monitoring (Charles and Greggio 2021). There is also no one measurement which can be used to describe overall water quality for all water sources at a global level (WHO and UNICEF 2019b). Furthermore, Onda *et al.* (2012) argue that more water sources are likely to be unsafe than microbiological indicators alone indicate. For this reason, the development of a composite index which quantifies the extent to which a number of water quality measure deviate from normal, expected or ideal concentrations, could provide a means to successfully evaluate the quality of drinking water based on a variety of factors (Rickwood and Carr 2007).

2.4.2. Accessibility

Access implies that sufficient water to meet domestic needs is available close to home (WHO and UNICEF 2017c). Millions of individuals must fetch water every day to meet household needs (Venkataramanan *et al*. 2020). 2020 estimates show SSA only 31% of the population have drinking water that is accessible on premises (JMP 2021a). The accessibility of services significantly impacts the amount of water available to households, as mode of access limits the amount that can be collected.

There are two key aspects of accessibility: the distance to a water source or service, and the time taken to collect water (Yu 2018). As such, the JMP and WHO classify an improved service as being accessible within 1 km from place of residence or taking up to 30 minutes to travel to (World Health Organization 2017b). When a water service is off premises improved water sources located within 30 minutes from the point of use are considered as being a basic service, whereas if the source is located above 30 minutes then the level of service is classified as limited (Cassivi *et al*. 2018). Overall, drinking water services that are located on premises are more likely to be improved, while collection from unimproved sources is more likely to take more than 30 minutes (WHO and UNICEF 2017c).

Numerous definitions of accessibility exist, however, from a public health standpoint, the proportion of the population with reliable access to safe drinking water is the most important single indicator of the overall success of a drinking water service programme. The Committee on Economic Social and Community Rights (2003) note that there are four overlapping dimensions of accessibility. The first is physical accessibility which determines that water services are within safe physical reach of all sections of the population, and that the special needs of certain groups and individuals are taken into consideration. For example, paths leading to facilities and the facility or water source itself should be safe and convenient for all users, from children and older people, to persons with disabilities, women- including pregnant women, and chronically ill people (United Nations 2010b). Secondly, economic accessibility considers whether water is affordable for all- the associated cost must not compromise or threaten other rights. Accessibility must also be non-discriminatory, meaning that water services must be available to all, regardless of whether they may be a vulnerable or marginalised population. Finally, accessibility includes the right to seek, impart and receive information concerning water issues. While the JMP does not formally recognise these four aspects of accessibility, they are critical to ensuring that populations are not unnecessarily affected by poor accessibility.

Accessibility particularly impacts the quantity of water consumed; Cairncross (1999) coined this phenomenon as the ‘water plateau’. This phenomenon states that when a water service is not located at or on premises, the relationship between the quantity collected and the time take to fetch it is non-linear with a steep decline when you reach a collection time of 3 minutes. After this, the quantity of water collected is consistent and plateaus at 30 minutes when there is a further decline in quantity for longer collection times (Cassivi *et al*. 2018).

Measuring accessibility poses several difficulties, most notably upward bias as a result of a reliance on self-reporting (Hutton and Chase 2016). The JMP use a travel time indicator that is routinely collected in household surveys and censuses; respondents are asked to estimate how long it takes them to reach their water service, to queue if this is required, to fill their containers and to return home (WHO and UNICEF 2017c). Despite this method of reporting being imprecise in nature, it provides a useful indicator of the relative time burden of water collection, although they do fail to give an indication of variation in access and practices amongst different household members (Hutton and Chase 2016). These factors are especially important given the nature of accessibility and the fact that it can be affected by prohibitive charges, daily or seasonal fluctuations in availability or lack of services to remote areas (United Nations 2010b).

2.4.3. Availability

The availability of water concerns the nature of a water service system. For a water service to be considered available it must be sufficient and continuous for personal and domestic uses. ‘Continuous’ refers to a regularly consistent water service, ‘sufficient’ means that users are able to me*et al*l their needs and ‘uses’. Such uses include drinking, personal sanitation, food preparation, washing of clothes and personal and household hygiene (UN Water 2019b). While all populations meet their water needs somehow, it is often not sufficient, reliable, safe, convenient, affordable or dignified (Hutton and Chase 2016). At present, it is estimated that at least 309 million people are served by water services that are only available for less than 12 hours a day – the majority of these people are in SSA and South-East Asia (Majuru *et al*. 2016).

Since the inclusion of availability as a key criterion in the SDG development agenda, problems that are caused by non-functioning water points have been captured (Carter and Ross 2016). Pressures on water services such as overuse, competing demands, unsustainable water extraction and water pollution, as well as climate change and variability, population growth, migration and urbanisation all serve to limit the availability of water (Hutton and Chase 2016). A dichotomy between service quality and quantity also exists, with the quality of water supplies affecting functionality as disruptions to services occur over concerns of unsafe water (Nowicki *et al.* 2020). In order to deal with these issues national practices such as intermittent water services (see section 2.4.3.2) and household coping strategies, such as the use of multiple sources and storing water, have become ever more common in order that water needs are met (Purshouse *et al*. 2017). Despite availability of sources being relatively understudied, its influence on the health and welfare of populations are adverse (Majuru *et al*. 2016). As daily per capita use decreases, the risk of faecal-oral and other hygiene related diseases increases, and people with an average use of 20 litres per capita per day are considered to be at a 'high level of health concern' by the WHO (Howard and Bartram 2003).

Multiple indicators for the measurement of availability exist and are used for data collection (as shown in section 2.1), namely the hours of supply a day, the frequency of breakdowns and the quantity of water available or used within a given time period (WHO and UNICEF 2017c). The latter has seen the evolution of several benchmarks for the amount of water required in order to meet the needs of users. Definitions have included the benchmark of availability as at least 20 litres per capita per day (Lee and Floris 2003), whereas more recently this benchmark has risen to the recommendation of between 50 and 100 litres per capita per day in order that domestic needs such as personal hygiene, washing and cleaning, and personal consumption requirements can be met (Howard and Bartram 2003).

Measuring availability and water use is far from straightforward. Both the setting and time throughout the year have significant influences on the amount of water available. The interaction of numerous factors such as the number of water services used, storage facilities and their capacity, day to day variability, seasonal and cultural influences and water ownership all make measurement increasingly complex (Tamason *et al*. 2016). Methods such as water meters have been favoured as the most accurate measurement system; it is estimated that of those who use piped water, 1 billion people do not have a continuous service. The application of water meters to capture this information is critical, however. Water meters do not account for factors such as the use of multiple sources, thus when piped networks are not used meters are a less viable option (Bivins *et al*. 2017a).

Alternative methods used in order to account for the variability of behavioural patterns of water consumption include single-time questionnaires, multi-day observations, self-reporting and interviews, all of which can enable direct measurement that can be used for larger scale estimation (WHO and UNICEF 2017c).

2.4.3.1. Reliability and Functionality of Services

Understanding and examining the availability of a water service is in part dependent on its reliability and functionality. Current evidence suggests that one third of water points in SSA have functionality issues (Rural Water Supply Network 2009). When a water service is perceived as being problematic and unreliable, it is characterised by downtime, slow repairs and significant breakdowns. There are two main ways of considering reliability. The first examines the water service itself and whether or not it is running and the second concerns the perspective of the user and whether the service meets their needs (Majuru *et al*. 2018).

Water services which fail to achieve their optimum levels of pressure, quantity and quality lack reliability (Kudat *et al*. 1993). For these reasons there are three concepts to consider when defining reliability: continuity, predictability and functionality. Continuity focuses on whether or not a water service provides water 24 hours a day, or whether it is only running/working for part of the day; this tends to be the most common criterion used to assess water service reliability (Majuru *et al*. 2018). By comparison, the concept of predictability determines that a service may not be continually available, but it is available at regular intervals. It therefore does not affect households or individuals in their ability to undertake day to day activities as there is a regular schedule to their water service (Galaitsi *et al*. 2016). Finally, functionality, which tends to disproportionately affect the poor, concerns breakdowns of a system and the pressure of the water service which can result in limited or no service (Majuru *et al*. 2016).

There is no single accepted definition of functionality (Bonsor *et al*. 2018), however Garriga *et al*. (2015) define it as the percentage of improved water sources that are functional at the time of a spot-check. Poor functionality of services is defined by minimal to no expenditure on water infrastructure and the implementation of sub-standard, standardised, infrastructure designs (Furey 2013). For example, the functionality of boreholes is often affected by limited quantity of water at the service or a malfunction of the pump (Carter and Ross 2016). The functionality of a water service is particularly difficult to measure, but usually involves the assessment of whether a water service is working or not. Measurements are usually undertaken using qualitative methods, with direct quantitative measurements being particularly rare (Bonsor *et al*. 2018). Data collection is usually restricted to one season and different water points may be surveyed on different days and times resulting in discrepancies in the data which make comparison particularly difficult. Nevertheless, Carter and Ross (2016) call for a focus on three elements: the short-term quantity/yield of a water service, water quality and seasonality.

2.4.3.2. Intermittent Services

In addition to considering the reliability and functionality of drinking water sources when assessing the availability of water, the intermittency of services is also used. Intermittent services consider the intentional halting of piped water services in order to ration water (Kumpel and Nelson 2016). Reasons for adopting intermittent services are discussed in detail in section 2.6.2, generally in LMICs however, this is undertaken in order to regulate water in resource limited areas and ensure that it is distributed to more people. At present, it is estimated 118.8 million people live with an intermittent water service (Kumpel and Nelson 2016). It is frequently seen as a solution to high demand for drinking water when building new water services is not achievable due to the financial burden involved (Matsinhe *et al*. 2014). Generalising intermittent water services is difficult, since as a practice its use is highly variable across the world and both temporal and seasonal variations occur. Services may be rationed and intermittent for several hours in a day, or for multiple days within a week (Galaitsi *et al*. 2016). That said, the use of intermittent services is particularly prevalent in arid and densely populated areas of LMICs. For example, in Mozambique the average number of service hours in the majority of cities is less than 12 hours (Gumbo *et al*. 2003).

The knock on effects of intermittent services range from inequitable distribution of resources (Gottipati and Nanduri 2014), to unreliable delivery times (Vairavamoorthy *et al*. 2007). As Matsinhe *et al*. (2014) note, inconveniences that intermittent services cause to consumers are inherent, and as such often result in consumers turning to alternative water services which can be incredibly costly. The failure to provide a continuous water service significantly affects the biological, physical and chemical mechanisms that degrade water quality (Kumpel and Nelson 2013). Changes in water pressure that occur throughout intermittent services can result in contaminants entering the system when pipes are at low pressure and when back-flow occurs. As both Mermin *et al*. (1999) and Hightower *et al*. (2002) examine, the resultant impacts on water quality have resulted in several outbreaks of waterborne diseases which are associated with pressure changes. As such, intermittent services are one of the leading causes of water contamination and resultant health issues (Matsinhe *et al*. 2014).

2.5. Drinking Water Services and Availability

By nature of design, the availability of drinking water differs depending on the type of source in question. Natural resources, also referred to as 'raw water' or 'source water', in the form of groundwater, rainwater and surface water such as dams, reservoirs, lakes, and rivers, are fundamentally the sources of all drinking water (Rickert *et al*. 2016). In order to extract source water and take it from being an unimproved drinking water service to an improved service that has been processed, treated and is protected (meaning it is safe for consumption), numerous methods have been developed. It is these methods that make sources prone to interruptions which subsequently affect their availability.

Drinking water service methods have been classified into ten types which are determined by the technology of the service or extraction facility, and the storage and transportation method used to deliver water to the user (Yu 2018) (Table 2-2). Of these ten categories, those which are improved service methods include: piped water connections including public standpipes or taps, tubewells or boreholes, protected dug wells and springs, rainwater and vended water that is packaged or delivered. Conversely, unimproved services include surface water and unprotected springs and dug wells. The following sections explore these different types of improved and unimproved water services, with specific attention given to how their availability can be affected.

Table 2-2: Water services by JMP classification (Source: WHO and UNICEF 2017)

Improved sources	Unimproved sources
• Piped water into plot, dwelling or yard • Public tap or standpipe • Tubewell or borehole • Protected dug well • Protected spring • Rainwater • Vended, packaged or delivered, water	• Surface water- dams, rivers, lakes, ponds, streams, canals or irrigation canals • Unprotected dug well • Unprotected spring

2.5.1. Improved Drinking Water Services

2.5.1.1. Piped Water Services

Piped water systems can directly provide drinking water to the end user and as such are often perceived as the most desirable water service. A piped source may include one that is piped directly into the home, as most households in developed countries will have, or it can include a tap in the yard or plot of a household or homestead, or a public tap or standpipe used by multiple households within the community. Piped sources within the home often provide the most viable, sustainable and optimal option for a water service and are seen as the “gold standard” (Howard and Bartram 2003; OHCHR 2010).

With all types of piped sources, water is extracted from ground or surface water sources and usually treated and purified. It is then stored in facilities such as tanks, cisterns and reservoirs, before being distributed via piped networks using energy sources such as gravity, electricity and diesel (Trifunovic 2006). As a result of the efficiency of this system, it is able to provide households with over 100 litres per capita per day when there is a tap within the dwelling and between 50 and 100 litres per capita per day when a yard tap is present (Wurzel 2005; Yu 2018). In both cases, this amount enables basic consumption and health needs to be met and maintained, as well as enabling adequate quantities for domestic and hygiene needs (WHO and UNICEF 2017c).

Piped services within the home tend to be disproportionately available in richer communities, notably within urban ones, as a result of the capital they require (Bain, Wright, *et al*. 2014). Not only are there expenses related to their installation, but upkeep and maintenance costs for both human resources and material resources such as fuel and chemical services can also be high (Torbaghan and Burrow 2019). Their installation also incurs additional costs of tariffs and user fees which are managed and enforced by providers and local authorities (WHO and UNICEF 2017c). Importantly, the cost of these fees is determined by context. For households and individuals the expense of having a piped connection is highly variable, however most tariffs are progressive with those using small volumes of water, for instance the poor, paying less per litre (Holm et al. 2016; Adams and Smiley 2018).

Despite the desirability and higher standards of this service method, the availability of water from piped water connections varies. Infrastructure is prone to interruptions due to breakages of pipes and breakdowns at water processing plants and a lack of fuel to run water pumps (Ngwenya and Kgathi 2006). Shortages of chemicals required to treat water and staff to run treatment plants can also serve to effect availability. The duration of these outages and the resultant interruptions caused at the household level can vary due to the availability of funds, parts, skilled labour and lack of proper governance (Rugemalila and Gibbs 2015). Non-revenue water, defined as water which is lost from a piped system as a result of issues such as old infrastructure prone to leakages or illegal connections, also reduces service availability (González-Gómez *et al*. 2011). Increased usage due to population pressures and a lack of network expansion can also mean the pressure in piped sources is affected and those at the end of piped networks experience outages or insufficient water pressure (Rugemalila and Gibbs 2015; Rawas et al. 2020). As discussed in section 2.4.3.2, intermittent services are also used as a rationing technique when surface water stores are limited. Institutional corruption has also been cited as implicating service availability as favouritism and nepotism result in water being allocated and redirecting to wealthier neighbourhoods or majority ethnic groups (Stålgren 2006).

Public Taps and Standpipes

Public taps and standpipes (hereafter jointly referred to as standpipes) which are connected to piped networks are very common in LMICs (Figure 2-4; Figure 2-3). For households where having a private piped connection is unattainable due to the cost, using public standpipes is often the second-best option (Keener *et al*. 2010). Standpipes are often installed and financed directly by water providers, local authorities or through charitable grants from donors or NGOs. They are often present in low-income areas where the population is able to benefit from better quality water but only pay for the amount of water they can afford (Massachusetts Institute of Technology 2004). Increasingly, private connections are being used as public standpipes with connections originally installed for single households used by multiple households, both within a homestead compound or further afield within communities (*ibid*.). This practice of 'domestic reselling' has been reported in Accra, Ghana for instance (Höllermann et al. 2010; Grönwall 2016).

Figure 2-3: Piped water being stored in tanks (Source: Kabisch, 2014)

Figure 2-4: Public standpipe in South Africa (Source: Mabaso, 2016)

Although standpipes offer multiple benefits in terms of monetary savings, there are often additional costs incurred. Long periods of time are often spent collecting water, both in travelling to and from the service and queueing to fill containers (Gross *et al*. 2018). The OHCHR (2010) reports incidences in South Africa (IRC 2003) of women and children '*walking long distances about 2 to 3 kilometres daily to a public tap; carrying heavy containers on our heads 20 to 25 litres per trip; long queues at the point of taps*'. As Yu (2018) notes, water consumption from standpipes can be quite low and often ranges from 10 to 40 litres per capita per day, which is mainly as a result of limitations to how much can be transported for use. In additions to these limitations in the amount available, standpipes are also prone to the same interruptions as piped sources. Critically, household piped connections prevent the need for physical exertion and time wasting, as well as ensuring that there is no limit to the quantity available to an individual or household (Mahasuweerachai and Pangjai 2018).

2.5.1.2. Boreholes, Tubewells and Protected Water Wells

Direct extraction of groundwater plays a critical role in water provision in LMICs. The high spatiotemporal availability of groundwater, its resilience to seasonal and climate-related fluctuations (MacDonald et al. 2011; Hope et al. 2012) and protection from pollution, all lend itself to being highly desirable in resource limited locations (MacDonald and Calow 2009). Boreholes, handpumps, tubewells and dug wells (particularly those that are machine dug or drilled (Figure 2-6; Figure 2-5)), are one of the more common mechanisms in place to supply groundwater directly to communities and remain the preferred method of extraction in rural communities (Hope *et al.* 2012). These sources consist of creating a large hole that enables access to groundwater that is being stored in underwater aquifers (van der Wal 2010).

Figure 2-6: Water-well being drilled by machine (Source: Rural Water Supply Network, 2018)

Figure 2-5: Hand dug well being created (Source: IAAAE, 2021)

Water wells are largely dependent on the geology and hydrogeology of an area, thus location is a defining feature of their presence and they may be dug using manual or machine techniques (Macdonald *et al*. 2008). Manual techniques are more time consuming than machine drilling however they are significantly cheaper compared to the often unattainable expense of machine drilling (Baumann 2000). Typically drilled wells range from 25m to 200m in depth and they often require mechanised pumps or hand pumps to lift the water to the surface. Mechanised pumps in particular may be powered by the grid, diesel, wind or solar power (Abramson *et al*. 2014). In 2012 the UNICEF and WHO (2012) estimated that the 'ubiquitous hand-pump-fitted-borehole' is used by 1.3 billion across the world (Figure 2-7) (Abramson *et al*. 2014). In some cases, significant pressure is created from groundwater being stored in aquifers surrounded by impermeable rock, and as a result water naturally flows to the surface meaning a pumping mechanism is not required. Such wells are referred to as artisan wells (Figure 2-8) (Yu 2018).

<u>Figure 2-7:</u> Borehole with hand pump (Source: News of the South, 2016)

<u>Figure 2-8:</u> Artesian Well (Source: Dales Water, 2013)

The availability of groundwater fed services can be affected by seasonal variations in water levels in stores such as aquifers. As climatic change and water scarcity increases, this could worsen especially if the borehole is not deep enough into the groundwater store (Kumamaru *et al*. 2011). The short term effects of climate change on the water available in groundwater stores are less than those experienced by water surface stores however (MacDonald *et al*. 2011). The availability of water at boreholes and tubewells tends to be most affected by the resilience of the infrastructure and their functionality. Over usage and excessive pressure can result in the pumping mechanism breaking, leaving communities without water for extensive periods (Machingambi and Manzungu 2003). Given boreholes and tubewells are more prevalent in remote and rural localities, the presence of skilled manpower and parts required to fix breakages can lengthen the duration of the outage even further (Kumamaru *et al*. 2011). Privately owned sources tend to have fewer interruptions as they are used less intensively and the complexities of collective actions that characterise public sources can be sidestepped, meaning faster repair times (Foster *et al*. 2018). Even short term breakdowns of services can impose considerable hardship and inconvenience as users must revert to using further-away sources, which further limits the amount they are able to collect (Carter and Ross 2016).

2.5.1.3. Protected Springs

Where groundwater naturally flows to the surface, natural springs develop and in some instances create water holes (Lajçi *et al*. 2017). Most commonly, these are found in mountainous or hilly terrain where solid or clay layers block underground water flow, forcing it to the surface. Alternatively, there may be discontinuities in the rock strata which result in fissures and cracks for the water to escape through (van der Wal 2010). As springs are naturally occurring, they can be located in inaccessible and remote areas far from homesteads and villages, which subsequently requires long and difficult travel often undertaken by foot (Yu 2018). As such, the availability can be significantly influenced and it has been reported that springs provide an average of 16 litres per capita per day (Howard and Bartram 2003).

In most instances springs are utilised and developed to create a piped water service and the resultant overland drainage system ensures that water remains free from contaminants and is properly protected (Smet and van Wijk 2002). While spring water is naturally of good quality, this is dependent on the thickness of the soil layer, type of soil and velocity of infiltration of the surface water (Keesstra *et al*. 2012). For this reason, springs provide a high quality and low-cost resource, which in poorer areas is a particularly attractive and critical resource. That said, as a result of requiring piped infrastructure to access them, they are prone to breakages and interruptions especially as they are overland.

2.5.1.4. Rainwater Harvesting

Rainwater provides a low cost drinking water service which has the additional benefit of reducing physical and time expenditure on water collection (Worm and Van Hattum 2006). The harvesting of rainwater has been advocated as a critical practice which needs to be implemented in resource limited areas and areas that face pressures on water demand (Amos *et al*. 2016). This is especially the case in areas where climatic, environmental and societal changes are increasing. In particular, rainwater harvesting is perceived as being a significant water conservation tool (GhaffarianHoseini *et al*. 2016).

Numerous methods exist which can be employed to harvest rainwater. Fundamentally, roofing of buildings and houses must facilitate surface runoff and a water storage tank is also required. In LMICs, design configurations generally include tin or corrugated roofs, from which rain runs off into a series of guttering and pipes that direct the water to a storage tank from where it can then be used. The type of tank used is crucial and is primarily reliant on the use of the water and the likely amount of water that can be collected. Both depend on annual rainfall and seasonal variations (Pelak and Porporato 2016). Typically, the choice is between larger below-ground tanks (Figure 2-10) and above-ground 'rain barrels' (Figure 2-9). Above ground rain barrels vary in size and are usually plastic or metal, these are often favoured where water is used for either irrigation or household level consumption. Alternatively, larger, belowground storage tanks can be installed; these are made of concrete and designed to supply water to larger or multi-purpose buildings such as schools or healthcare facilities (Mithraratne and Vale 2007). The latter require significantly more space for their installation and are often more costly and complex to develop.

<u>Figure 2-9:</u> Above ground plastic storage tank (Source: Tusaidiane Uganda, n.d.)

<u>Figure 2-10:</u> Underground concrete storage tank (Source: Mwenge and Taigbenu, 2011)

Inevitably, the availability of rainwater fed services is reliant on the presence of rainfall. In drought prone areas, rainwater does not provide a reliable drinking water source and given the heightened effects on the hydrological cycle as a result of climate change, variability is likely to increase (Pedro-Monzonis *et al*. 2015). That said, in areas where there is unpredictable or seasonal rainfall, the harvesting and storage of rainwater can provide a critical coping strategy during periods of low rainfall (Staddon *et al*. 2018). They are also often used as a coping strategy when centralised piped water services fail (Nnaji *et al*. 2018).

2.5.1.5. Vended Water

Vended water is that which can be purchased by the consumer. A variety of vended water mechanisms exist including vehicle delivered water, tanker delivered water, packaged and bagged water, bottled water, kiosks and water vending machines (Yu 2018) (Figure 2-11). The majority are most common where water is naturally scarce and where a lack of sufficient infrastructure exists, thus preventing water from being accessed (WHO and UNICEF 2000). Since the World Bank advocated water privatisation in the late 1990’s (Goldman 2007), there has been a growth in informal water vending, which as a result has developed into an informal and private sector of water services (Wutich *et al*. 2016). Additionally, vended water, especially that delivered by tanker trucks, can be operated by local authorities (WHO and UNICEF 2017c). Delivery may be undertaken door-to-door or it may require users to actively purchase it from a small stall and transport it themselves.

Since the raw source of the water used for vended services is very varied, subsequently its classification as an improved source is somewhat tenuous (WHO and UNICEF 2017b). Water may come from treated surface water or groundwater sources, or it may come from unprotected sources such as polluted wells and contaminated drainage channels; the latter is often the case in informal settlements in particular (OHCHR 2010). Bayliss and Tukai (2011) comment that vended water often costs 4 to 30 times more than a municipal piped water service. In a world that is attempting to be more environmentally and sustainably minded, the consumption of packaged vended water has been criticised for its inherent contributions to waste and problems in disposing large quantities of plastic packaging (Wardrop *et al*. 2017).

<u>Figure 2-11:</u> Vended water being: sold at a kiosk (top left, source: Bayliss, 2016); delivered by hand cart (top right, source: BASSAN, 2011); sold and distributed in plastic sachets (bottom left, source: Murdock, 2009); and delivered via tanker (bottom right, source: Ngubane, 2018)

Households may rely on vended water as their primary service, though more often than not it is used as a coping strategy when their main service is not available, for example when municipal piped sources are rationed (Stoler *et al*. 2013). Vended water can be highly unreliable and limited in its availability. Not only is it subject to hazards at origin source waters, but if vended water requires collection, then household consumption is reliant on the amount of water that can be transported and stored (WHO and UNICEF 2000). Additionally, vendors at standpipes have been known to lock access to water for large portions of the day and those selling packaged or sachet water also have restricted timings of availability (Kulinkina *et al*. 2016). Remote and rural communities that rely on tanker delivered water rely on the supply arriving when scheduled which can be highly varied, especially due to the quality of roads (Bayliss and Tukai 2011).

2.5.2. Unimproved Drinking Water Services

2.5.2.1. Unprotected Water Wells

As noted in section 2.5.1.2, machine drilled wells require substantial investment and capital. In comparison, hand dug wells provide an intermediate water service that is often more viable for many in LMICs. Not only are they cheaper to develop, but they also require minimal maintenance, skills and equipment due to their simple design (Gadgil 1998). Hand dug wells are often between 5m and 25m in depth and subsequently are commonly known as shallow wells (Schram and Wampler 2018). Unfortunately, as a result of their location nearer to the surface, shallow wells are prone to contamination from additional surface water and seepage from latrines (UNICEF *et al*. 2010), as well as external contamination due to being uncovered (Figure 2-12). Water does tend to be of better quality than surface water however as it is less susceptible to microbial and chemical contaminants (Stevenazzi *et al*. 2017).

Figure 2-12: Unprotected hand dug well (Source: Appropedia, n.d.)

Figure 2-13: Excavation of hand dug well (Source: GWI, n.d.)

The development of shallow wells is primarily reliant on shallow aquifers and soft geological formations, both of which enable easy digging when creating the open wells or scoop holes. Several methods can be used to dig shallow wells (Figure 2-13). These include the use of (1) a hand auger which is manually rotated, (2) sludging which involves the use of water which is circulated to bring drilled soil to the surface, (3) jetting which uses high pressure water to erode soil to create an opening and (4) manual percussion which uses a heavy hammering or cutting bit (van der Wal 2010). Once the well has been created, it is lined with cement or bricks and then often fitted with manual pumps or windlasses in order to extract the water. In some cases, simple buckets and ropes are used where resources are limited (Lifewater 2019).

As with drilled wells, the availability of water at hand dug wells is predominantly dependent on the presence of water in either the underground aquifer that has been tapped into or at the water table. As these are often communal sources, the availability can also be affected by overuse and the depletion of resources. Hand dug wells in particular offer little resilience to drought (MacAllister *et al*. 2020) and may experience large declines in water yield during dry seasons (Ibrahim *et al*. 2021). The amount consumed by households is in part reliant on the quantity that can be collected. As hand dug wells can be relatively low-cost to develop, they are also used as a coping strategy adopted by households when municipal or other services are not available, for example in Nigeria (Ahile *et al*. 2015).

2.5.2.2. Surface Water

When water from formal services is unavailable, the infrastructure that enables the extraction of groundwater is not viable and when vended water proves too expensive, often the only water service available is that of surface water (Figure 2-14). 'Surface water' as a water service refers to non-saline, raw water, which is directly open to the elements (Yu 2018). Examples include rivers and dams, lakes and ponds, reservoirs and irrigation channels. In 2020, almost 75 million people continue to collect and rely on drinking water from surface water sources in SSA (WHO *et al*. 2020b).

Figure 2-14: Examples of unimproved surface water

(Sources: (clockwise from top left) Abidi, 2017; AAWF, n.d.; Leichman, 2017; Indiegogo, 2012)

Although the use of surface water is free for the user, it is often of the poorest quality and is contaminated by both industrial waste, and human and animal faeces; humans often share such resources with livestock and animals (Wardrop *et al*. 2018). Furthermore, collection of surface water can be both physically exerting and require long collection and travel times (Cassivi *et al*. 2018), it can be prone to both seasonal and climatic changes (Panthi *et al*. 2019), and can lead to conflicts between users (Sánchez and Rylance 2018) which all serve to affect its availability.

2.6. Household, Provider and Contextual Drivers of Drinking Water Availability

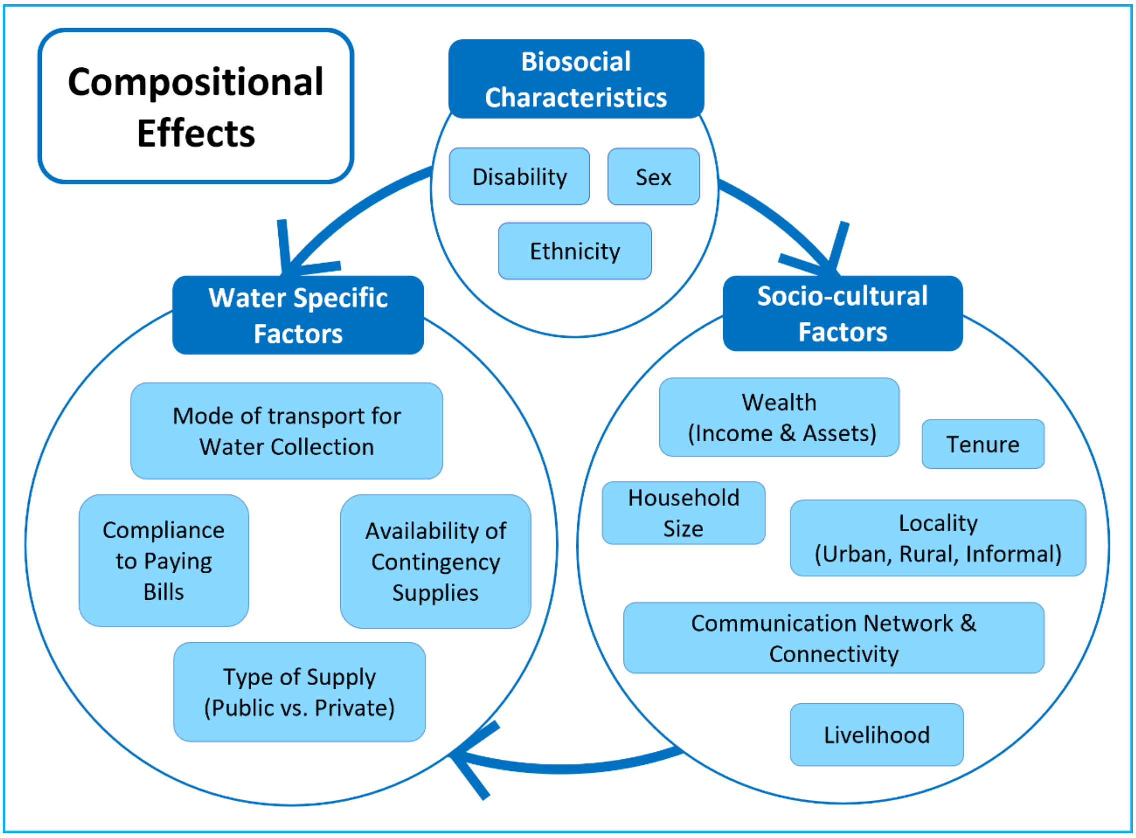
As has been illustrated throughout section 2.5, regardless of the type of drinking water service used the factors associated with experiencing an interrupted and unavailable drinking water source are numerous, complicated and intertwined. In understanding these complexities, it is important to consider the contributions of both composition and context. Compositional effects are characteristics of individuals comprising a household, whereas contextual effects are those that are related to the environment, such as broader neighbourhood attributes or those that are location-specific (Armah *et al*. 2018).

Overall, distinguishing whether an effect on water service availability is compositional or contextual can be difficult, as such research is increasingly concerned with the relationship between people and where they live (Cromley and McLafferty 2011). This is especially pertinent when exploring the contribution of compositional and contextual effects on drinking water availability. Regarding the latter, Chitonge (2020) highlights four orders of water scarcity that are reflective of the breadth of contextual factors that affect drinking water availability: (1) physical water scarcity, (2) economic water scarcity, (3) social, economic and political influences and (4) institutional barriers.

The following section begins to unpick the breadth of household compositional factors that affect water service availability, as well as the broader contextual drivers, including those specifically relating to water providers. More detailed discussion of the factors associated with supply interruptions is undertaken in the second analysis chapter, chapter 5 of this thesis, where discussion also concerns Chitonge's (2020) four orders of water scarcity and how they relate to water service availability.

2.6.1. Underlying Compositional Characteristics of the Household

Compositional characteristics typically refer to those that relate to the socio-demographic characteristics of individuals (Armah *et al*. 2018). Given drinking water sources are typically used by households, in this research compositional characteristics also need to be considered at the household level (Ekumah *et al*. 2020). Such characteristics play a key role in household decision making and act as both barriers and enables to water services (Figure 2-15) (Dreibelbis *et al*. 2013). Compositional effects may include biosocial characteristics that are physical or biological components of an individual which cannot be changed and are present at birth, for example, sex, ethnicity and disability (Collins *et al*. 2017).



<u>Figure 2-15:</u> Compositional characteristics affecting household availability of services

The availability of drinking water sources is also affected by relational and social barriers between groups due to ethnicity, class, nationality, disability, gender, age, religious affiliation, or political stance. Chitonge (2020) outlines these barriers as the fourth order of water scarcity. Whilst these factors operate at a micro-level and can often be very subtle, they can have a huge impact at the household level. For instance, gender can affect physical access to water resources, having control over the requirements needed to meet water needs and ability to exercise agency (e.g. to participate in decision-making, including intra-household decision making, public participation and freedom of movement) (Caruso *et al*. 2021). Accessibility plays a key role in the amount of water available in households and the ability to meet needs (Cassivi *et al*. 2019). Minority groups that are discriminated and prejudiced against may not be able to access water supplies, particularly in areas where there are competing demands from different population groups (Chitonge 2020). As such, minority groups and other vulnerable populations are often excluded, marginalised further and are voiceless meaning complaints about interrupted supplies often go unheard (Mehta 2014; Geere and Cortobius 2017).

Alternatively, they may include socio-cultural factors that relate to customs, beliefs, lifestyle or values (Armah *et al*. 2018). In the context of drinking water availability, socio-cultural factors comprise household size, wealth, tenure, and location of home. These characteristics have been shown to directly affect water insecurity, the type of service used, and resultant risk of experiencing an interruption (Stoler et al. 2013; Kulinkina et al. 2016; Bisung and Elliott 2018). Household or individual communication networks or connectivity and the subsequent capacity to make a complaint about source interruptions, as well as livelihood type (for example, subsistence farmers require more water than households with other livelihoods) all also serve to influence service availability (Maingey *et al*. 2022). Additional water-specific compositional factors exist which relate to individuals or households. Amongst others, these include compliance to paying bills (Adams and Vásquez 2019) and mode of transport for collecting water (Jeil *et al*. 2020).

2.6.2. Contextual Drivers of Water Providers

Characteristics of the population cannot alone explain the distribution of water service-related problems within the population. Cromley and McLafferty (2011) argue the context of the social group, neighbourhood or region must be accounted for when researching health-related issues. As such, in the context of drinking water services, the role of the service provider must also be considered given the direct impact they have on the availability of services.

Van den Berg (2015) state that within the municipal sector water productivity is less than optimal, with a large difference between the amount of water put into the distribution system and that which reaches and is billed to the consumer, a concept referred to as non-revenue water. Across SSA an estimated 5.2 billion metres cubed of water is lost every year through non-revenue water (Liemberger and Wyatt 2019). Causes range from drinking water that has not been billed to customers and is unauthorised, metering inaccuracies, authorised consumption that has not been billed, to leaks in piped water networks, the latter is especially prevalent in LMICs (González-Gómez *et al*. 2011). High levels of non-revenue water correlate with inefficient water management, which directly effects the amount of water available for household consumption (van den Berg and Danilenko 2017).

Adequate operation and maintenance budgets to enable the repair of broken infrastructure is also a leading cause of interruptions to water services (Simukonda *et al*. 2018a). Mehta (2014) refers to this as economic water scarcity: without the required funds, water providers are unable to address issues of water point functionality (see section 2.4.3.1). This results in leakages and mechanical failure due to infrastructural breakages of pumps and taps (Carter and Ross 2016). Estimates suggest one in four handpumps in SSA are non-functioning at any one time (Foster *et al*. 2019). The lack of investment in the water sector leads to users facing prolonged outages and insufficient quantities of water to meet their needs (Simukonda *et al*. 2018b).

As touched on in section 2.4.3.2, the practice of using intermittent services, as undertaken by water providers, significantly affects water service availability. The use of intermittent services and rationing of water where demand outstrips supply has emerged for multiple reasons. Most notably, water demand has been increasing in LMICs as a result of population growth. This results in water systems that are unable to keep up with demand meaning water is subsequently rationed (Matsinhe *et al*. 2014). As population growth has increased, so too have living standards and income per capita. This growth in wealth often leads to a more materialistic lifestyle which tends to coincide with increased water usage. For example, ownership of multiple cars and amenities such as swimming pools both significantly increase household water consumption. Intermittent services are not only affected the rationing of water, but are also caused by the rationing of other technical, economic and social inputs such as power supply and chemicals required for water treatment which in LMICs are costly (Totsuka *et al*. 2004).

2.6.3. Contextual Effects on Service Availability

In addition to the contextual factors of water providers that affect water service availably, related research often cites a complex array of contextual factors that have key effects on drinking water sources (Armah *et al*. 2018) As illustrated throughout section 2.3, these range from population growth and urbanisation, climatic variability, political and economic stability and the interlinkages of the WEF nexus and its impacts on the availability of services.

Figure 2-16 demonstrates the interlinkages of these contextual factors and how the complexities interact to affect drinking water availability. For example, population growth puts additional pressures on the WEF nexus and requirements to sustain society, and these increased pressures exacerbate political and economic instability in often fragile SSA countries (Gain *et al*. 2016). The latter faces further burdens as it deals with the challenges of climatic variability and the resultant unpredictability of water resources for example (Sofuoğlu and Ay 2020). Climatic variability subsequently leads to urbanisation as rural residents struggle to sustain their subsistence livelihoods under increasingly variable conditions and subsequently move to cities (UNESCO *et al*. 2016).

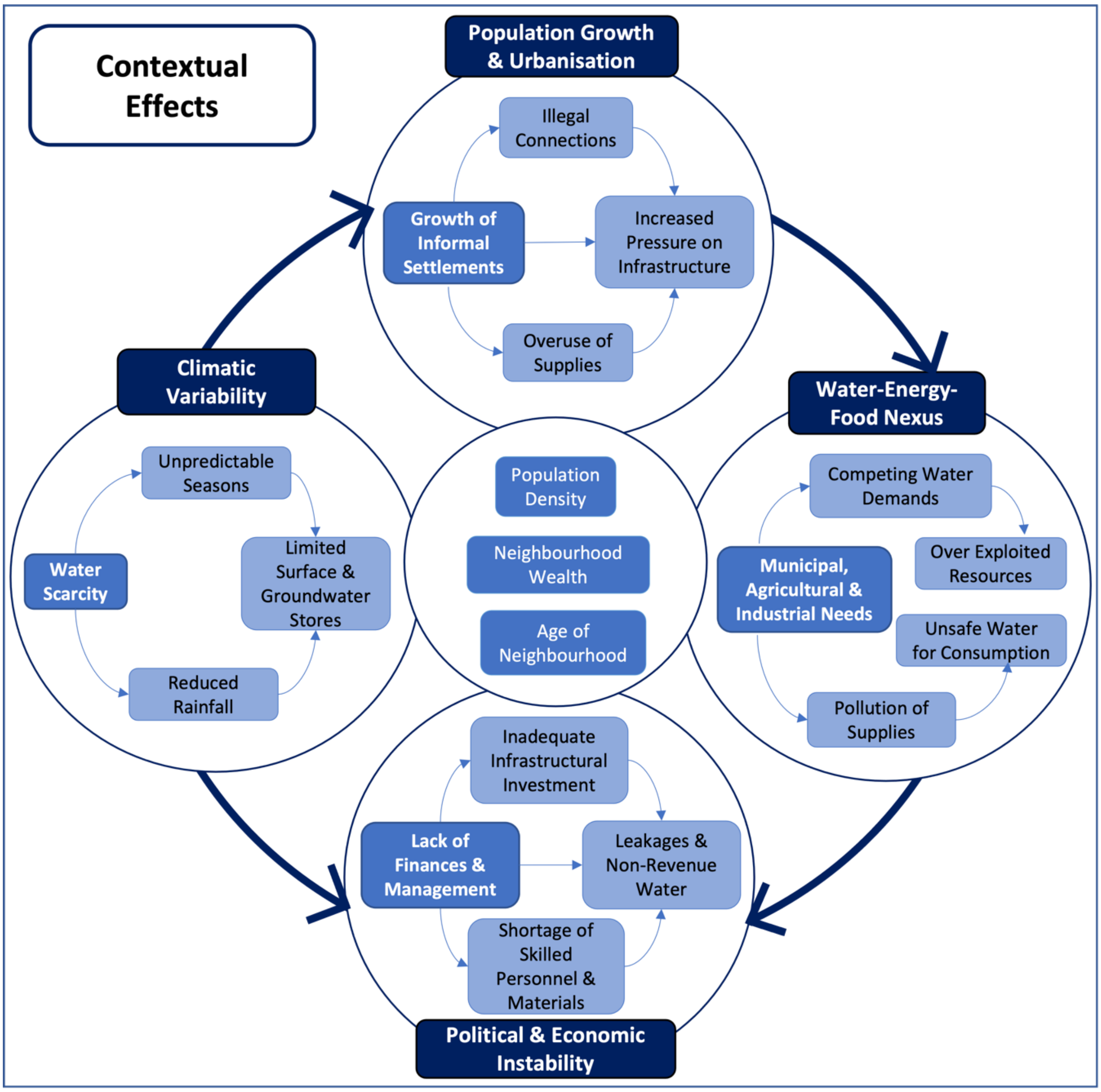


Figure 2-16: Contextual characteristics affecting household availability of services

Within each of these broad effects, more direct contextual characteristics influence the availability of drinking water. For example, political and economic instability can often mean water service infrastructure is not invested in, and services are prone to breakages, these effects are exacerbated when skilled manpower is limited and resources inaccessible and result in dependence on surface water and non-networked sources (Garrick *et al*. 2020). If surface water stores are limited and water is scare, there are competing demands within the WEF nexus and overexploitation through agriculture can lead to less water being available for municipal services (Hamududu and Ngoma 2020). Municipal services are further restricted as a result of overuse of services which lead to breakages, prolonged outages and an increase in illegal connections as individuals and households try to meet their water requirements (Bellaubi and Visscher 2014).

2.7. Conclusion

In summary, global monitoring of drinking water has undergone numerous transitions throughout the MDG and SDG eras. To reflect these changes, the JMP have had to adapt and redesign their monitoring efforts in order to capture all elements of safely managed drinking water services. This is evidenced through the ongoing changes to the drinking water ladder as well as the change in emphasis from purely focusing on the accessibility and quality of sources, which have received notable attention, to considering their availability. This shift in focus has led to the availability of drinking water being a relatively new, and understudied concept, hence the focus of this thesis.

As these changes in monitoring have occurred, shifts have also been undertaken in the data used by the JMP. An initial reliance on provider-based datasets subsequently transitioned to the ongoing use of user-based data, which is made available through household surveys and censuses, as well as that from regulators. All three datasets have their merits as well as their limitations, as have been discussed. Gaps remain in understanding how well these datasets align with one another however, and whether they depict a similar picture of service availability.

The quality and accessibility of drinking water have been examined given their direct impact on the availability of drinking water. The complexities of service availability have also been illustrated through discussion of concepts such as reliability, functionality, continuity and intermittency. The review reveals the breadth of drinking water sources used by households across SSA whilst illustrating how the availability of each can be affected and the role that contextual and compositional factors play. This is of particular importance given the inequalities that exist in the availability of drinking water and the need to account for and consider these in order to ensure that ‘no one is left behind’ during the 2030 Agenda whilst seeking to achieve SDG 6.

Chapter 3

Outline of Analysis Chapters

3.1. Overview

In this chapter an overview of the three empirical papers, Chapters 4, 5 and 6, of this thesis is provided. Collectively they address the thesis research objectives outlined in Chapter 1, section 1.5. The three empirical chapters have been designed to progressively narrow in scope based on geographical location of the study countries, rurality and the type of water service focused on (Figure 3-1).

In the following subsections an outline of each of the three papers is given, including the research questions that are addressed, the chosen study areas and the methods used. Details regarding publication are also provided.

Each empirical chapter is an extended paper compared to that which has been, or will be, submitted for publication. The choice of study country and data used, as well as the methods undertaken, are discussed in great depth. For this reason, a separate methodological chapter is not specifically included in this thesis.

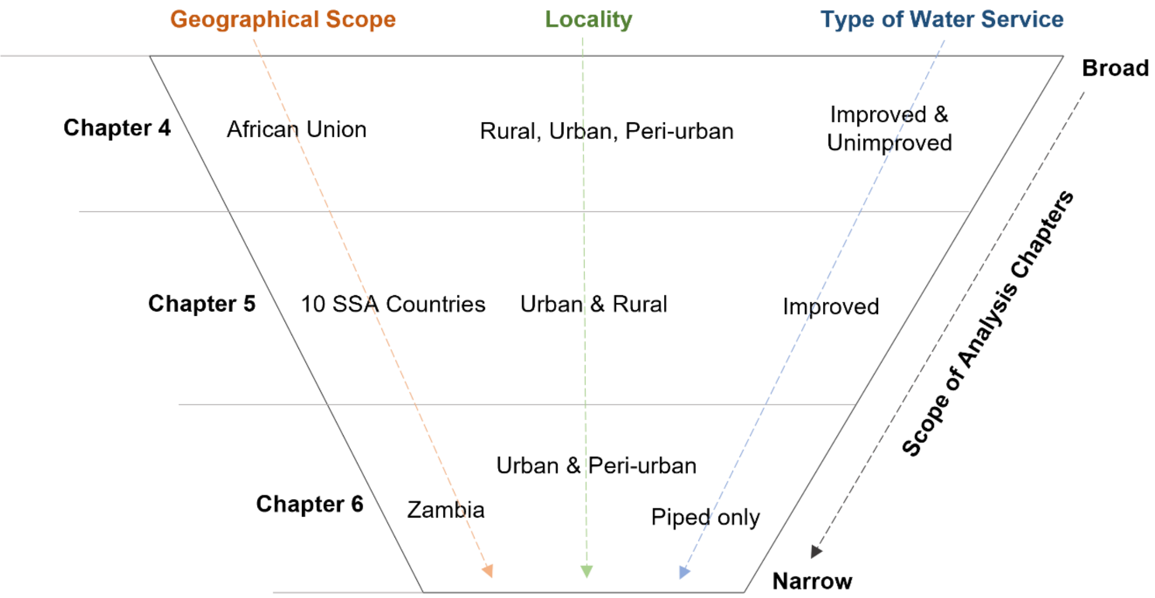


Figure 3-1: Diagram depicting the narrowing of scope of this thesis' three empirical chapters

3.2. Chapter 4

The first empirical paper in this thesis, entitled "*Household-reported availability of drinking water in Africa: a systematic review*", aims to examine the methods used to measure drinking water availability whilst synthesising existing evidence on African domestic drinking water availability.

Both improved and unimproved drinking water services in rural and urban African union countries are explored. Analysis also includes discussion of the causes of interrupted and unavailable services and the coping strategies adopted by households.

To do this, using the PRISMA guidelines (Moher *et al*. 2009), literature published between 2000–2019 was systematically reviewed. Structured searches were conducted in five databases: Web of Science Core Collection, Scopus, GEOBASE, Compendex and PubMed/Medline. This study has been published in the MDPI journal *Water* (Thomas *et al*. 2020).

The research questions for this study were:

- How does household-reported water supply availability vary between urban, peri-urban and rural areas of Africa?
- Are households across Africa meeting the WHO benchmark for water availability?
- Does household-reported water availability and the prevalence of interruptions differ for improved versus unimproved water source types?
- What methods are currently being used to measure household water availability as defined by the JMP?
- What are the perceptions of the underlying causes of interruptions to a water supply?
- What coping strategies do households develop as a response to poor availability of drinking water?

3.3. Chapter 5

The second empirical paper in this thesis, entitled "*A multi-country comparison of household, community and environmental factors associated with household drinking water availability in sub-Saharan Africa*", is a cross-sectional analysis which aims to explore the determinants of household reported interruptions to urban and rural improved drinking water services in Ethiopia, Gambia, Malawi, Nigeria, Sierra Leone, South Africa, Tanzania, Uganda, Zambia and Zimbabwe.

In order to achieve this, nationally representative demographic and health surveys (DHS) from 2015-2020, are used to provide household perspectives of interruptions within the two weeks prior to being surveyed. Multi-level models are used to determine household- and community-factors associated with the reporting of interruptions, with focus given to characteristics such as: household wealth, type of supply used, tenure, number of household members and housing quality, as well as, water stress, blue water scarcity, change in urbanisation, population density, neighbourhood wealth and age of neighbourhood.

In doing so, the following research questions are addressed:

- How do household experiences of interruptions to water sources vary between selected countries across SSA?
    - Do variations in service interruptions exist based on water source type (e.g. piped sources versus boreholes)?
- What household and community characteristics are associated with household-reported water supply interruptions across selected countries in SSA?
- Are water scarcity and water stress associated with household-reported water supply interruptions across selected countries in SSA?
- How much of the variation in household reported availability is explained by household-level factors compared to community-level contextual factors?

3.4. Chapter 6

The aim of the third and final empirical paper in this thesis, entitled "*Comparing provider, regulator and user reported availability of piped drinking water services in urban and peri-urban Zambia: a cross-sectional analysis*", is to assess the consistency of data from water providers, government regulators and water service users (households) when reporting on drinking water service availability in Zambia. Emphasis is given to the value of using user data and ensuring the households perspective is included in monitoring, and inequalities experienced by households are also considered.

Analysis is restricted to urban and peri-urban piped drinking water services and includes the use of multi-level models. 2018 user data from the DHS is used alongside 2018 provider data made available through IBNET, this includes performance data for the eleven public water service companies in Zambia. In conjunction, Government regulator data from Zambia's National Water Supply and Sanitation Council 2018 sector report is also used.

The following research questions are addressed:

- Are the three data streams, and metrics of water availability used, consistent with one another when analysing the availability of piped water and the population supplied?

    - If consistencies exist, can one data stream be used to represent all three perspectives, i.e. that of the user, regulator and provider?

- Can monitoring of piped water providers be enhanced by considering household survey data and the experiences of the user?

    - Do user-reported inequalities in piped water interruptions vary by provider coverage area?

    - To what extent are differences in the socioeconomic characteristics of users and the characteristics of water providers associated with user-reported availability of piped water supplies?

3.5. Ethics Statement

This PhD research involved the use of published literature and publicly available secondary data that was aggregated to enumeration areas. It did not include data, or work, that concerned individual human subjects, nor did it include any primary data collection.

Ethical approval for Chapter 4 was not required as it involved analysing existing literature that had previously been published.

For Chapter’s 5 and 6, which used de-identified population data from household surveys and censuses, ethical approval from the University of Southampton’s Ethics and Research Governance Online (ERGO 2) system was sought:

- For Chapter 5 an application (ID# 66830) was submitted on the 11th August 2021 and approved by the ethics committee on the 23rd August 2021.

- For Chapter 6 an application (ID# 55516) was submitted on the 28th February 2020 and approved on the 10th March 2020.

Chapter 4

Household-reported Availability of Drinking Water in Africa: A Systematic Review

This paper was published in the MDPI journal, Water, on 17 September 2020 (received: 29 July 2020; accepted: 10 September 2020).

The published version is available at: https://www.mdpi.com/2073-4441/12/9/2603/htm (doi:10.3390/w12092603).

4.1. Introduction

For billions of people worldwide, the poor availability of drinking water restricts consumption patterns and affects quality of life. At present, globally, at least one billion people experience an interruption to their supply throughout a 24 hour period (Kumpel and Butler 2018) and around 3.1 billion individuals depend on unreliable, non-piped water supplies that are located off-premises (Tamason *et al*. 2016). Despite international progress towards achieving universal access to drinking water, in sub-Saharan Africa (SSA), only 57% of the population report having an improved water supply that is fully functional, available when needed, easily accessible and provides good quality and safe water (WHO and UNICEF 2019b). Currently there are insufficient data in Africa to estimate the population using a water source that is "available when needed", suggesting a need for evidence to fill this gap (WHO and UNICEF 2017b). In addition, systematic evidence about how related measurement criteria are used in studies of water availability is limited, as is the extent to which reported availability varies by setting or study design. This systematic review aims to (i) assess drinking water availability across Africa from a household's perspective; (ii) examine household perceptions of causes and coping strategies adopted; and (iii) examine methods used to measure drinking water availability.

In African societies, complex and sometimes crippling social, economic and political difficulties and instabilities are often faced and affect the availability of water through inadequate investment in infrastructure, competing demands on resources, unsustainable water extraction, and pollution of water supplies (Hutton and Chase 2016). Additional pressures on supplies are also faced due to ongoing unpredictable climatic and seasonal variability. At the household level, the amount of water available and used varies based on setting and the time-period within a year (Kumpel, Cock-Esteb, *et al*. 2017) and additional challenges include the choice of water source, number of water sources and distance to it, the number of occupants and the type of needs they have, as well as cultural influences on water, water storage and ownership of water (Tamason *et al*. 2016). Mode of access, for example bike compared to foot, also inherently affects the volume of water that can be collected, as does the type of water container being used (Sugita 2006).

The capacity for governments to provide a water supply to its population is difficult at best with hardship often disproportionately affecting those of both lower economic and social status, as well as those living in rural localities (Carter and Ross 2016). Rationing of limited domestic water supplies and the resultant intermittent provision that is delivered, is often stifled with corruption as water is redirected to those of higher status (Campos and Pradhan 2007; Bapela et al. 2018). As such, access to water in an intermittent system can range from predictable to unreliable (Galaitsi *et al*.

2016). Interruptions to supplies are further affected by the functionality of water sources. A lack of continuity can lead to prolonged periods without supply, obliging households to search for alternative sources which are often of inferior availability and poorer quality (Garriga *et al*. 2015). Breakages in pipes and pumps, unreliable delivery times of tanked water, reduced water pressure due to high demand, wear and tear at distribution sites, poor quality infrastructure and accidental interruptions are all too common (Kumpel and Nelson 2016).

The effect of poorly functioning and intermittent water supplies at the household level has resulted in the development of individual and community coping strategies (Guragai *et al*. 2017). These include strategies such as using multiple water sources and storing as much water as possible, to collecting rain and dew water when the season and climate allows and buying water from vendors and kiosks (Lekouch et al. 2011; Meran et al. 2018). Coping strategies can also involve domestic budgeting of water, resulting in the neglect of 'nonessential' activities such as laundry and bathing. Similarly, altering of daily routines to accommodate additional collection of water is not uncommon, nor is making illegal connections to piped networks (Rugemalila and Gibbs 2015). These coping strategies often lead to financial and social hardship, as well as contribute to inequalities in other aspects of life. Women and children are often most affected by poor water availability due to cultural and traditional expectations, such as the burden of collecting water (UNICEF 2003; Rimi Abubakar 2018). The additional energy, time and resources required to achieve sufficient water when water is unavailable results in poor educational attainment (Howard and Bartram 2003), loss of employment opportunities and subsequent productivity and economic losses to households and society (Geere and Cortobius 2017).

The World Health Organization (WHO) outline a global drinking water availability benchmark which recommends that between 50 and 100 litres/capita/day (LPCD) is required to meet domestic needs, including washing, personal hygiene and cleaning (Howard and Bartram 2003). Meeting this benchmark is crucial, especially given an estimated 368,000 deaths annually in SSA are attributed to water, sanitation and hygiene (WASH) related diarrhoea (Prüss-Ustün *et al*. 2014). However, quantifying and measuring availability is complex, not least because in many African and low-income settings many households use multiple water sources, which in turn, creates multiple sites of measurement. At present a range of approaches to measure availability are often used, from qualitative discussions to quantitative assessments (Bonsor *et al*. 2018). With no one accepted method, each method currently used poses its own issues. For example, methods for measuring non-metered supplies are not standardised, with recall periods for questions on water usage ranging from 24 hours to a week, and others using consecutive daily visits to monitor water consumption or direct observation (Tamason *et al*. 2016).

Methods also include direct measurement and estimation, and range from single-time questionnaires to multiday observations (Tamason *et al*. 2016). In some instances, households have been asked to quantify their water by placing stones in buckets every time a water container of a known size is filled (Ensink *et al*. 2002), or to use picture prompts of local water containers of known sizes for quantification (Esrey *et al*. 1992). Interviews and questionnaires are often faced with problems regarding recall periods, and it is not uncommon for limitations of bias to occur. Calls have been made (Tamason *et al*. 2016) for the 'end goal' of measuring water use to be quantification using LPCD, which has been shown to be used in multiple contexts but by no means across the board.

The acceptance of availability as a key concept of WASH is also reflected in the sixth Sustainable Development Goal (SDG) which aims to ensure availability and sustainable management of water and sanitation supplies for all, by 2030. Critically, unlike its predecessor, target 7.C of the Millennium Development Goals (MDG), it considers availability. While MDG target 7.C was met in 2010, it was largely criticised for failing to consider both the reliability of available water sources (Majuru *et al*. 2018). Thus whilst providing continuity with the MDG, namely by continuing to consider accessibility (Onda *et al*. 2012), this SDG target includes additional criteria in order to provide enhanced monitoring and address these criticisms, limitations and shortcomings. It is also closely linked to the Human Right to Water (United Nations 2010a) which states that water must *be 'available continuously and in a sufficient quantity to meet the requirements of drinking and personal hygiene, as well as of further personal and domestic uses, such as cooking and food preparation, dish and laundry washing and cleaning. […] Supply needs to be continuous enough to allow for the collection of sufficient amounts to satisfy all needs, without compromising the quality of water'* (United Nations 2010a, p. 6).

The recent incorporation of drinking water availability into international monitoring indicators has been facilitated through the inclusion of core questions, developed by the Joint Monitoring Programme (JMP) of the WHO and United Nations Children's Fund (UNICEF) (WHO *et al*. 2020c), within major international survey programmes. These are designed to provide global measurement standards to ensure consistent monitoring through the standardisation of information collected within household surveys and censuses. Core questions are supplemented by expanded questions that can be asked should resources allow, and response categories have been designed to be universally applicable. The JMP's core question which addresses water availability, asks 'In the last month, has there been any time when your household did not have sufficient quantities of water when needed?' (WHO and UNICEF 2018a). Expanded questions focus on aspects of unavailability, continuity, intermittency, and household water tanks, as well as seasonal variations in availability (see appendix A.1).

As the diversity of core and expanded questions illustrates, service availability is increasingly seen as a critical WASH element. However, while the JMP has thus far been relatively successful in streamlining their core and expanded questions into international survey programmes, a greater understanding of the suitability of the methods used to measure availability in Africa, in light of the JMPs new set of questions, is merited. Given the importance of capturing the viewpoint of the user, examination of the full spectrum of approaches used to measure components of water availability is also warranted. Given this, this systematic review will help in evaluating the effectiveness of the JMP's core questions and most importantly, provide a synthesis of the existing evidence on availability of drinking water supplies in the African context.

Several related systematic reviews explore the reliability of supplies (Majuru *et al*. 2016), deficiencies in supply systems (Ercumen *et al*. 2014) and methodologies used to measure water availability (Tamason *et al*. 2016). However, two of these review the implications of poor water availability for health (Ercumen et al. 2014; Tamason et al. 2016), whilst the third examines population coping strategies in response to insufficient supplies (Majuru *et al*. 2016). Similarly, the scope is either global (Ercumen *et al*. 2014) or primarily focuses on low and middle income countries (LMICs) (Majuru et al. 2016; Tamason et al. 2016), rather than regional. Often related reviews exclude certain water supply types, or focus solely on domestic piped supplies (Ercumen *et al*. 2014). No known review has compared availability in the context of improved and unimproved supplies. While Tamason *et al*. (2016) explored the methods used to measure household water availability, the review predates revised core questions and results are not assessed against the WHO's global availability benchmark. Consequently, this review aims to address the following research questions:

- How does household-reported water supply availability vary between urban, peri-urban and rural areas of Africa?
- Are households across Africa meeting the WHO benchmark for water availability?
- Does household-reported water availability and the prevalence of interruptions differ for improved versus unimproved water source types?
- What methods are currently being used to measure household water availability as defined by the JMP?
- What are the perceptions of the underlying causes of interruptions to a water supply?
- What coping strategies do households develop as a response to poor availability of drinking water?

4.2. Materials and Methods

4.2.1. Literature Search Methods

The systematic review was undertaken following PRISMA guidelines (Moher *et al*. 2009). A protocol is available via the PROSPERO register of systematic reviews (ID# 124139) and provides a record of the key features of the review and any changes made throughout the review process. During February 2019 a search of electronic databases, including Web of Science Core Collection, Scopus, GEOBASE, Compendex, PubMed/Medline, was undertaken by one reviewer (MT). In addition, backward citation tracking was undertaken for all included studies. Search terms related to water availability, drinking water, interruptions, types of water source and households (see appendix A.2) and listed African Union countries (see appendix A.3). Searches used the following structure:

[Continuity/interruptions/availability] AND [domestic water] AND [water supply type] AND [African Union country]

Thus, terms for each of these four concepts, including truncation terms, for example 'contin*' and 'reliab*'were combined with Boolean operators such as OR, before being combined with AND, in order to maximise search sensitivity.

4.2.2. Inclusion and Exclusion Criteria

Any study reporting an improved or unimproved groundwater or piped drinking water source was included. Studies reporting only packaged water, rainwater or surface water (such as rivers, dams, lakes or ponds) were excluded due to such sources' frequent use as alternatives in the absence of other improved source types (Kjellén and Mcgranahan 2006). Only studies undertaken in the 55 African Union countries were included (The African Union Commission 2019). English, Portuguese and French language studies were included as these are the main international languages for publication on the African continent and were the main languages spoken by the reviewers.

Studies were included that reported any of three pre-defined measures of drinking water availability: (1) quantities of water available and/or used within a given period, (2) hours of supply a day and (3) frequency of supply breakdowns. These measures were developed in alignment with the WHO's global benchmark and are based on the literature, as well as both the JMP's core and expanded questions.

The review's primary focus was on the experiences and perspective of domestic users of water supplies; therefore, its focus was only on domestic water availability reported by households or individuals. Studies of water availability in schools, healthcare facilities and agricultural or industrial water supply were excluded. Similarly, domestic water supply interruptions that were reported by service providers, rather than households or individuals, were excluded.

This review focused on academic research studies and the following research report types were included; peer-reviewed journals, conference proceedings and theses. Reports by statistical agencies based on household surveys or censuses were excluded since these were likely be picked up elsewhere by the JMP. However, academic studies that used this data were included as the data may have been manipulated in innovative ways, offering an alternative perspective and interpretation of results. Conference proceedings were included to try to reduce the effect of publication bias (Knobloch *et al*. 2011). Studies based on data collected from 2000 onwards were included; this marks the year that the JMP developed the standard set of drinking water assessment criteria (Bisung and Elliott 2018) and when international monitoring of WASH targets began through the MDGs. All forms of study design and research methods were included, for example, focus groups, questionnaires, surveys, interviews.

4.2.3. Study Selection

All titles and abstracts of the retrieved citations were exported by MT into Endnote X8.2 and duplicates were identified and removed. Following initial screening of abstracts and titles, full texts were screened and characterised. For all studies in English, screening was undertaken by MT using the Metagear package (Lajeunesse 2017) in the software R. This enabled objective screening through the use of its abstract screener which purposefully helps to scan and evaluate each title and abstract of the papers. JW screened six studies in French, no Portuguese studies were returned in the searches.

Following preliminary screening, a random sample of 10% (*n* = 240) of all studies were independently screened by one of MN, AC and JW (henceforth referred to as the secondary reviewers). This sample of studies was randomly selected by using the random number generator formula, (=RANDBETWEEN()), in Microsoft Excel. The results from the secondary reviewers' screening and MT's screening were cross-checked to identify any discrepancies. Abstracts and titles of reports with such discrepancies were re-reviewed by MT and a revised inclusion decision made based on only their titles, keywords and abstracts. Cohen's Kappa (k) was calculated to determine the level of agreement between MT's and the secondary reviewers' screening of the sub-sample of reports.

Full-text articles were screened for all studies included on the basis of abstract and title. Where multiple reports were produced for one study, these reports were characterised independently however for analysis the results for the one study were accumulated to provide one sample for the study (e.g. Kettab *et al.* (2006) and Masmoudi *et al.* (2008)). Where any uncertainty by MT regarding a study's inclusion occurred, the studies were independently reviewed by both JW and AC. A final decision regarding inclusion was then made following a joint discussion.

4.2.4. Data Extraction

At the characterisation stage, five different categories of information were collected and recorded from all eligible studies. Basic descriptive information, such as title, author, year of publication and research objectives, were extracted. Studies were also classified based on their study design; the sample size, sampling strategy and design of each study were all collated. Studies were classified as longitudinal if they comprised a duration of at least six months and more than two repeated samples at each household. Any form of random sampling (e.g., simple random, systematic, and stratified-random) was classified as representative. All other sampling strategies (i.e., convenience, purposive and quota sampling) were classified as non-representative. Characteristics relating to the study's research setting and population were also extracted, for example, country, location, and the size and type of settlement.

The water supply type and supplier (e.g., private, public, community, self, non-governmental organisation (NGO)) were also collected. The water supply used by the majority of the study population in each study was recorded as the 'dominant water source'. Each dominant water supply type was reported based on the JMP's improved/unimproved classification. Where a study reported multiple water supplies, these were grouped and classified as either improved or unimproved. Where colloquial language or terminology for certain supply types was used, these were grouped based on geographical region and classified as improved/unimproved based on JMP criteria.

If the specifics of the supply were unclear then they were reported as unclassified, for example, often the type of well was unreported thus such instances were recorded as 'unclassified well'. Similarly, if totally insufficient information was provided about the water supply type, then it was excluded and noted as 'unknown'. Required conversion factors, such as for converting numbers of jerry cans of water into litres were drawn from published estimates (Water Engineering and Development Centre 2011). In this instance, a jerry can on the African continent is usually 20 litres in capacity, therefore any such reporting was converted based on this metric.

Data were extracted to evaluate which of the three measures of water supply availability were used. Intermittent supplies were differentiated from supply breakdowns by the study's description of a supply's availability. For example, study reports using terms such as 'broken' or 'breakdown' were characterised as breakdowns. Where reported, the question(s) used by the study was extracted (see: Table 4-1), together with the recall period and nature of the household respondent. Measures of uncertainty of estimates, such as standard error and confidence intervals, were also collected, together with household size.

<u>Table 4-1:</u> Measures of water availability.

Measure of Water Availability		Questions Used by the Included Study	Example of Reported Metric of Availability Used in the Study
1	Quantity of water used by households	Sufficient water available during last month?	Yes/No
		Do you have a sufficient amount of water to cover your needs?	Yes/No
		On average, how much water do you use in a day?	Litres per capita per day
			% of households > XX litres per capita
2	Average hours of service	On average, for how many hours a day/days a week is your supply available?	XX hours per day
			% of households > 12 h per day (or >4 days a week?)
		Water available "continuously"	Yes/No
3	Frequency of breakdowns	Is water available from the main water supply at the time of the study?	Yes/No
		Main supply functioning?	% of households reporting yes
		Can you predict when an interruption is going to happen to your water supply?	Yes/No

For all included qualitative studies, data extraction entailed the collection of first order constructs (participants' quotes) and second order constructs, which are researcher 'interpretations, statements, assumptions and ideas' based on first order constructs (Aspers 2009). Where the distinction between the two types of construct was not evident, then information was classified as a second order construct (Toye *et al*. 2014).

4.2.5. Critical Appraisal of Study Quality

Study quality was assessed based on ten criteria in the STROBE Statement (von Elm *et al*. 2007) (see appendix A.4), with an additional four criteria for quantitative studies only. No study was excluded based on it being low quality. Instead, the influence of study quality issues, such as non-representative sampling, were considered through narrative synthesis.

Due to reporting complexity and diversity in the included studies, formal tests for publication bias, such as funnel plots, and for heterogeneity, such as Higgins I^2, could not be undertaken. For example, most studies did not report measures of confidence or standard errors for summary statistics. As a result, representativeness of the sampling strategy and sample size were used as indicators of study precision and error.

As an additional study quality measure, where studies failed to report household sizes, but did report both litres/household/day (LPHHD) and LPCD, the household size was calculated and its plausibility assessed based on contextual knowledge of the study location. For example, a seemingly implausible household size of 30 for a study in northern Ghana (Alhassan and Kwakwa 2014) could have reflected homesteads consisting of an extended household structure, linked through kinship to the same head of household.

4.2.6. Water Scarcity Variable

In preparation for the quantitative analysis, which was undertaken on the results of the included studies, a water scarcity variable was created. Names of study site locations were geocoded with town/city or neighbourhood precision using the MapQuests Application Programming Interface (API) (MapQuest 2020). Coordinates were cross-checked against reported study site names and any geocodes less precise than neighbourhood level were manually reviewed and geocoded. The resultant coordinates were linked, using ArcMap 10.7, to the Water Footprint Network's (WFN) blue water scarcity map layer (Mekonnen and Hoekstra 2011), which comprises a ratio of blue water consumption to blue water availability. This data was used as it is publicly available, has undergone peer-review and most closely relates to the implementation years of included studies. Water scarcity was approximated for each of the geocoded locations, using a buffer based on the area of the study site. Where a study had multiple study sites (n = 9), an average water scarcity score was calculated.

4.2.7. Analysis

Given the diversity of included studies, a balance between narrative synthesis, thematic discussion and explorative quantitative analysis was undertaken (Butler *et al*. 2016). For the first measure of availability (LPCD and LPHHD) elements of a meta-summary have been undertaken. Qualitative findings have been quantitatively aggregated by extracting, grouping and formatting findings that related to the standard of the water supply and rurality. In contrast, analysis of the second two measures of availability (hours of supply a day and frequency of supply breakdowns) provides a more narrative understanding of the experiences and perceptions of water availability, especially with regards to interruptions and continuity of supply.

Insufficient data and a lack of reporting of measures of uncertainty (i.e., standard deviations for estimates or confidence intervals for summary means and proportions) precluded the use of quantitative meta-analysis techniques such as meta-regressions and forest plots. In the absence of uncertainty measures, mean water consumption (LPCD) per study was plotted on a bubble chart to visualise the study findings analogously to a forest plot. Where studies reported multiple figures for different population sub-groups rather than mean consumption in LPCD, a population-weighted average was calculated.

Since LPCD was the most commonly reported availability metric, single country studies reporting LPCD were included in a multiple linear regression analysis. This was undertaken in Stata version 16.1 and predicted LPCD from rurality (i.e., rural/urban), gross domestic product (GDP) per capita, purchasing power parity (PPP) in constant 2017 prices (USD), if the study was an intervention, water supply type (i.e., piped/other) and water scarcity. Prior to running the multiple linear regression model, exploratory bivariate regressions were undertaken between LPCD and each of the explanatory variables.

In the multiple linear regression, freshwater scarcity was included since it may have restricted drinking water availability, especially in Africa where seasonal variations and drought are common (McNally *et al*. 2019). Piped supply was included since more water may be consumed when piped to the yard or home rather than fetched from further away (Overbo *et al*. 2016). GDP per capita (PPP) (World Bank 2020a) for each study's publication year was used as a proxy for development level (Felice 2016), which affects national WASH investment (Luh and Bartram 2016). Rurality of study site was included since rural areas typically have lower WASH infrastructure levels and, thus, lower water availability (WHO and UNICEF 2019b). Studies evaluating interventions were also examined through a binary covariate, since such interventions often increase water availability and consumption. Standard regression assumptions were checked, and the model was re-estimated to exclude any outliers that had a large influence on the coefficient estimates.

4.3. Results

A total of 4948 reports were returned from the database searches (Figure 4-1). In addition to this, 13 other reports were identified from backwards reference searching, resulting in 4961 studies for review. Of these, 2555 were duplicates.

Of the sub-sample of reports (n = 240) screened by secondary reviewers, there were thirty reports for which the secondary reviewer's decision differed from MT's initial screening decision (Table 4-2). The secondary reviewers disagreed with the inclusion of 33% of reports MT included based on their titles and abstracts. They felt that 11% of the reports MT excluded should be included. A Kappa statistic suggested fair agreement between MT and the secondary reviewers' judgment regarding the inclusion of these reports, k = 0.376 (p = < 0.005). For the purpose of calculating this test statistic, three reports classified as ambiguous were excluded, therefore n = 237.

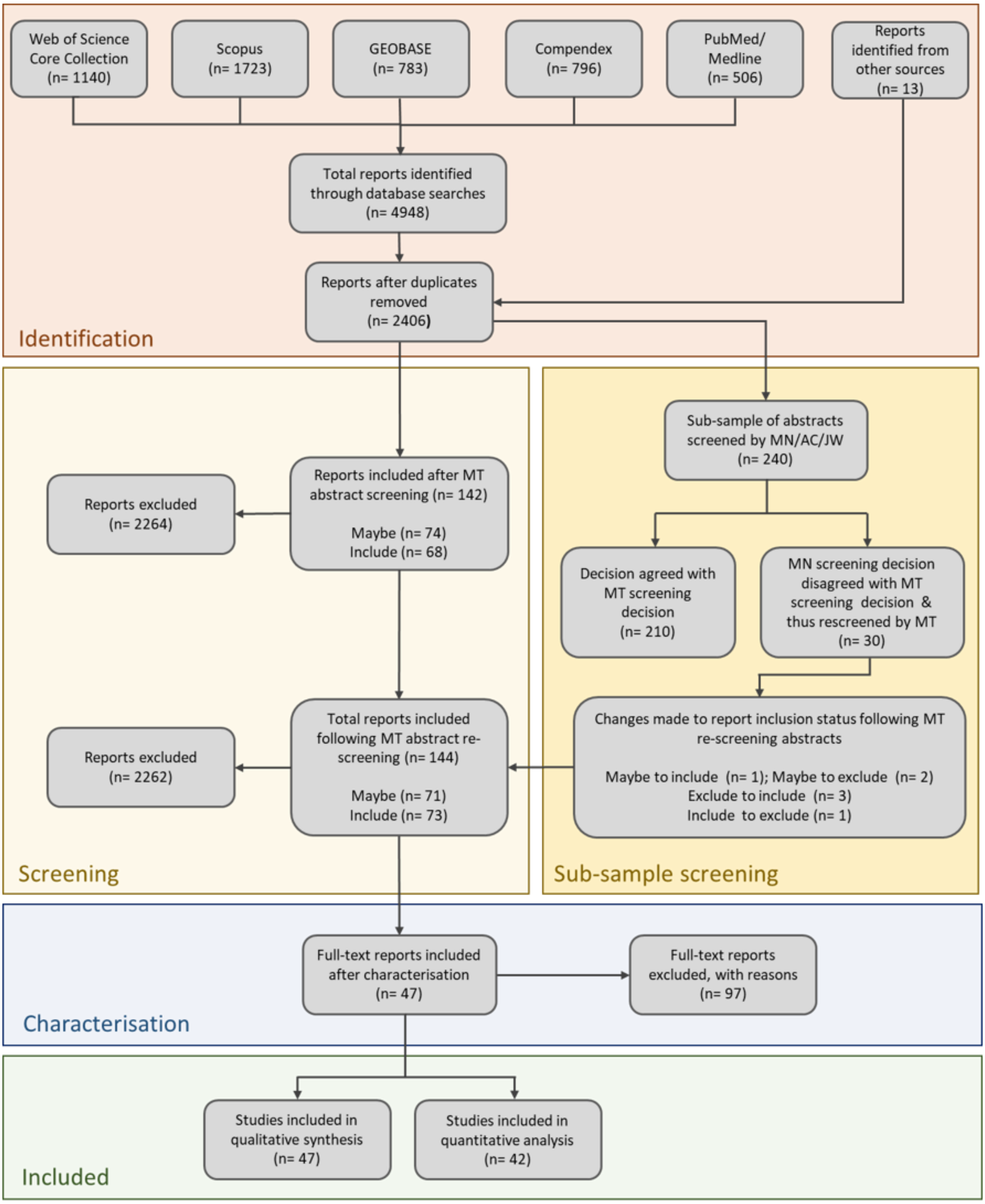


Figure 4-1: Flowchart of study selection process

Table 4-2: **Cross-tabulation of MT's screening results and the results from MN/JW/AC's screening of a 10% sub-sample.**

		MT Screening Results			
		Include	Exclude	Ambiguous	Total
MN/JW/AC screening results	Include	10	24	0	34
	Exclude	3	200	3	206
	Total	13	224	3	240

Shaded figures represent those which MT and MN/JW/AC (n = 30) disagreed on following their independent screening of a 10% sample of reports.

Reanalysis of the thirty papers disagreed upon by MT and the secondary reviewers resulted in one report originally classed as ambiguous being included due to its mention of availability, and two reports which were originally ambiguous being excluded. These reports were excluded because one focused on water quality and its safety and the other modelled willingness to pay for water. Three out of the 24 reports were reincluded after MT originally excluded them. Human error was the cause of these reports having been excluded during MT's original abstract screening stage. One report was excluded which MT had initially included. Therefore, 144 reports were included for subsequent characterisation.

Analysis of the full texts resulted in the inclusion of 47 studies which m*et al*l inclusion criteria. A further 97 reports were excluded (see appendix A.5/A.6); 22% did not me*et al*l the inclusion criteria. 32% discussed water availability, however they did not report one of the pre-defined availability measures and thus were excluded. A further 14% did not give the household perspective, while 11% focused on accessibility to water. Thirty-four studies reporting LPCD were included in regression analysis after excluding one such multi-country study

4.3.1. Study Quality

Among the fourteen study quality criteria (Table 4-3), there were some generic strengths, such as the study rationale being stated. 94% of studies successfully reported the water supply used by respondents and its characteristics, 96% effectively extracted data and themes which lead to justified conclusions and 81% reported the sampling strategy used, including details regarding the sample size. Generic weaknesses also existed, for example reporting of precision. More than three quarters (81%) reported the sampling strategy used, but methods were rarely described in enough detail to enable replication. Most studies did not discuss limitations of their research nor did they address issues of bias. On the whole studies did not document the number of participants involved at each stage of the study.

Of criteria specific to quantitative studies, all studies failed to account for missing data, 91% did not describe statistical methods used therefore preventing replication and 97% did not justify their choice of variables. Furthermore, most studies did not report levels of precision, preventing meta-analysis or forest plot production.

4.3.1. Study Characteristics

Most studies were published from 2010 onwards (66%), with the majority being post-2015 (41%), and most were cross-sectional (87%) (Table 4-4). Quantitative household surveys were the dominant research method used to collect information on water availability (43%). In some cases (Smiley 2016), additional methods such as unspecified interviews (meaning it was unknown whether they were structured or unstructured) were used to complement the household survey and gain greater detail on water availability. Structured questionnaires were also frequently used (15%); Katsi *et al.* (2007) used complementary participatory rural appraisal techniques to verify results. A tenth of the studies (11%) used unspecified interviews and a further 11% used unspecified questionnaire designs. Water-meters were used by three studies, all of which examined piped water supplies.

<u>Table 4-3:</u> Assessment of study quality

	Item	Criterion	Content	Met criteria (% of Total Studies)
Core criteria for all studies (*n* = 47)	1	Rationale for study stated	Study objective clearly stated	100%
	2	Rationale for chosen participants	Eligibility criteria for study participants described.	64%
	3	Water supply characteristics documented	Water source/supply characteristics used by study participants documented.	94%
	4	Sampling strategy reported	Sampling strategy described (e.g., purposive; simple random; multi-stage etc.). For secondary data studies; sources and dates of access are given.	81%
	5	Arithmetic error has been eliminated	All descriptive statistics and percentages reported were arithmetically correct.	89%
	6	Limitations and bias	Limitations of the study are discussed, taking into account potential bias and precision.	23%
	7	Participants recorded throughout	Numbers of individuals at each study stage reported (e.g., those ineligible; declining to participate; unavailable for interview).	17%
	8	Justification for methods	Choice of interviews, questionnaires, focus groups, surveys etc. justified.	32%
	9	Replicability	Methods suitably described to enable replication.	23%
	10	Extraction of data and themes	Conclusions have been explained and justified.	96%
Criteria for quantitative studies only (*n* = 42)	11	Statistical methods	All statistical methods described in sufficient detail to enable replication.	9%
	12	Justification for variables	Use of all chosen quantitative variables explained.	3%
	13	Missing data	Missing data acknowledged, and how addressed is clearly explained.	0%
	14	Precision	Confidence intervals, odds ratios, standard errors and/or standard deviations reported for water continuity/availability estimates.	12%

Table 4-4: Characteristics of included studies.

	Study Characteristics		% of Included Studies (*n*)
Basic characteristics	*Year of publication*		
		2000–2004	10.6% (5)
		2005–2009	23.4% (11)
		2010–2014	25.5% (12)
		2015–2019	40.5% (19)
	Study design		
		Case-control	2.1% (1)
		Cohort study	2.1% (1)
		Cross-sectional	87.2% (41)
		Longitudinal	6.4% (3)
		Quasi-experimental	2.1% (1)
	Sampling		
		Representative	36.2% (17)
		Non-representative	55.3% (26)
		Not stated	8.5% (4)
	Dominant method		
		Household survey	42.6% (20)
		Household water-meters	6.4% (3)
		Semi-structured interview	4.3% (2)
		Semi-structured questionnaire	6.4% (3)
		Structured interview	4.3% (2)
		Structured questionnaire	14.9% (7)
		Unspecified interview	10.6% (5)
		Unspecified questionnaire	10.6% (5)
Setting	*Rurality*		
		Rural	40.4% (19)
		Urban	55.4% (26)
		Peri-urban	4.3% (2)
Dominant Water Supply	*Standard of water supply*		
		Improved	59.6% (28)
		Unimproved	40.4% (19)
	Dominant water source		
		Borehole/tube-well	14.9% (8)
		Communal water kiosk	2.1% (1)
		Groundwater	6.4% (3)
		Open well	2.1% (1)
		Piped water connection (in the dwelling, yard or from neighbour)	27.7% (13)
		Public standpipe	10.6% (5)
		Tanker	2.1% (1)
		Unclassified well	21.3% (10)
		Unprotected well (including shallow dug wells)	10.6% (5)
	Dominant water availability measure reported		
		Quantifies the amount of water available/used in a given time	89.4% (42)
		Hours of supply a day/week	6.4% (3)
		Frequency of breakdowns within a supply system	4.3% (2)

Studies reported sample sizes as the number of households and/or the number of individuals (see appendix A.7). The majority (77%) reported samples of households (min. = 15, max. = 20,000, S.D. = 3302.7)). A total of 11% of studies reported both individual and household sample sizes. Excluding Adekalu *et al.'s* (Adekalu *et al*. 2002) sample of 20,000 households, the mean sample size was 316 (min. = 20, max. = 1860, S.D. = 406.7). In comparison, 23% of studies reported samples of individuals; the mean sample size was 431 people (min. = 4, max. = 1080, S.D. = 364.3). Half of the studies (55%) used non-representative sampling techniques such as convenience sampling (6%) (min. = 40, max. = 653, S.D. = 289.7) and purposive sampling (19%) (min. = 20, max. = 683, S.D. = 198.3). In addition, multi-stage sampling was used by 26% of studies (min. = 114, max. = 1203, S.D. = 337.9), whereas Booysen *et al.* (Booysen *et al*. 2019) reported using quota sampling. Representative sampling methods were undertaken by 36% of studies, and included methods such as systematic sampling (min. = 50, max. = 1015, S.D. = 538.9), stratified random sampling (min. = 674, max. = 1860, S.D. = 838.6) and simple random sampling (min. = 4, max. = 1080, S.D. = 371.3). Examples of systematic random sampling methods included choosing every tenth house along a street (Tumwine *et al*. 2002), or every fifth household when starting from a junction (Oumar and Tewari 2010). Four studies failed to report the sampling strategy used.

A total of 61% of studies reported the dominant water supply as being improved. Piped water connections were reported by 39% of studies (the precise location of this supply was often unstated, i.e., whether or not it was from a neighbour, in the yard or within the dwelling), while other dominant improved supplies included boreholes (15%), dug wells (6%) and public standpipes (6%). Unimproved or ambiguously defined water supplies primarily included unclassified wells (21%). Examples of unclassified wells include Malian wells (Bauchspies 2012) and marigots (Hadjer *et al*. 2005). Vended water supplies were reported by 4% of studies and included communal water kiosks and tankers.

Figure 4-2 shows most studies were undertaken in eastern and western Africa, with 17% of studies in Nigeria. In eastern Africa, Kenya and Tanzania were the most frequently studied countries. In southern Africa, the studies were undertaken in South Africa (9%), Eswatini (2%), Zimbabwe (9%) and Botswana (4%). The only study country in northern Africa was Algeria where 9% of studies were undertaken, likewise in central Africa, Cameroon was the only study country. Half of the studies (51%) explored drinking water availability in urban areas, 40% in rural areas and 9% in peri-urban areas. No study specifically considered informal settlements.

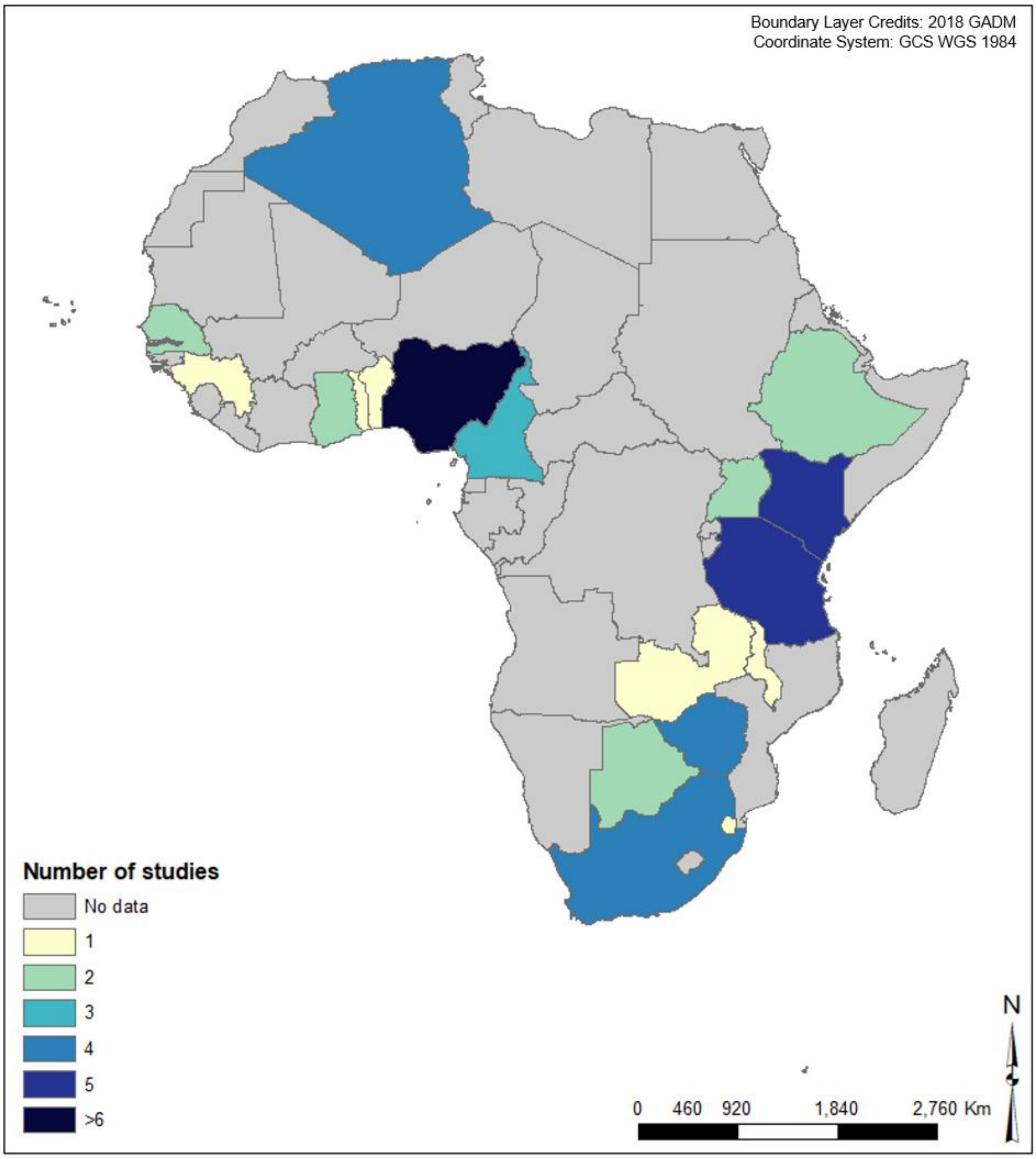


Figure 4-2: Geographical distribution of included studies

4.3.2. Monitoring Drinking Water Availability

The majority of the studies (89%) reported water availability using either LPCD or LPHHD. The other two measures, hours of supply and the frequency of breakdowns, were reported by only 11% of studies. Hours of supply were reported per day (Oumar and Tewari 2010) or per week (Adams and Smiley 2018), whereas the frequency of breakdowns were reported in an informal manner, often without quantification.

4.3.2.1. Measure One: Quantity of Water Available

Figure 4-3 shows per capita water availability based on rurality, water supply status and the sampling strategy and size. Figure 4-4 shows the same but for household drinking water availability. Where studies have a sample size based on individuals, rather than households, the median household sample size has been used as a proxy.

The smallest sample sizes of less than forty households were in studies from Vogel *et al.* (Vogel *et al*. 2015) and Hadjer *et al.* (Hadjer *et al*. 2005). Small sample sizes were more common in studies researching rural areas. Studies which had large, representative samples included Hall and Vance (Hall *et al*. 2014), Tumwine *et al.* (Tumwine *et al*. 2002), and Adekalu *et al.* (Adekalu *et al*. 2002), with the latter sampling 20,000 households. Eleven urban studies used non-representative sampling strategies compared to eight rural studies. Studies that did not report their sampling strategy had comparatively small sample sizes below 500 households, e.g., (Bauchspies 2012).

In comparison, in Figure 4-4 where household drinking water availability is reported, the majority of sample sizes were less than 200 households; Juma *et al.* (Juma *et al*. 2018) had the smallest sample size of 98 households. Study site rurality and whether it was urban or rural had minimal effect on sample size. Most studies used unrepresentative sampling strategies, with some exceptions (e.g., (Ahile *et al*. 2015),(Boateng *et al*. 2018)).

Unimproved water supplies were more common in rural areas than urban areas (Figure 4-3). For example, 44% of studies reported using unimproved sources as their dominant water supply in urban areas, compared to 63% in rural areas. The greatest amount of drinking water available in an urban study was 130 LPCD (Smith 2010), compared to 47 LPCD (Kanda *et al*. 2017) in a rural study. Overall, the lowest reported water availability in rural areas was 4 LPCD (Rugemalila and Gibbs 2015) and 9 LPCD (Bauchspies 2012) in urban areas.

Overall, only four studies reported water availability which met the WHO benchmark of between 50 and 100 LPCD: all were urban study sites. Smith (2010) reported the greatest amount with an average of 130 LPCD. All however used unrepresentative sampling strategies and small sample sizes. No study conducted in a rural location reported average daily water availability which met this WHO benchmark, although Kanda *et al.* (2017) marginally missed the benchmark.

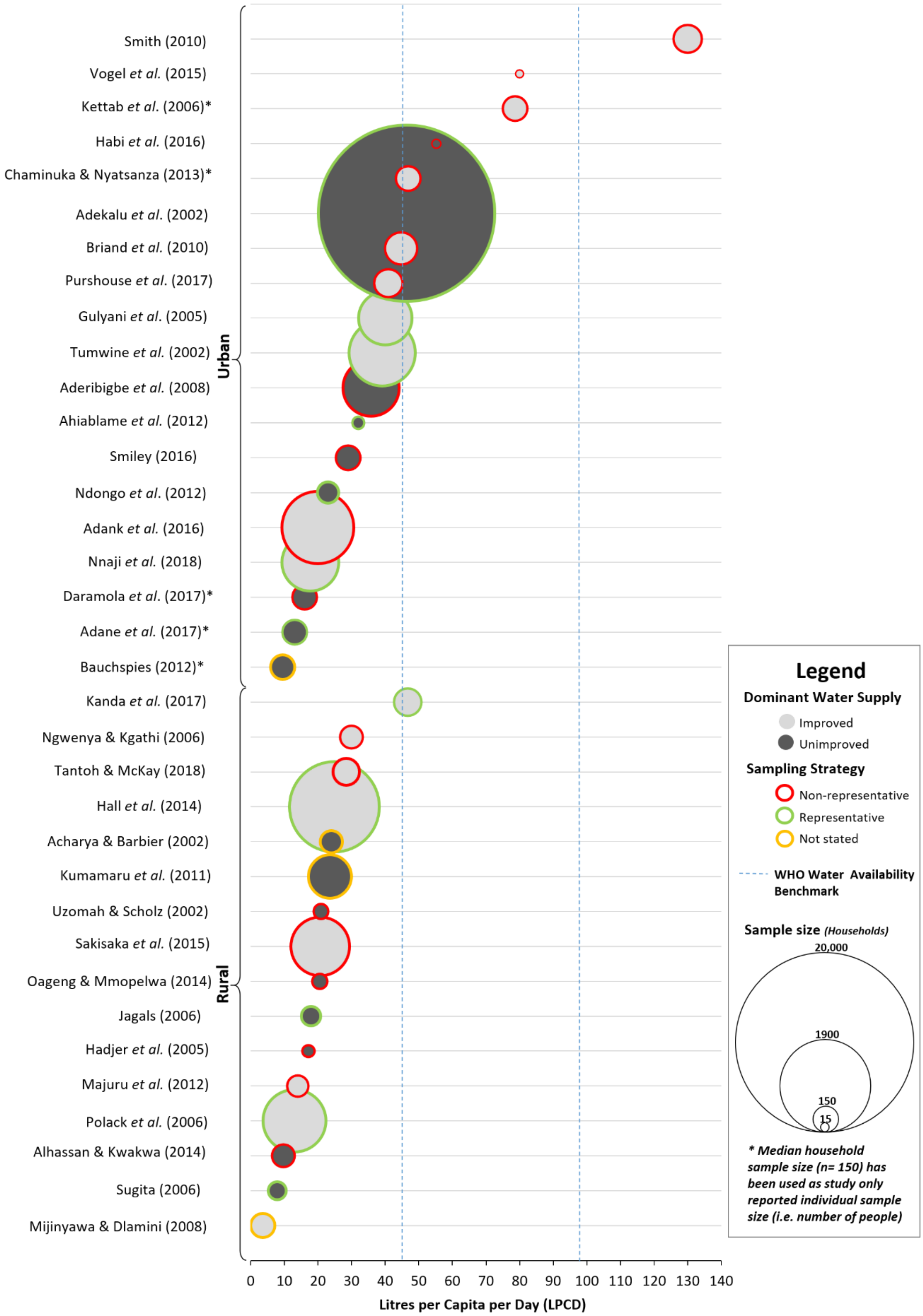
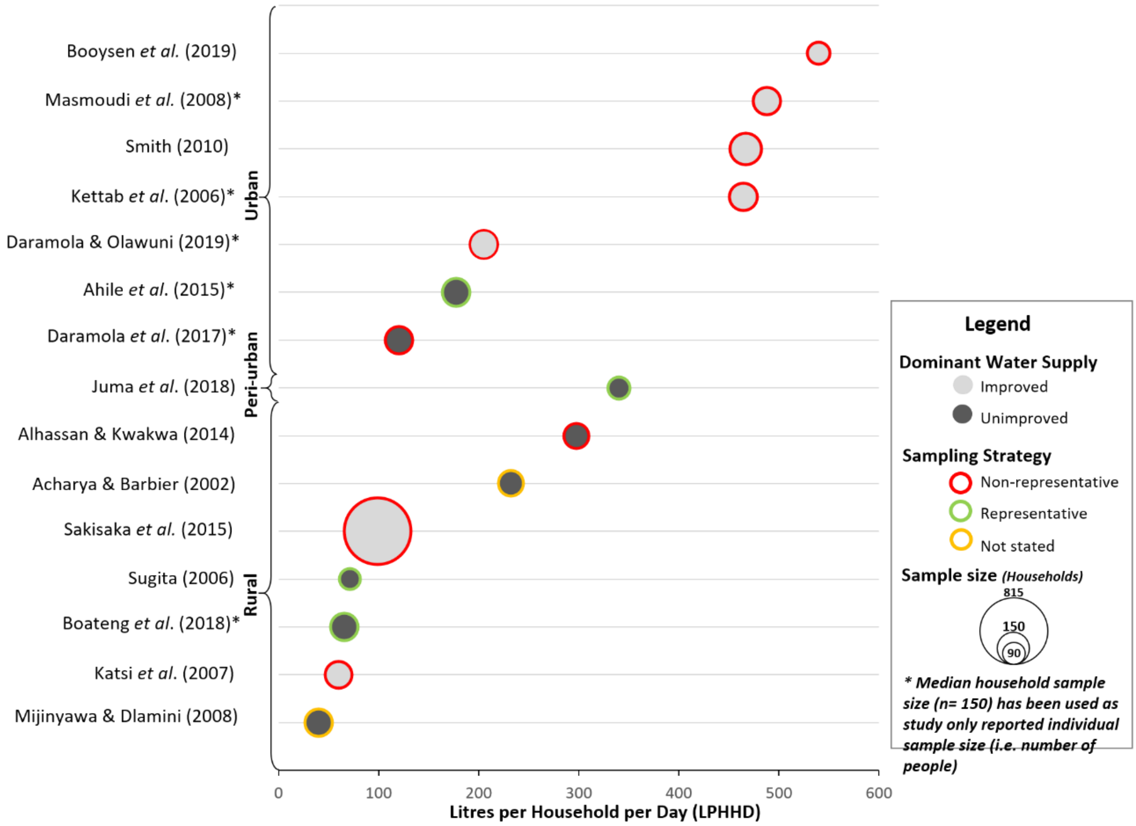


Figure 4-3: Daily per capita drinking water availability based on dominant household supplies relative to the WHO's benchmark of 50 to 100 LPCD

Figure 4-4 shows that of the studies which had urban study sites and improved water supplies, 80% had over 400 LPHHD. In contrast, Juma *et al.* (2018) reported having higher LPHHD in a peri-urban study site than the three highest rural areas, with 340 LPHHD. Booysen (2019) reported the highest amount with households in South Africa having 540 litres a day. Despite being an urban study site and the dominant supply being improved, Daramola and Olawuni (2019) report considerably less available water at 205 LPHHD in Nigeria.



<u>Figure 4-4:</u> Daily household drinking water availability, based on dominant household supplies

All rural studies reported having average water availability per household as less than 300 litres per day. Mijinyawa and Dlamini (2008) report the lowest at 40 LPHHD, with an average household size of eleven people, thus suggesting that per capita water availability is likely to be significantly lower than the WHO benchmark. Only three studies (Katsi *et al*. 2007)(Hall *et al*. 2014)(Sakisaka *et al*. 2015) reported improved water supply use in rural areas. In all three, average drinking water availability was less than 100 LPHHD.

4.3.2.2. Measure Two: Hours of Supply

Three studies, (Oumar and Tewari 2010; Rugemalila and Gibbs 2015; Adams and Smiley 2018), reported hours of supply within a given time period. A further two studies (Gulyani et al. 2005; Aderibigbe et al. 2008), reported hours of supply as a secondary availability measure.

Intermittency in drinking water supply ranged from a supply being unavailable for less than two hours a day, to disruptions lasting a whole day or more. Oumar and Tewari (2010) note that 64% of households had water available for only two hours a day, whereas Adams and Smiley (2018) reported that 77% of their study sample lacked a continuous supply. More often than not, discontinuous supplies were piped water connections or public standpipes. For example, Gulyani *et al.'s* (2005) respondents report that '36% of the households with private connections, […] and 47% of those with yard taps had water available for less than 8 hours per day.' (Gulyani *et al*. 2005, p. 19).

Common categories used in reference to days of supply a week included once every two weeks, once a week, one to two days, three to six days or the optimum of seven days. Aderibigbe *et al.* (2008) found the majority of their respondents (53%) had a continuously available water supply, whereas Adams and Smiley (Adams and Smiley 2018) reported only 40% of households had water available seven days a week. However, in contrast, Adams and Smiley (2018) reported that between 25% and 30% of their study sample had water available once every two weeks. Rugemalila and Gibbs highlight issues with piped connections, commenting that '…even those who are connected experience inadequate and unreliable water supply: 98% reported not receiving water every day' (2015).

4.3.2.3. Measure Three: Frequency of Breakdowns

Only two studies formally reported supply breakdown frequency (Kulinkina *et al*. 2016),(Machingambi and Manzungu 2003). Metrics used to report the frequency of breakdowns of a water supply were highly varied and primarily involved discursive prose or comment. For example, Machingambi and Manzungu noted the frequency of breakdowns of multiple supply types '12.1% of boreholes broke down very often, as did 6% of canals and taps; 5% of deep wells broke down an average amount, as did 3% of dams' (2003, p. 1045). In contrast, Kulinkina *et al.'s* reporting of breakdowns involved discussion of their respondents experiences, for instance, a respondent using a piped water supply remarked that '…sometimes water does not flow from the system for up to three days, even though there is no power outage and residents are not given a reason' (2016, p. 297).

4.3.3. Modelling Drinking Water Availability

An initial multiple linear regression model (*n* = 34) (see appendix A.8) was run and standard regression assumptions were checked. One outlier (Smith 2010) was identified and subsequently removed from the dataset, before both the exploratory bivariate models and final multiple linear regression model were re-estimated.

Exploratory bivariate regressions (see appendix A.9) identified significant relationships between LPCD with urban study location ($F(1,31) = 8.53$, $p = 0.0065$) and water scarcity ($F(1,31) = 4.64$, $p = 0.039$). The model containing urban location explained more of the variance in LPCD ($R^2 = 0.22$, adj.$R^2 = 0.19$), than the model with water scarcity ($R^2 = 0.13$, adj.$R^2 = 0.10$). Water scarcity was inversely related to LPCD in this model.

Table 4-5: Multiple linear regression model of reported litres/capita/day (LPCD) from dominant household supplies across Africa, based on a subset of studies published between 2000 and 2019.

Final Model	
GDP (per capita) (USD)/1000	0.055 (0.68)
Water Scarcity	0.766 (1.47)
Urban study	−6.158 (7.58)
Intervention study	0.526 (5.50)
Piped water connection (in yard/house)	9.399 (6.14)
Urban *GDP (per capita)	4.461 (1.25)**
Constant	17.865 (6.15)*
Observations (n)	33
R-squared	0.614

Note: estimated standard errors in brackets. * significant at 5% ** significant at 1%.

Results from the final multiple linear regression model (Table 4-5) show that the independent variables explained 61.4% of the variance in LPCD ($R^2 = 0.61$, adj.$R^2 = 0.53$). Of the five explanatory variables, only two (GDP per capita (PPP) and rurality) were significantly related to LPCD when controlling for all other independent variables, $p < 0.05$. This, however, only holds in urban locations, where a USD1000 increase in GDP per capita (PPP) increased water availability by 4.52 LPCD ($p = 0.001$). In rural localities, a relationship was not found between GDP per capita (PPP) and LPCD. Evidence of a relationship between LPCD and piped supplies was present, however this was not significant ($p = 0.138$). Water scarcity ($p = 0.608$) and an intervention study design ($p = 0.924$) were also insignificant predictors of LPCD.

4.3.4. Causes of Poor Water Availability

Several key causes were reported across all studies. The most frequently referenced cause, by 35% of studies, was seasonal variation in water availability. The result of which includes periods of increased water supply as well as periods of significantly reduced availability. For example, Adams and Smiley (2018) and Alhassan and Kwakwa (2014) had reports of water tables being too low for boreholes and wells to run, as well as dams drying up, whereas, Sugita (2006) noted that when water levels are too high then people cannot reach their chosen water source. Poor water quality as a result of industrial practices or farming were also noted by 6% of studies, for example Katsi *et al.* (2007) reported instances of rivers being contaminated by upstream gold panning which resulted in significantly high levels of sediment and water that was not usable.

Poorly functioning systems were all too common, with causes such as leakages within the system (2% of studies), old, poor quality or broken infrastructure (24%), insufficient pressure (2%), overuse, carelessness and vandalism of supplies (2%), power outages (6%) all being reported. The reasons for these issues of functionality were cited as being a result of loose components and missing parts (Katsi *et al*. 2007) and wear and tear and rusting systems (Machingambi and Manzungu 2003). Insufficient resources for the number of users often affected availability, with long queues resulting in slow water flows (4%) and a failure of authorities to expand piped networks in order to keep up with population growth (6%).

Inadequate means to run the supply systems such as absenteeism of water engine operators due to illness (2%), a lack of purification chemicals (4%) and no fuel to run pumps (4%), were also common. Issues with governing bodies or higher powers were also frequently mentioned. For instance, 6% of studies referred to a lack of governance and management of systems and corruption and political instability, 2% reported water vendors limiting access, unreliable pricing structures was cited by 4% of studies and 8% mentioned governing bodies rationed supply. The latter was stated to result in unpredictable water supplies (Aderibigbe *et al*. 2008) that in some instances occurred for three days a week (Crow and Odaba 2010). In addition, underfunding, mismanagement of donors and privileging of party strongholds were also commonly referenced (Smiley 2016), as well as the diversion of water to higher income areas (Crow and Odaba 2010).

4.3.5. Coping Strategies Adopted

In 46% (n = 22) of included studies households reported the coping strategies adopted to deal with unavailable and interrupted services. The most frequently adopted coping strategy, as reported by

30% of studies, included using surface water, rain water or other unimproved water supplies which in some instances is shared with animals (Kanda *et al*. 2017). 19% used an alternative improved water source. While rain and dew water collection tended to be the most common resource used, Mijinyawa and Dlamini (2008) reported that the collection of dew and rain in pots is not always an option because of low levels of rain and thatched roofs. Water was often stored for use when household's main supply was unavailable (15% of studies), storage vessels ranged from plastic buckets and jerry cans to more formal installations of private tanks. In one instance, prolonged issues of poorly functioning piped connections lead a community in urban Nigeria to construct motorised boreholes with a 500,000m^3 overhead tank which was designed to easily distribute water to various houses (Aderibigbe *et al*. 2008).

The reuse of water was reported by 4% of studies, for example dirty water from washing was given to livestock for drinking (Mijinyawa and Dlamini 2008), whereas 13% mentioned that households often changed their patterns of consumption and stopped 'non-essential' activities such as bathing and laundry (Ngwenya and Kgathi 2006). The latter was attributed to living in compromised conditions (Mijinyawa and Dlamini 2008). Additional coping strategies included walking longer distances to get water (Ahile *et al*. 2015), making illegal connections to piped networks (Rugemalila and Gibbs 2015) and households asking neighbours if they could use their water source.

4.4. Discussion

In almost all the studies included in this review, the WHO international benchmark for the amount of water available to households was not met. Except for Smith (2010), Vogel *et al*. (2015), Habi *et al.* (2016) and Kettab *et al*. (2006), the mean reported water availability was less than 50 LPCD (Figure 4-3). This pattern emulates findings reported by the International Benchmarking Network (IBNET) for Water and Sanitation Utilities. Figures from water providers and utilities across Africa show that water availability in five out of thirteen countries, and 81 of 173 municipalities falls below the WHO benchmark (van den Berg and Danilenko 2017). While this offers a more optimistic picture than findings from this review, it is evident that a significant proportion of urban water supply systems provide less than 50 LPCD. Nevertheless, Tamason *et al.* (2016) provide further systematic evidence, including the rural perspective, to suggest the 50–100 LPCD benchmark is rarely being met. Settings that are reliant on non-piped water and in rural localities remain under-studied. However, in examining water availability in rural versus urban locations, our review responds to calls (Majuru *et al*. 2016) for research which includes the rural perspective.

Results suggest lower domestic water availability in rural than urban areas, thus supporting known rural-urban differences in access to improved sources and water safety (Bain, Wright, *et al*. 2014). We also find, however, that this disparity between localities in the quantity of water available is not as significant as one could arguably expect. This suggests that while developing improved supplies in rural areas and rapidly developing peri-urban areas is critical, urban areas also require a focus to ensure water is available continuously. This is especially the case considering that classifications of rural, peri-urban and urban areas over-simplify a complex continuum (Schäfer *et al*. 2007). Having said this, it is clear that an inability to maintain existing piped supplies is a fundamental cause of interruptions and limits the amount of water available to households. Therefore, in support of Rugemalila and Gibbs (2015), ensuring upkeep of improved supplies is at the forefront of government agendas is also key.

Our quantitative analysis further explores the relationship between rurality and water availability, by finding that GDP per capita (PPP) significantly increases reported LPCD in urban areas only (Table 4-5). This provides evidence to suggest that greater levels of development increase the availability of drinking water in these urban locations. Conversely, this relationship was not present in rural areas where economic investments differ based on their scale, demand, institutions and finance (Hope *et al*. 2020). Improvements to rural water supplies often encounter different challenges, with the ability to improve supplies through installing a piped network affected by both the physical artefact and the associated institutional construct [*ibid.*]. Although evidence is supplied to suggest that having a piped supply can increase availability, it is not conclusive. Thus, ensuring that economic development, especially the development of piped supplies, in rural areas is possible, is crucial in improving water availability. It must however be undertaken inclusively with the involvement of communities and local management systems, as well as wider governance systems, to ensure that supplies are maintained and do not result in further unreliable and intermittent systems (Whaley and Cleaver 2017).

Overall, the literature from this review provides an understanding of water supply interruptions and availability that previously has been lacking. In providing evidence from a range of countries and localities across Africa, it is evident that despite improved water sources being the dominant supply type, and piped supplies in particular having a significant impact on the quantities of water available, they seldom provide the quantities required to maintain a good standard of living, with some evidence that supply is not continuous. The development of community and individual coping strategies is evident with methods such as building alternative supplies (Aderibigbe *et al*. 2008), collecting rainwater (Nnaji *et al*. 2018), adapting patterns of consumption (Smiley 2016) and storing water (Ngwenya and Kgathi 2006) being utilised. Evidence is provided to suggest that the prevalence of interruptions in a water supply is not dependent on whether the supply is improved or unimproved, rather that each supply type is prone to discontinuities. This review also shows that households across Africa continue to rely on unimproved water supplies, which by nature deliver poor quality water and subsequently compromise health (Ercumen *et al*. 2014). This is especially worrying given the evidence provided that the use of unimproved supplies, which are often shared with animals, is a key coping strategy of households (Garriga *et al*. 2015).

Most included studies reported on the quantities of water available (LPCD), but few reported on the hours of supply or frequency of breakdowns. The JMP has recently published a core and expanded set of questions for household surveys that reflect the Human Right to Water (WHO and UNICEF 2018a). The core question set, which is being incorporated into household surveys, includes a subjective assessment by the household on whether they had enough water in the last week. It is a binary variable, which does not discriminate between differing degrees of unavailability, nor does it detail specifics such as whether households are using stored water or water from multiple sources to meet their needs. It also sets a benchmark that allows for water services that are not continuously available to households. Nearly one billion people globally do not have water that is continuously available (Kumpel and Butler 2018), therefore, deciphering the degree to which water is available is important. In order to address this issue, household surveys may wish to consider a stricter definition of availability or additional questions that cover other types of unavailability, to gain a more granular understanding of the challenges facing households.

Several excluded studies (e.g., Tsai *et al*. (2016) and Adank *et al*. (2018)) quantified availability using methods such as sustainability frameworks and the Household Water Insecurity Access Scale (HWIAS). The latter involves the use of household containers and measuring tools such as jerry cans and plastic bottles of standard volumes. Similarly, the Household Water Insecurity Experience (HWISE) scale was specifically designed to produce comparable measures of availability, especially across disparate cultural, ecological and environmental settings (Young, Boateng, *et al*. 2019). The capacity to consider environmental elements is especially important given it allows for local water scarcity to be considered. Household reports from the included studies support this in showing that seasonal and climatic variations are perceived as a key cause of intermittent and unavailable supplies. And whilst our statistical analysis suggests environmental factors such as water scarcity are not associated with reduced LPCD, this is unexpected and likely a result of our analysis being reliant on a small sample size, with many studies using unrepresentative data. This lack of a relationship also supports our argument that current methods being used to quantify availability are insufficient, given that they do not account for local factors such as water stress. Arguably, both these methods, the HWIAS and HWISE scale, could provide supplementary information within household surveys to distinguish whether a source is available as per the JMP's core question. Although few studies in this review reported on breakdowns and supply interruptions in Africa, it is encouraging that they feature in the JMPs expanded question set and this may support uptake in future national household surveys and research.

It is evident from the literature reviewed that there is a current reliance on using LPCD/LPHHD as the main method of measuring water availability, supporting Tamason *et al.'s* (2016) call for it to be a dominant method. For households however, when asked as part of a survey to quantify their daily water availability, using LPCD/LPHHD is not the most intuitive method. As this review finds, the use of technologies such as water meters to measure water availability is evident and wider use could address the problem of recalling the availability of water, though they must be used tentatively given the nature of intermittent supplies (Richards *et al*. 2010). While water meters provide an objective measure of water consumption (Tamason *et al*. 2016), they have typically been deployed on piped water supplies, which, as shown, are not widely available to all populations (Thomson et al. 2012; WHO and UNICEF 2017b). In the context of Africa and other developing regions, complicating factors, such as household use of multiple supply types for multiple uses (Elliott *et al*. 2019), make the comprehensive quantification of water consumption even more challenging. Alternative approaches, such as the HWIAS and HWISE, could therefore offer resolutions to this issue.

As shown in this review, the realities of water use are complex. A range of different supply methods are relied upon by different populations, perceptions of the causes are multifaceted, and households respond through a range of coping strategies. Given this, the difficulties and complexities of measuring availability further reflect the inadequacies of using measures such as LPCD/LPHHD, which are not necessarily intuitive to household respondents, despite suggestions (Tamason *et al*. 2016) that it should be the 'end goal' for measuring water availability. As such, using methods such as water meters is of particular interest in quantifying poor water availability through robust measurement. As Tamason *et al.* (2016) note, developing methods that can cross-validate water use values are critical in ensuring precise measurements.

4.4.1. Methodological Problems Affecting Included Studies and Review Findings

The overall representativeness of this assessment of drinking water availability is largely hindered by the inherent methodological issues evident in the included studies. These in part are due to the diversity of methods used.

The majority failed to report household sizes or missing data, further complicating the representativeness of this study's findings. This is especially evident in the similarities of the quantity of water available in rural and urban locations; a relationship which we would have expected to have differed greatly (Bain, Wright, *et al*. 2014). Several instances of arithmetic error were identified when reviewing studies; thus, the correctness of some reported results must be considered. Despite random sampling strategies stated as being used, many studies either did not report their sampling strategy or used unrepresentative and non-random sampling approaches, potentially introducing selection bias (Schouten *et al*. 2009). Selection bias could have resulted from studies targeting areas of high-water stress, undermining their representativeness.

The failure of most included studies to report any measures of uncertainty concerning their estimates of water availability prevented any meta-analysis from being undertaken. Without such measures of uncertainty, heterogeneity in study findings could only be explored graphically, by visualising study characteristics such as sample size and sampling strategy.

The regression performed used all the data that was possible, with one outlier study removed as it was a highly influential point. The results must be interpreted based on the data that is used: many of the figures are taken from unrepresentative small-scale studies. There does not appear to be a systematic bias of representative studies being more likely in urban or rural areas, but the estimates may be influenced by small scale, unrepresentative studies.

Measuring water availability is complex. In the African context, and that of most lower income countries, it is routine to use multiple sources in order to build resilience to water shortages (Elliott *et al*. 2019). The exact wording of questions and responses used by included studies to ask households about water availability was very seldom available in published reports, nor were recall periods reported. It is therefore unknown what essential information was collected alongside details of drinking water availability, for example, the coverage of storage tanks and the nature of alternative supplies. Nearly half of included studies did not document the identity of the respondent. For those that did, this was often the household head (with the definition of this undefined), rather than the household member responsible for water collection and management, increasing the risk of recall bias.

Furthermore, it is difficult to know whether the quantities of water reported consider household use of multiple water sources. Few studies explicitly asked about the use of secondary sources, nor was it clear whether reported amounts of water consumed represented only one dominant supply. If the reported amount of water available does only represent one dominant supply, then the apparently low pattern of household water availability in our review could have been because of under-estimation and failure to account for multiple source use in many of the included studies.

A total of 87% of the studies (Table 4-4) were cross-sectional studies, which explored water usage and availability over a short period of time, from one day to two weeks. They did not consider the role of longer-term causes of intermittent water supplies, such as seasonality. The three longitudinal studies included in the review focus solely on a specific water supply intervention and its effect on availability. Given the nature of the included studies, we were thus unable to assess seasonality of intermittent supplies.

At review level, there is evidence of an anglophone bias in part, as a result of search terms being predominantly in English. This is despite studies reporting in English, French and Portuguese falling within the review's scope. The culture of publication and differences by language and location are likely to have further affected this. Other than the three studies from Algeria, the included studies were written in English, and most were conducted in Anglophone countries (Figure 4-2). Likewise, no data was available for fragile states, such as the Democratic Republic of Congo or Sudan, likely to suffer poor water availability because of impaired service delivery. Finally, by limiting the review's scope to only peer reviewed articles, potentially relevant grey literature has not been included.

4.4.2. Future Research

The JMPs core and expanded question set concerning water availability for international monitoring, is necessarily restricted in scope by the logistical and financial constraints of conducting national household surveys. Therefore, smaller scale studies of water availability will continue to be valuable going forward. This would enable related concepts, such as water demand and its implications for water availability, to be considered in conjunction. When reporting findings from such studies, we recommend reporting of measures of uncertainty around means and/or reporting of standard deviations alongside means. Doing so would make it possible for future reviews to conduct meta-analysis.

For quantitative studies, reporting on sampling strategies and missing data, as well as using representative sampling strategies, would significantly improve the usefulness of findings in informing policy. Alongside recall periods and the identity of household respondents (as per Tamason *et al.'s* (2016) systematic review), it is unclear whether the current literature captures multiple source use through probing about secondary sources. All of these aspects need to be reported and advocated as common practice in water sector research. Research could also be undertaken to examine the sensitivity of current reported water availability to such study design aspects.

This review found that a specific subset of studies used water meters as their main method of measuring water availability. These studies were conducted in wealthier urban areas of richer nations, where piped water supplies are more prevalent (Bain, Cronk, Wright, *et al*. 2014). There is, therefore, the need for water meters as a methodology to be used in a range of settings. It would also be appropriate to adopt the use of methods such as the HWISE (Young, Collins, *et al*. 2019) and HWIAS (Tsai *et al*. 2016), where resources allow (such as in research studies), in order to provide more rigorous and nuanced estimates of availability.

Additionally, smaller scale, more detailed studies over a longer time period, using complex and/or multiple methods of measuring water availability (e.g., novel water meters; diaries; complicated multiple question methods like HWISE/HWIAS), alongside simple single questions that the JMP can reasonably include in their core/expanded question sets, could offer a valuable insight into the limitations of a single survey question as recommended by the JMP for the SDGs. This builds on Tamason *et al.* (2016) through the need to cross-validate simple questions against more comprehensive and thorough methods. In undertaking more detailed studies, the full depth of the water experience and its different dimensions within a household or with a user, such as variations between weekdays and weekends, can also be captured. Finally, informal settlements and fragile states, which could have very specific water usage patterns, appear under-studied and therefore should be priorities for future study.

4.5. Conclusions

Despite the MDG target concerning safe drinking water being met in 2015, evidence from 43 studies suggests insufficient drinking water remains a substantial issue across Africa. Almost all studies reported average water availability below the benchmark of 50–100 LPCD. Water insufficiency was more severe in studies of rural localities than in urban settings. These findings are broadly consistent with utility-provided figures and earlier related systematic review evidence (Tamason *et al*. 2016). Causes of insufficient supplies are clearly complex, with environmental pressures and ever-changing climatic variations intertwining with societal, institutional and governmental challenges and pressures. Studies show that households and communities have adapted to the challenges of unreliable and insufficient supplies through a range of coping strategies. This review also responds to calls for research that is nuanced and provides a regional exploration of drinking water availability.

There is considerable diversity in study methods, primarily a reliance on household surveys with small sample sizes and a lack of detail in reporting, limiting the ability to draw quantitative patterns and undertake substantive meta-analysis. It is recommended that future studies report methods of measurement in order that variation in availability can be examined through systematic review. The findings of this review point to a significant gap in the evidence base concerning water availability, thus, there is an ongoing need for rigorous studies to understand how best to measure water availability. This is particularly the case given challenges such as widespread household use of multiple water sources.

Chapter 5

A Multi-Country Comparison of Household, Community and Environmental Factors Associated with Household Drinking Water Availability in sub-Saharan Africa

5.1. Introduction

Across sub-Saharan Africa (SSA) almost two fifths of the population do not have a drinking water source that is available when they require it (WHO *et al*. 2020d). Instead, they are faced with inadequate sources that are characterised by periodic or unpredictable interruptions, longstanding infrastructural breakages, rationing of supplies and insufficient quantities of water (Thomas *et al*. 2020). Natural freshwater scarcity and human induced pressures all serve to cause interrupted and unavailable supplies, painting a multifaceted and complex web of interrelated causes.

The sixth Sustainable Development Goal (SDG) states that by 2030 water and sanitation should be available and safely managed for everyone (UN Water 2018). SDG indicator 6.1.1 measures progress towards target 6.1., which outlines that by 2030 universal and equitable access to safe and affordable drinking water should be achieved for all. This indicator measures the proportion of the population using *safely managed* drinking water sources, where safely managed water sources are defined as those that are on premises, free from faecal and priority chemical contamination and available when needed (WHO and UNICEF 2018a). Water sources that are available when needed include those that are reliable and provide *water most of the time* or *sufficiently,* i.e. for at least 12 hours per day or four days per week (WHO and UNICEF 2021), thus meeting the needs of users by being free from interruptions, water shortages and outages.

Uneven distribution and variability of freshwater availability across time and space means households do not have the water required for their needs (Giupponi and Gain 2016). This will likely increase with annual renewable water resources predicted to have the greatest rate of decline in SSA, at up to 75% between 2015 and 2050 (Baggio *et al*. 2021). Pressures on water resources are further exacerbated by contextual and social factors, including population growth and urbanisation (Chitonge 2020). It is expected that domestic water demand in SSA will increase by 300% over the period 2010-2050 as a result of water services expanding in urban areas (Boretti and Rosa 2019). Growing water use demands are also magnified by the WEF nexus, which considers the benefits, trade-offs and synergies across sectors and play a key part in increasing water scarcity (Albrecht *et al*. 2018). In some regions, agricultural water use has exacerbated water scarcity, competing with municipal supply systems for scant water resources (Siebert et al. 2010; Hamidov and Helming 2020). The WEF nexus also creates competing demands for electricity, leading to power outages and water supply interruptions as pumps and treatment works cannot function (Galaitsi et al. 2016; Simukonda et al. 2018a). As such, full-pressure supplies that run 24 hours, 7 days a week remain unattainable for many, with widespread inequalities across socio-economic groups, geographical areas and between individuals (WHO and UNICEF 2019b).

Water scarcity has been cited as a key contributor to interrupted and unavailable household water sources (Klingel 2012). Induced by a physical lack of natural freshwater, land use, environmental and climatic changes have all been found to aggravate water scarcity (He *et al*. 2021). By 2025 it is expected that 230 million people in Africa will be living under water scarce conditions (African Development Bank *et al*. 2000), defined as a situation where long-term average demand for water cannot be satisfied fully due to insufficient availability of freshwater resources (Liu *et al*. 2017). 58% of children in SSA live in areas with high or extremely high water vulnerability meaning they experience the highest level of water scarcity risk and use sub-optimal drinking water sources (UNICEF 2021a, 2021b). In addition to water scarcity, water stress, a broader concept, refers to the ability to meet human and ecological water demands. An outcome of water scarcity, water stress includes water quality, accessibility of water and environmental flows (Schulte 2017). Across Africa, of particular concern are Botswana and Eritrea which currently experience extremely high water stress, Niger, Nigeria and Burkina Faso which are under high water stress and countries such as Sudan, South Africa, Lesotho and Mauritania which have medium-high water stress (World Resources Institute 2019b).

Variations in the effects of water scarcity on the availability of household sources exist based on the origin of the drinking water source (MacDonald *et al*. 2011). Freshwater either originates from groundwater stores, such as underground aquifers, or surface water stores like reservoirs and dams. At surface water stores the outcomes of climate change and water scarcity are more immediate than at groundwater stores, which are more resilient and better at maintaining water supplies during periods of little to no rainfall (Hope *et al*. 2012). Reduced water supplies in surface stores can lead to piped water rationing and periodic scheduled interruptions (Stoler et al. 2013; Galaitsi et al. 2016). Whilst evidence suggests boreholes perform well under drought conditions (MacAllister *et al*. 2020), under extreme circumstances when water levels reduce these groundwater fed supplies fail to recharge as they are over-exploited through abstraction (Calow *et al*. 1997). Groundwater depletion directly reduces the quantity of water available to households, whilst indirectly, increased pumping accelerates breakages of borehole infrastructure, especially in older neighbourhoods, thus exacerbating source outages (Fisher et al. 2015; Kelly et al. 2018).

In all cases, when a drinking water source is not available, households are often forced to use alternative sources, which themselves may be impacted by conditions of water scarcity. For example, rainfed water storage tanks may not be replenished under drought conditions, though there is some debate about the impact of climate change on rainwater harvesting (Campisano et al. 2013; Musayev et al. 2018). Where households do not have contingency water supplies, they may make illegal connections to piped networks which subsequently reduce the water pressure in the system, affecting users connected further down the network (González-Gómez *et al*. 2011). These additional stresses, on an often already fragile system, can lead to significant periods where households are served with supplies that are not available when needed.

Thinking beyond water scarcity as being solely a physical lack of water, Chitonge (2020) argues for a more disaggregated approach that specifically considers social and human induced water scarcity. An additional three orders of water scarcity are outlined in the form of: (a) economic water scarcity, (b) water scarcity arising from specific social, economic, and political arrangements and (c) institutions, relational barriers and social relations between different groups of people that cause water scarcity. Given the close association between water scarcity and drinking water source availability (Klingel 2012), these three additional orders of water scarcity are reflective of community factors associated with interruptions to drinking water sources. Broadly speaking, they account for demographic and economic dynamics and the resultant water demands that rapid urbanisation and population growth are creating (Simukonda *et al*. 2018a). 41% of SSA's population is currently urban (Zhongming *et al*. 2020); over the next 30 years it is expected that a further 950 million people will move to urban areas, whilst the continent's population will double to 2.5 billion (OECD 2021). With urbanisation comes water supplies that are unable to meet demands and water service providers whose capacity is outstripped (Chitonge 2020). Managing scarcer and less reliable water resources efficiently is therefore even more critical (UNESCO *et al*. 2016).

Economic water scarcity and causes of unavailable supplies occur when there is a lack of investment in the water sector (Mehta 2014). This can result in interrupted water sources with prolonged outages where households have insufficient or next to no water. Infrastructure is not maintained and ages, shortages of skilled personnel at water plants exist, as well as inadequate system management and operations, all impacting upon supply continuity (Fisher et al. 2015; Simukonda et al. 2018a). Immediate causes of supply disruption include insufficient water production to meet demand, excessive leakage, and breakages to infrastructure such as pumps and taps (Simukonda *et al*. 2018b). Evidence suggests a lack of investment means water infrastructure is not expanded to keep up with population and urbanisation pressures, resulting in over stretched networks with decreased water pressure and subsequent interruptions (Garrick *et al*. 2020). Often countries with more economic resources and institutional capacity are able to navigate water scarcity better than those with fewer resources, even if the latter have more natural water available. For example, South Africa has less than 50% the amount of freshwater available than Zambia, however drinking water is available for a significantly larger proportion of the population as South Africa has greater economic means to invest in infrastructure (Chitonge 2020).

Thinking beyond the existence of water 'hardware' (infrastructure), water scarcity and the effect on source availability can also be caused when the social means, also referred to as the 'software', required to manage the original physical lack of water are not present (Chitonge 2020). For instance, in rural Ghana tariff collection has been found to correlate with the functionality of boreholes constructed by water providers (Fisher *et al*. 2015). Mdee (2017) highlights how this angle of water scarcity concerns institutional dimensions and barriers resulting from arrangements surrounding the allocation and provision of water services and resources. For example, in low income urban areas and informal settlements water services are often seen as a low political priority compared to those in wealthier areas where breakages and supply issues are dealt with more quickly (Chitonge 2014). Similar to the disparities experienced in informal settlements, supply availability also varies between urban and rural areas with recent JMP estimates showing urban areas fair best (WHO and UNICEF 2021). Rural areas lack expertise and parts required if infrastructure breaks and are reliant on local water committees for system operations and maintenance which can vary in their successes (Kelly *et al*. 2018).

The availability of drinking water sources is also affected by relational and social barriers between groups due to ethnicity, class, nationality, disability, gender, age, religious affiliation, or political stance. Chitonge (2020) outline these barriers as the fourth order of water scarcity. Whilst these factors operate at a micro-level and can often be very subtle, they can have a huge impact at the household level. For instance, gender effects physical access to water resources, having control over the requirements needed to meet water needs and ability to exercise agency (e.g. to participate in decision-making, including intra-household decision making, public participation and freedom of movement) (Caruso *et al*. 2021). Accessibility plays a key role in the amount of water available to households and the ability to meet needs (Cassivi *et al*. 2019). Minority groups that are discriminated and prejudiced against may not be able to access water supplies, particularly in areas where there are competing demands from different population groups (Chitonge 2020). As such, minority groups and other vulnerable populations are often excluded, marginalised further and are voiceless meaning complaints about interrupted supplies often go unheard (Mehta 2014; Geere and Cortobius 2017).

Specific compositional factors within households also serve to affect supply availability. Home ownership for instance determines the capacity to deal with supply interruptions within the house, as well as the ability to install contingency plans such as water tanks (Staddon *et al*. 2018). Drinking

Water provisions are also a hallmark of housing quality, with households in poorer quality housing reliant on poorer quality water sources prone to supply issues (Bradley and Putnick 2012). Larger households will have greater water demands and consumption levels putting pressure on drinking water that is available (Dungumaro 2007; Arouna and Dabbert 2010). Household size may also correlate with reliance on subsistence farming or cottage industries that put additional pressures on water demands (Adeoye and Bhadmus 2016; Siphesihle and Lelethu 2020). Intertwined with all these factors is household wealth which has been shown to effect the type of supply used in Nigeria, the capacity to fix broken supplies, ability to have contingency sources, mode of transport used to collect water and the likelihood of making illegal connections which worsen the effects of non-revenue water (Bellaubi and Visscher 2014; Zoungrana 2020).

Given the complexities of supply availability and the breadth of associated stressors, effectively managing resources to better achieve international development agendas such as the SDGs is critical yet challenging. With the pressing nature of climate change and its impact on water scarcity and the intertwined socioeconomic issues that are exacerbating variations in drinking water source availability, there is an emerging need to understand experiences at the household level and the factors associated with drinking water source availability across SSA.

Aspects of household drinking water have previously been studied through multi-country analysis using representative household surveys, though emphasis has been on water quality (Poulin et al. 2020; Bain et al. 2021). Comparatively, multi-country analysis which explores drinking water source availability is limited. A recent review which synthesised evidence on African domestic water availability by systematically reviewing the literature from 2000–2019, found only one multi-country analysis (Thomas *et al*. 2020). This study focused on Uganda, Kenya and Tanzania but supply availability was not its primary focus (Tumwine *et al*. 2002). A more recent comparison of drinking water source availability was undertaken in Peru, this also included a global assessment and outcomes specifically for Tanzania and Zimbabwe however the multi-country comparison was a secondary part of analysis and lacked specific detail (Rawas *et al*. 2020). Similarly, a recent multi-country study from Duchanois *et al.* (2019) explored the continuity of water sources, but was not nationally representative and focused solely on rural sources.

Generally speaking, analysis of supply availability is not nationally representative and focuses on either rural or urban areas, not both (Thomas *et al*. 2020), with a pre-eminence of urban-based analyses (e.g. McDonald *et al*. 2011, He *et al*. 2021) and focus on larger cities at the expense of smaller centres. Positively, studies have tended to focus on both groundwater and surface water fed drinking water sources (Tumwine et al. 2002; Hadjer et al. 2005; Cherunya et al. 2015; Boateng et al. 2018), though there has been a focus on availability rather than withdrawal (He *et al*. 2021). Analyses which explore the factors associated with supply interruptions has begun to emerge but does not consider water stress or scarcity. Given the need for evidence which sufficiently accounts for the effects of environmental associations with supply availability and the effects of local water scarcity, and which has a future perspective within, addressing this research gap is of particular relevance.

In this study, a multi-country analysis of the determinants of household reported interruptions to drinking water sources is undertaken. Analysis includes 10 SSA countries totalling 100,202 households from Ethiopia, Gambia, Malawi, Nigeria, Sierra Leone, South Africa, Tanzania, Uganda, Zambia, and Zimbabwe. In doing so, focus is given to the role of water scarcity and water stress, as well as a range of household and community socioeconomic factors, on drinking water availability. We aim to address the research gaps identified by answering the following research questions:

- How do household experiences of interruptions to water services vary between selected countries across SSA?
    - Do variations in service interruptions exist based on water service type (e.g. piped sources versus boreholes)?
- What household and community characteristics are associated with household-reported water service interruptions across selected countries in SSA?
- Are water scarcity and water stress associated with household-reported water service interruptions across selected countries in SSA?
- How much of the variation in household reported availability is explained by household-level factors compared to community-level contextual factors?

5.2. Methods

5.2.1. Study Site Selection

An assessment of the available DHS datasets for all African Union countries was undertaken in order to decide which countries had the correct characteristics to include. It was paramount that the dataset included information on the availability of household water sources which was included from 2013 during the roll out of phase 7 of the DHS and the question '*In the past two weeks, was* *the water from this source not available for at least one full day?'* was included in all surveys (Croft *et al*. 2018). In total, 11 African Union countries had DHS surveys that included details of availability: Ethiopia, Gambia, Liberia, Malawi, Nigeria, Sierra Leone, South Africa, Tanzania, Uganda, Zambia and Zimbabwe.

During initial analysis, closer examination of the DHS data found that in Liberia 95% of households use a borehole/tubewell. Less than 1% (72 households) used a neighbour's piped source, less than 1% (43 households) used a piped source on their premises and less than 3% (154 households) used a public standpipe or tap. There was thus minimal variation in the supplies used by households. Closer examination of the JMP's country file (JMP 2021b) for Liberia found significant variation in piped drinking water estimates depending on the data source. For example, the 2013 DHS reports that nationally 2% of the population use a piped source whilst the 2016 Malaria Indicator Survey reports 9% use a piped source. However, the World Bank's Household Income and Expenditure Survey from 2016 reports 34% of the population use a piped source, whereas the 2015 survey reports 51% use a piped source. Given the discrepancies in reporting on piped supplies we decided the data could be unreliable. In addition to this, Liberia had no indicated variation in water stress over the whole country meaning it could not be included in our modelling and it was not possible to address this analysis' research questions. We therefore decided to exclude Liberia from this analysis.

The final 10 countries included in this analysis are Ethiopia, Gambia, Malawi, Nigeria, Sierra Leone, South Africa, Tanzania, Uganda, Zambia and Zimbabwe.

5.2.2. Study Sites

Located in eastern Africa, Uganda has a 2020 population of 45.7 million, Tanzania 59.7 million and Ethiopia 114.9 million (World Bank 2020b). With the addition of Zambia (population 18.3 million) and Malawi (population 19.1million), there are five countries in the study located in the African Great Lakes region, which is home to over a quarter of the world's unfrozen surface fresh water (Upton *et al*. 2013). GDP per capita (current 2020 US$) (World Bank 2020c) ranges from $625 in Malawi to $1077 in Tanzania and urban population varies from 17% of the total population in Malawi to 45% in Zambia (World Bank 2020d).

Further south is landlocked Zimbabwe and at the southern tip of the continent, South Africa, home to 14.8 million and 59.3 million people respectively. South Africa has a heavily urban population (67%) and despite having the highest GDP per capita (US$5090) (World Bank 2020c) of all 10 countries, disparity is significant with 56% living below the national poverty line (World Bank

2020e). In contrast, 68% of Zimbabwe's population live in rural areas, whilst 16% of the total population live in extreme poverty and a further 63% live in poverty.

Sierra Leone, the Gambia and Nigeria are all located in western Africa on the Atlantic Ocean. Whilst the Gambia and Sierra Leone have comparatively small populations of 2.4 million and 5.1 million, Nigeria accounts for almost half of western Africa's population with 206.1 million people (Bank 2020), of which 43% are under 14 years (World Bank 2020f). Nigeria is also home to the megacity Lagos, the sixth largest city in the world. All four countries have between 43% and 63% living in urban areas. Of the 10 countries, Sierra Leone has the lowest GDP per capita (US$484), whereas Nigeria's is second highest at US$2097.

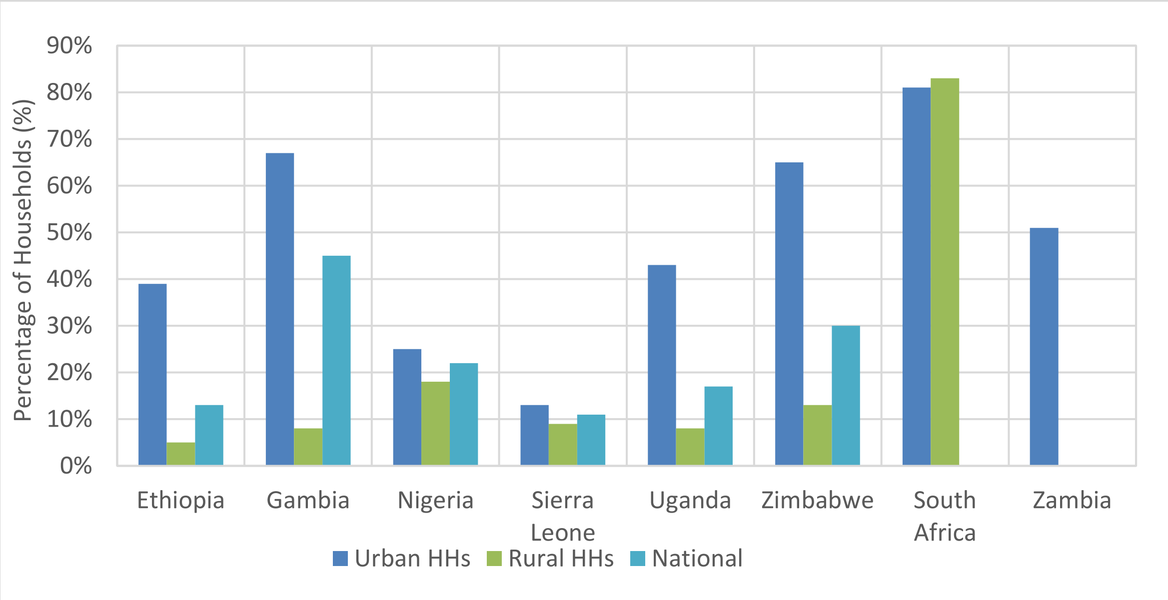
Table 5-1: Coverage of improved drinking water and surface water sources in 2020 for all 10 case-study countries (Source: WHO, UNICEF and JMP, 2020d)

Type of source	Coverage	Ethiopia	Gambia	Malawi	Nigeria	Sierra Leone	South Africa	Tanzania	Uganda	Zambia	Zimbabwe
Improved drinking water source	Urban HHs	99%	68%	97%	95%	92%	100%	95%	92%	90%	98%
	Rural HHs	70%	86%	91%	69%	58%	90%	59%	80%	57%	67%
	National	76%	90%	92%	83%	73%	97%	72%	83%	72%	77%
Surface water	Urban HHs	1%	0%	3%	1%	1%	0%	3%	1%	1%	2%
	Rural HHs	6%	0%	3%	10%	19%	6%	19%	6%	12%	10%
	National	5%	0%	2%	6%	12%	2%	13%	5%	7%	7%

Across all 10 countries, political, social and economic stresses are present and ongoing climate pressures serve to exacerbate these. In particular, late rainy seasons, longer and harsher drier spells and erratic weather patterns are becoming ever more common and are expected to worsen (Masson-Delmotte *et al*. 2021). Extensive impacts to dam and reservoir levels, as well as the capacity to harvest and store water at the household level, are subsequently implicating the availability of clean drinking water (Mason *et al*. 2019). Lake Kariba, on the Zimbabwe-Zambia border, saw water levels decrease by six metres in the three years preceding 2017 (Gibbons 2020), whilst in 2018 Cape Town, South Africa, was faced with 'Day Zero' where high demand was met with inadequate source and municipal water sources almost ran out (Pascale *et al*. 2020).

Drinking water is supplied by a combination of private and public suppliers, with national coverage of improved sources exceeding 72% in all countries (Table 5-1) (JMP 2021b). Variations between rural and urban areas exist, with urban areas faring better in all countries other than Gambia where

86% of rural households have an improved source compared to 68% of urban areas (JMP 2021b). Reliance on surface water, such as rivers, dams, lakes, streams and canals, is evident for between 2% and 10% of the study countries, other than in Gambia.



<u>Figure 5-1:</u> Coverage of safely managed drinking water sources for all study countries where data were available in 2020 (Source: WHO/UNICEF JMP (2021)) *(NB: estimates are not available for Tanzania or Malawi, nor are national estimates for South Africa and Zambia. Zambia also lacks a rural estimate. The JMP only estimates safely managed sources when information is available for at least 50% of the population on quality of drinking water and either accessibility or availability (JMP 2021b))*

Use of safely managed sources, that are available when needed, ranges from as little as 11% nationally in Sierra Leone to 55% in the Gambia (Figure 5-1). For all 10 countries, inequalities between rural and urban areas are clear, with the greatest difference in the Gambia where 67% of urban households have a safely managed source compared to only 8% of rural households. The inverse is observed in South Africa where 83% of rural households and 81% of urban areas have a safely managed source, this could however be due to data issues and the overrepresentation of water quality in municipality data.

5.2.3. Data Sources

5.2.3.1. Demographic and Health Survey Data

Nationally representative data from DHS were used for all 10 study countries. The DHS is a multi-stage cluster household survey (The DHS Program 2020b), which also includes questionnaires of all men aged 15-59 and women aged 15-49 in selected households. Details of the year of each country's DHS and the dates the survey was conducted are available in Table 5-3. In all cases the sampling framework used was based on the most recent national population and housing census. All DHS's followed a stratified two-stage cluster design.

Geospatial data georeferenced to cluster level (The DHS Program 2018) was used. This data includes the mean location of GPS coordinates for all participating households. These are given as the centre of the sampling cluster from which the household was selected. To retain anonymity, GPS coordinates are displaced within 2km for urban areas and within 5km for rural areas (Burgert *et al*. 2013). Sampling clusters were not displaced outside of their administrative district.

Geospatial covariates, made available through the DHS, were also used. These are standardised files which include multiple data sources that have been linked to the DHS datasets using the household cluster GPS coordinates (Mayala *et al*. 2018). The geospatial covariates used in our analysis included information on urban-rural settlements and population density (Table 5-2).

Table 5-2: Additional datasets used from the DHS geospatial covariates

Dataset	*Dataset Source*	*Summary of Dataset*	*Description*
SMOD Population (2015)	Global Human Settlement Layer (GHSL) Settlement Model (SMOD) (Pesaresi and Freire 2016)	This data provides the 'degree of urbanisation' classified as 'urban centres' (cities), 'urban clusters (towns and suburbs), 'rural' and 'unpopulated'.	Urban-rural population classification of the area with within 2km (urban) or 10km (rural) buffer.
Population Count (2015)	WorldPop, University of Southampton (Linard et al. 2012; WorldPop 2021)	This data provides a more up to date population count than census data at a high resolution (100m x 100m).	The count of individuals living within each buffered area.

Table 5-3: **Nationally representative Demographic and Health Surveys (DHS) that included drinking water availability, 2015-2020**

Country (DHS round)	Year of Survey	Dates of Fieldwork	Households Interviewed (response rate)	Men Interviewed (response rate)	Women Interviewed (response rate)	Clusters	Implementing Agencies
Ethiopia[1] (DHS-VII)	2016	18th January – 27th June 2016	16,650 (97.6%)	12,688 (85.8%)	15,683 (94.6%)	645	Federal Ministry of Health, Central Statistical Agency
Gambia[2] (DHS-VIII)	2019-20	21st November 2019 - 30th March 2020	6,549 (97.2%)	4,636 (86.9%)	11,865 (95.1%)	281	The Gambia Bureau of Statistics and The Ministry of Health
Malawi[3] (DHS-VII)	2015-16	19th October 2015 – 17th February 2016	26,361 (99.2%)	7,478 (94.6%)	24,562 (97.7%)	850	National Statistical Office and The Ministry of Health
Nigeria[4] (DHS-VII)	2018	14th August - 29th December 2018	40,427 (99.4%)	13,311 (99.2%)	41,821 (99.3%)	1400	National Population Commission
Sierra Leone[5] (DHS-VII)	2019	15th May – 31st August 2019	13,399 (98.5%)	7,197 (96.9%)	15,574 (96.7%)	578	Statistics Sierra Leone
South Africa[6] (DHS-VII)	2016	27th June – 4th November 2016	11,083 (83.4%)	3,618 (73.1%)	8,514 (86.2%)	750	Statistics South Africa and South African Medical Research Council
Tanzania[7] (DHS-VII)	2015-16	22nd August 2015 – 14th February 2016	12,563 (98.4%)	3,514 (91.9%)	13,266 (97.3%)	608	National Bureau of Statistics and Office of Chief Government Statistician (Zanzibar)
Uganda[8] (DHS-VII)	2016	20th June – 16th December 2016	19,588 (98.2%)	5,336 (94.0%)	18,506 (97.0%)	697	Uganda Bureau of Statistics
Zambia[9] (DHS-VII)	2018	18th July 2018- 24th January 2019	12,831 (99.1%)	12,132 (91.6%)	13,683 (96.4%)	545	Zambia Statistics Agency and The Ministry of Health
Zimbabwe[10] (DHS-VII)	2015	6th July- 20th December 2015	10,534 (98.8%)	8,396 (91.9%)	9,955 (96.2%)	400	Zimbabwe National Statistics Agency

[1](Central Statistical Agency (CS) [Ethiopia] and ICF 2016); **[2]**(Gambia Bureau of Statistics (GBoS) and ICF 2021); **[3]**(National Statistical Office Malawi and ICF 2017); **[4]**(National Population Commission and ICF 2019); **[5]**(Statistics Sierra Leone (StatsSL) and ICF 2020); **[6]**(National Department of Health (NDoH) *et al*. 2019); **[7]**(Ministry of Health Community Development Gender Elderly and Children (MoHCDGEC) [Tanzania Mainland] *et al*. 2016); **[8]**(Uganda Bureau of Statistics and ICF 2018); **[9]**(Zambia Statistics Agency and ICF 2019); **[10]**(Zimbabwe National Statistics Agency (ZIMSTAT) and ICF 2016)

5.2.3.2. Environmental Data Selection

A review of available environmental data was undertaken (Table 5-4) to identify the dataset that would be used in this analysis. The inclusion of 10 key elements were assessed for each dataset, including the specificity of its coverage, temporal scale, and spatial resolution, as well as ease of linking it to the DHS household data. The key limitations of each dataset were also identified. The chosen dataset(s) needed to represent water scarcity/stress and subsequently consider freshwater availability (renewable ground and surface water) and demand (including domestic, agricultural, and industrial). Several options were available including modelled data, direct measurements, and the DHS's preprepared geospatial covariates.

The DHS covariates did not include a dataset solely for water scarcity but had several related datasets that represented core elements of water scarcity. For example, precipitation, drought, temperature and irrigation. Three datasets based on direct measurements of ground and surface water were identified. Two of these use satellites to capture surface and ground water levels (Schwatke et al. 2015; Landerer et al. 2020), whereas the third was a database of historical dams greater than 15m in height or with a reservoir of more than 0.1km (Lehner *et al*. 2011). Of the modelled datasets, two specifically calculated global water scarcity: the Water Footprint Network's (WFN) (Mekonnen and Hoekstra 2011; Hoekstra et al. 2012), blue water scarcity (BWS) dataset (Water Footprint Network 2021) and the Water Resources and Institute's (WRI) (Hofste *et al*. 2019) Aqueduct water stress dataset (World Resources Institute 2019a). Critically both datasets included freshwater availability and demand, were at a high spatial resolution and available in formats that allowed easy linkage to the DHS household survey data.

Table 5-4: Review of available environmental data

Source	Dataset	Components of Water System/Scarcity Included	Year	Easy to link data to DHS HH Clusters?	Specificity of Coverage (General or local level?)	Temporal Scale (Annual or monthly? Is seasonality covered?)	Spatial Resolution of Data (Fine scale e.g. 1kmx1km or greater?)	Meta-data Available?	Data Open Access?	Data Peer-Reviewed?	Is the data well-cited and used? (Citations in Google Scholar & Web of Science)	Datasets Included	Main Limitations for Analysis
Datasets based on Direct Measurements													
NASA Gravity Recovery & Climate Experiment (GRACE)& GRACE-FO (Landerer *et al.*, 2020)	Mascon Ocean, Ice & Hydrology Water Height (Wiese *et al.*, 2019)	GRACE satellite data captures variability in the Earth's gravity field that is induced by changes in total water storage, including surface water storage (canopy, reservoirs, wetlands, lakes, rivers and snow), soil moisture storage and groundwater storage. Data includes monthly global water storage as global water height in centimetres.	2002 - present	Complex- data is available in NetCDF format which is complex to use due to the dimensions of the data	N/A - water use not considered	Monthly	0.5° latitude by 0.5° longitude grid	Yes	Yes	Yes	Widely used (exact citations unknown).	N/A	-Data is available in levels, not volumes of water. -Data would need to be linked to data that considers freshwater demand (including agricultural needs and municipal sectors). - Format of data is complex to link to DHS clusters.
Database for Hydrological Time Series of Inland Waters (DAHITI) (Schwatke *et al.*, 2015)	Water level time series of inland waters (Technical University of Munich, 2015)	Satellite altimetry measures of water levels in lakes, reservoirs, rivers and wetlands. 1187 water level time series are available for Africa.	1992-present	Data is available in ASCII, NetCDF, CSV and JSON format but Python skills are required for download	Local	Varies: 1-2 days after the altimeter satellite crossed the inland water body	N/A	Yes	Yes	Yes	Cited over 300 times.	N/A	-Data is available in levels, not volumes of water. -Data would need to be linked to data that considers freshwater demand (including agricultural needs and municipal sectors). - Data access is complex and requires Python skills.
Global Dam Watch (Lehner *et al.*, 2011)	Global Reservoir and Dam Database (London *et al.*, 2021)	Information on the location and characteristics of dams, reservoirs, and river barriers. Including mapping the location and attribute data of 7,320 dams greater than 15m in height or with a reservoir of more than 0.1km	2000-present	Yes- shapefile available	Regional	N/A	High resolution- data has each dam/ reservoir as a polygon.	Yes	Yes	Yes	Cited over 2000 times.	N/A	-Data includes only static characteristics, it does not include information on water levels. -Incomplete dataset. -Data would need to be linked to data that considers freshwater demand and other sources of fresh water.
Modelled Datasets													
Climate Research Unit (CRU) University of East Anglia (UEA) (Harris et al., 2013)	Climate Variation (V.405) (Harris et al., 2020)	Variations in climate, including the following variables: cloud cover, diurnal temperature range, frost day frequency, potential evapotranspiration (PET), precipitation, daily mean temperature, monthly average daily maximum and minimum temperature, and vapour pressure.	1901-2020	Complex- data is available in NetCDF format which is complex to use due to the dimensions of the data.	N/A - water use not considered	Monthly	0.5° latitude by 0.5° longitude grid	Yes	CEDA account required	Yes	Cited 850 times (excluding citations of earlier versions of data)	N/A	-Data would need to be linked with industrial and consumptive water use, as well as freshwater availability. -Format of data is complex to link to DHS clusters.

Source	Dataset	Components of Water System/Scarcity Included	Year	Easy to link data to DHS HH Clusters?	Specificity of Coverage (General or local level?)	Temporal Scale (Annual or monthly? Is seasonality covered?)	Spatial Resolution of Data (Fine scale e.g. 1kmx1km or greater?)	Meta-data Available?	Data Open Access?	Data Peer-Reviewed?	Is the data well-cited and used? (Citations in Google Scholar & Web of Science)	Datasets Included	Main Limitations for Analysis
University of New Hampshire (UNH) Global Runoff Data Centre (GRDC) (Fekete, Vörösmarty and Grabs, no date)	Freshwater Runoff (Global Runoff Data Centre, 2021)	Precipitation, air temperature, soil type, and landcover are considered to estimate total freshwater availability (mm/year). Modelled data is calibrated using river gauge discharge data.	Undated	Pickering and Davis (2012) link the data to DHS household data.	N/A - water use not considered	Monthly	0.5° by 0.5° grid-based level (approx. 55km x 55km grid cell)	Yes	Yes	Yes	Related paper (Fekete, Vörösmarty and Grabs, 2002) is cited over 600 times	N/A	-Accurate analysis of the recent past is limited by delays in data access. -Monthly discharge regimes are not consistent as the time period of observation varies station by station. -Data needs to be linked to data that considers freshwater demand.
Water Footprint Network (Hoekstra et al., 2012), (Mekonnen and Hoekstra, 2011)	Annual Blue Water Scarcity (Water Footprint Network, 2021)	Fresh water availability including: natural runoff (including upstream) and the environmental flow requirement (80% of available water is needed for water dependent ecosystems thus 20% is available for humans). Fresh water demand including: agricultural needs (livestock and crops) and needs of municipal sectors. The effect of upstream water consumption on downstream areas is considered.	1996-2005 baseline	Yes- raster file available	Local	Annual	30 x 30 arc min	Yes	Yes	Yes	Cited over 4000 times.	UNH Global Runoff Data (Fekete, Vörösmarty and Grabs, no date) is used.	-Data is dated (>15 years). -Data does not account for seasonal variation as it is an annual average. -Annual figure that is not necessarily for the same year as household data
	Blue Water Scarcity (Water Footprint Network, 2021)					Monthly		Yes	Yes	Yes		UNH Global Runoff Data (Fekete, Vörösmarty and Grabs, no date) is used.	-Data is dated (>15 years).
AQUASTAT/ AQUAMAPS (FAO of the United States, no date)	Physical water scarcity(Food and Agricultural Organisation, no date)	Ratio between irrigation water that is consumed by plants through evapotranspiration and renewable freshwater resources (information on climate, soils and irrigated agriculture is included).	Unknown	Yes -shapefile available	General	Unknown	Major hydrological basins (global)	No	Yes	No	Unknown	Unknown	-Needs to be linked with industrial and consumptive water use, as well as freshwater availability. -Date of data is unknown.
WorldClim (Fick and Hijmans, 2017)	Climate Data	Variables include minimum, mean, and maximum temperature, precipitation, solar radiation, wind speed, water vapor pressure, and for total precipitation.	1970-2000	Yes- data is available in GeoTiff format which ArcMap supports	N/A - water use not considered	Monthly	Data is available for four spatial resolutions, between 30 seconds (~1 km) to 10 minutes (~340 km)	Yes	Yes	Yes	Unknown	N/A	-Outdated data (>20 years old). --Data would need to be used in conjunction with other environmental & freshwater demand data.

Source	Dataset	Components of Water System/Scarcity Included	Year	Easy to link data to DHS HH Clusters?	Specificity of Coverage (General or local level?)	Temporal Scale (Annual or monthly? Is seasonality covered?)	Spatial Resolution of Data (Fine scale e.g. 1kmx1km or greater?)	Meta-data Available?	Data Open Access?	Data Peer-Reviewed?	Is the data well-cited and used? (Citations in Google Scholar & Web of Science)	Datasets Included	Main Limitations for Analysis
US Geological Survey (USGS) MODIS (Wan, Hook and Hulley, no date)	Land Surface Temperature	Monthly land surface temperature and emissivity data.	2002-present	Complex to do- data is available in HDF-EOS format	N/A - water use not considered	Monthly	0.05 x 0.05 degrees (6km)	Yes	Yes	Yes	Unknown	N/A	-Data would need to be used in conjunction with other environmental & freshwater demand data.
Huang et al. 2018 (Huang et al., 2018)	Global Water Use	Country-scale estimates of sectoral water withdrawals are included, as is industrial water use including manufacturing, mining & cooling of thermal powerplants. Consumptive water use (domestic water use, outdoor purposes i.e. lawn and garden, and industries and urban agriculture that are connected to municipal sectors) and irrigation and livestock water use are also included, as well as consumptive water use efficiency (proportion of water consumed to that withdrawn).	1971-2010	No - ".nc" file type. Data is different files for each type of water use (domestic, electricity, irrigation, manufacturing, mining).	Sub-national level	Sub-annual (monthly)	0.5 x 0.5 degrees (55km)	Yes	Yes	Yes	Cited 48 times	AQUASTAT country-level sectoral water withdrawal estimates. USGS Global Change Assessment Model data on water withdrawal at state-level.	-Needs to be linked with water resources dataset as this is only water use data. -File type is not easily useable.
Water Resources Institute Aqueduct 3.0 (Hofste et al., 2019)	Water Stress (World Resources Institute, 2019b)	Ratio of water withdrawals (domestic, industrial, irrigation, livestock consumptive and non-consumptive uses) to renewable surface and groundwater supplies (upstream consumptive water users and large dams on downstream water availability).	1960-2014 baseline	Yes- shapefile available	Unknown	Monthly and annual baselines	Hydrological sub-basins (defined as an area that drains at a single point to an ocean or inland lake).	Yes	Yes	Yes	Cited 40 times.	PCRaster Global Water Balance hydrological model (Sutanudjaja et al., 2018) HydroBASINS level 6 hydrological sub-basins (Lehner and Grill, 2013)	-The underlying models that have been used are validated, though the results of Aqueduct are not. -Environmental flow requirements are not explicitly considered.
	Seasonal variability (World Resources Institute, 2019b)	Average within year variability of available water source (renewable groundwater and surface water).			N/A - water use not considered	Annual baseline		Yes	Yes	Yes			
DHS Geospatial Covariates (Mayala *et al.*, 2018)													
DHS	Annual Precipitation	Average precipitation within the DHS 2km/10km buffer zone over the last year.	2015	Yes- directly linked by DHS cluster ID	N/A - water use not considered	Annual	0.5 x 0.5 degrees (55km)	Yes	Yes	Yes	Yes	Climate Research Unit (CRU) data v4.01 (University of East Anglia Climatic Research Unit; et al., 2020)	- Data does not account for seasonal variation as it is an annual average.

Source	Dataset	Components of Water System/Scarcity Included	Year	Easy to link data to DHS HH Clusters?	Specificity of Coverage (General or local level?)	Temporal Scale (Annual or monthly? Is seasonality covered?)	Spatial Resolution of Data (Fine scale e.g. 1kmx1km or greater?)	Meta-data Available?	Data Open Access?	Data Peer-Reviewed?	Is the data well-cited and used? (Citations in Google Scholar & Web of Science)	Datasets Included	Main Limitations for Analysis
DHS	Wet Days	The average number of days receiving rainfall within the 2km/10km buffer. A synthetic measure t combines the number of observed days with rainfall from weather stations with the number of days that should have received rainfall.	2015	Yes- directly linked by DHS cluster ID	N/A - water use not considered	Annual	0.5 x 0.5 degrees (approx. 55km x 55km grid cell)	Yes	Yes	Yes	Yes	CRU data v4.01 (University of East Anglia Climatic Research Unit; *et al.*, 2020)	- Annual figure that is not necessarily for the same year as household data. - Missing data for clusters near water bodies. - Data would need to be used in conjunction with other environmental data to account for all elements of water scarcity. - Data would need to also be linked to data that considers freshwater demand (including agricultural needs and municipal sectors).
DHS	Mean Temperature	The average annual temperature within the 2 km (urban) or 10 km (rural) buffer surrounding the DHS survey cluster location. The mean temperature is a modelled surface based on weather station data.	2015	Yes- directly linked by DHS cluster ID	N/A - water use not considered	Annual	0.5 x 0.5 degrees (approx. 55km x 55km grid cell)	Yes	Yes	Yes	Yes	CRU data v4.01 (University of East Anglia Climatic Research Unit; *et al.*, 2020)	
DHS	Diurnal Temperature Range	Annual average daytime temperature (calculated by subtracting the gauging station maximum minimum temperatures) within the DHS 2km/10km buffer zone.	2015	Yes- directly linked by DHS cluster ID	N/A - water use not considered	Annual	0.5 x 0.5 degrees (approx. 55km x 55km grid cell)	Yes	Yes	Yes	Yes	CRU data v4.01 (University of East Anglia Climatic Research Unit; *et al.*, 2020)	Data does not account for seasonal variation as it is an annual average. - Annual figure that is not necessarily for the same year as household data. - Missing data for clusters near water bodies. - Data would need to be used in conjunction with other environmental data to account for all elements of water scarcity. - Data would need to also be linked to data that considers freshwater demand (including agricultural needs and municipal sectors).
DHS	Land Surface Temperature	Temperature of the land surface in degrees Celsius as detected by satellites (it is not the same as near-surface air temperature which ground stations measure) within the DHS 2km/10km buffer zone.	2015	Yes- directly linked by DHS cluster ID	N/A - water use not considered	Annual	0.05 x 0.05 degrees (6km)	Yes	Yes	Yes	Yes	USGS MYD11C3 MODIS data v.6 (Wan, Hook and Hulley, no date)	
DHS	Potential Evapotranspiration	Average annual potential evapotranspiration which uses the calculated mean, maximum & minimum temperature, vapor pressure and cloud cover surfaces. It is a synthetic measure which shows the millimetres of water that would be evaporated into the air over the course of a year if there was unlimited water at the location.	2015	Yes- directly linked by DHS cluster ID	N/A - water use not considered	Annual	0.5 x 0.5 degrees (approx. 55km x 55km grid cell)	Yes	Yes	Yes	Yes	CRU data v4.01 (University of East Anglia Climatic Research Unit; *et al.*, 2020)	

Source	Dataset	Components of Water System/Scarcity Included	Year	Easy to link data to DHS HH Clusters?	Specificity of Coverage (General or local level?)	Temporal Scale (Annual or monthly? Is seasonality covered?)	Spatial Resolution of Data (Fine scale e.g. 1kmx1km or greater?)	Meta-data Available?	Data Open Access?	Data Peer-Reviewed?	Is the data well-cited and used? (Citations in Google Scholar & Web of Science)	Datasets Included	Main Limitations for Analysis
DHS	Annual Aridity	Average yearly precipitation divided by average yearly potential evapotranspiration within the DHS 2km/10km buffer zone.	2015	Yes- directly linked by DHS cluster ID	N/A - water use not considered	Annual	0.5 x 0.5 degrees (approx. 55km x 55km grid cell)	Yes	Yes	Yes	Yes	CRU data v4.01 (University of East Anglia Climatic Research Unit; et al., 2020)	As above.
DHS	Drought Episodes	Average number of drought episodes for the DHS buffer zone. Drought events are identified when the magnitude of monthly precipitation deficit is less than or equal to 50% of its long-term median value for three or more consecutive months.	Based on 1900-2000 precipitation data	Yes- directly linked by DHS cluster ID	N/A - water use not considered	Annual	0.0417 x 0.0417 decimal degrees (5km)	Yes	Yes	Yes	Yes	Global Drought Hazard Frequency and Distribution v.1 (Dilley *et al.*, 2005)	-Outdated data (>20 years old). -Annual figure that is not necessarily for the same year as household data. -Missing data for clusters near water bodies.
DHS	Irrigation	The average proportion of the area within the 2 km (urban) or 10 km (rural) buffer surrounding the DHS survey cluster location equipped for irrigation.	2005	Yes- directly linked by DHS cluster ID	Sub-national units (districts, counties, provinces)	Annual	5 arc min. x 5 arc min. (10km)	Yes	Yes	Yes	Yes	AQUASTAT Global Map of Irrigated Areas v.5 (Siebert *et al.*, 2013)	-Outdated data (>15 years old). -Annual figure that is not necessarily for the same year as household data. -Missing data for clusters near water bodies.

Overall, of the 22 datasets identified, it was decided that modelled datasets provided the most complete overview of water scarcity and enabled the potential for forecasting the future impacts of water stress. Given this, both the WFN's and WRI's datasets for water scarcity and water stress were included in order to enable comparison between the two. The WRI's water stress data were used as these provide long term trends in water stress across each month so are more likely to be representative of the different months post-2014 when the DHS data are from. These also provided monthly water stress estimates meaning it could be linked to the exact month the DHS household survey was undertaken for each country and was available at the spatial resolution of hydrological sub-basins. Whereas the WFN's water scarcity data provide a ten-year average for the period 1995-2005 in order to incorporate climatic variability (Hoekstra *et al*. 2012). This usage also enabled continuity with the systematic review undertaken in the first analysis chapter. Both datasets were also publicly available and had undergone peer-review.

WRI Aqueduct 3.0 Baseline Water Stress Data

Using the PCRaster Global Water Balance (PCRGLOBWB 2) model (Sutanudjaja *et al*. 2018)'(Wada *et al*. 2014), WRI Aqueduct 3.0 (Hofste *et al*. 2019) calculates baseline water stress. This measures the ratio of total water withdrawals to available renewable surface and groundwater supplies. Water withdrawals include domestic, industrial, irrigation, and livestock consumptive and non-consumptive uses. Available renewable water supplies include the impact of upstream consumptive water users and large dams on downstream water availability (Hofste *et al*. 2019).

The data provides baseline water stress figures for each month or as an annual average (see Figure 5-3 for baseline water stress across Africa). In using a baseline measure a representation of the current situation is given but without anomalies (Hofste *et al*. 2019). To create baseline monthly figures, data from January 1960-December 2014 are used to create a time series of all months of January between 1960 and 2014, all months of February between 1960 and 2014, and so on to all months of December between 1960 and 2014. This is done for gross total withdrawal, net total withdrawal, and available water, which are then used to calculate baseline water stress using the equation in Figure 5-2.

The data are available at the hydrological sub-basin level, which is an area that drains at a single point to an ocean or inland lake. The assumption is that within each hydrological sub-basin, water resources are pooled and water withdrawal is satisfied using the water resources available to the sub-basin. Aqueduct 3.0 uses level 6 sized sub-basins which have a median area per sub-basin of 5,318 km^2.

$$ws_{m,y,b,ols10} = \frac{ww_{m,y,b,ols10}}{\max(Q_{m,y,b,ols10}) - wn_{m,y,b,ols10}}$$

IN WHICH,

$ws_{m,y,b,ols10}$ | Water stress per month, per year, per sub-basin in [-]

$ww_{m,y,b,ols10}$ | Gross (consumptive plus nonconsumptive) total withdrawal per month, per year, per sub-basin in [m/month]

$Q_{m,y,b,ols10}$ | Available water per month, per year, per sub-basin in [m/month]

$wn_{m,y,b,ols10}$ | Net (consumptive) total withdrawal per month, per year, per sub-basin in [m/month]

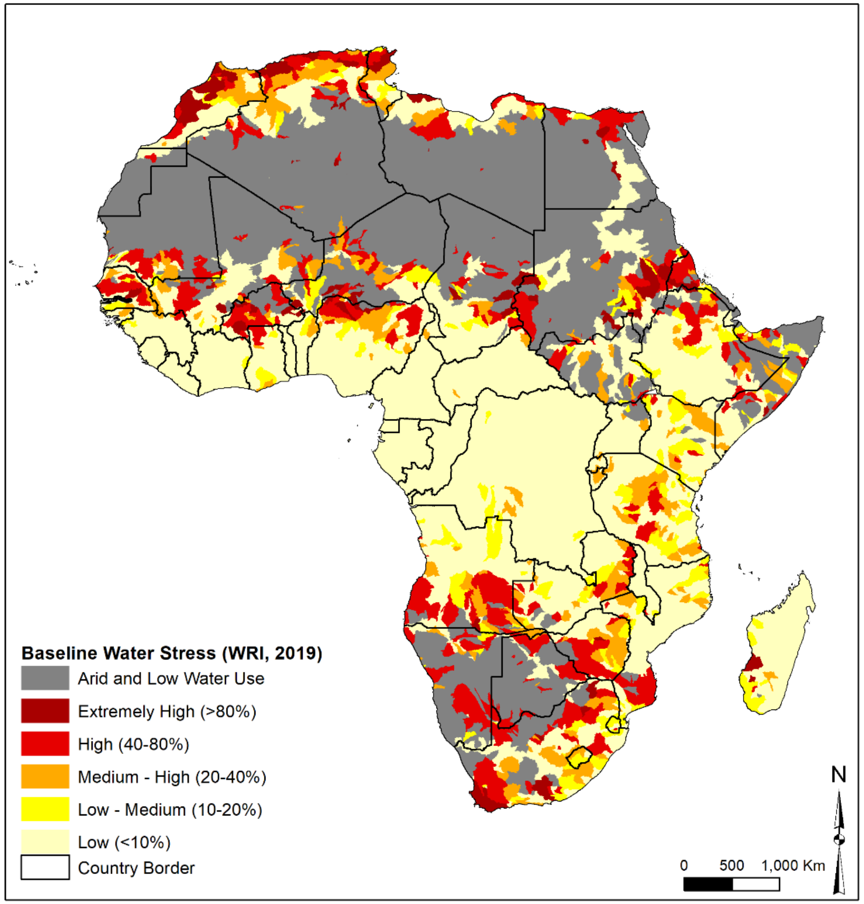
Figure 5-2: WRI Aqueduct 3.0 water stress calculation (Source: Hofste *et al*. 2019, p. 10)

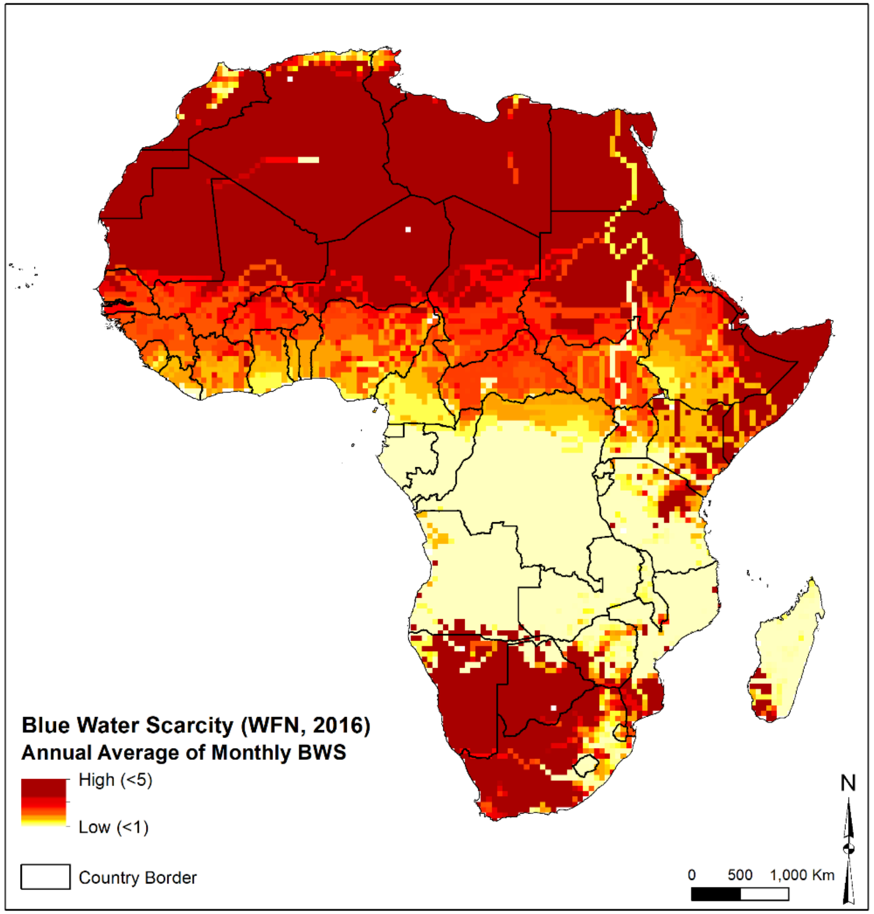
The water stress data are available as raw values (%), risk categories or as a score from 0-5 where 0-1 equals low water stress and 4-5 equals extremely high-water stress. Higher values indicate more competition among users. Additional categories for arid and low water areas are present; a sub-basin is "arid" if baseline available water <0.03 meters per year (m/yr), whilst "low water use" represents baseline gross total withdrawal of <0.012 m/yr.

WFN Blue Water Scarcity Data

The WFN's BWS data are the ratio of the local blue water footprint to the total blue water availability for 1996-2005 (see Figure 5-4 for blue water scarcity across Africa). Data are available as monthly estimates for each month of the year, including an annual average of monthly estimates, at a resolution of 30 x 30 arc minutes (Mekonnen and Hoekstra 2011).

Blue water footprint includes consumptive uses of ground and surface water flows, rather than simply water withdrawals, and include aggregated blue water footprints for the agricultural (crop





<u>Figure 5-3:</u> Baseline water stress across Africa (1960-2014)

(Data source: WRI Aqueduct 3.0, 2019 (Hofste *et al*. 2019))

<u>Figure 5-4:</u> Average annual monthly blue water scarcity across Africa (1996-2005)

(Data source: WFN, 2016 (Mekonnen and Hoekstra 2011))

and livestock), industrial and municipal sectors. The latter include estimations of industrial and municipal water footprints based on water consumption data and population densities per country. For agricultural water footprint, the footprint of crop production was estimated using crop maps, data on growing periods, estimated irrigation requirements and data on actual irrigation.

Blue water availability on the other hand, includes the sum of locally generated blue water and the blue water flowing in from upstream. Monthly runoff data from the Composite Runoff v1.0 database (Fekete *et al*. 2002) are used, whereas environmental flow requirements were used based on the presumptive environmental flow standard which states 80% of the natural runoff is allocated as environmental flow requirement; the remaining 20% can be considered as blue water available for human use without affecting the integrity of downstream water-dependent eco-systems and livelihoods (Hoekstra et al. 2011; Richter et al. 2012).

In order to avoid unrealistic water scarcity values, especially in the northern hemisphere, the WFN have set a condition that when the average monthly maximum temperature is equal to or below 10°C, water scarcity is set to be equal to zero. These conditions occur when precipitation and thus run- off are very small (sometimes zero or near zero), such that the water footprint/water availability ratio can become very large. In practice, this is not experienced as high water scarcity, because under these circumstances, water use is generally small as well (no crop growth in this period) and can be made available through small temporary water storage or melting of snow.

These data include BWS values classified into four ranges: low (<1.0), moderate (1.0-1.5), significant (1.6- 2.0), and severe (> 2.1). Water scarcity values that equal 1.0 mean that the available blue water has been fully consumed.

5.2.4. Collating and Preparing Data for Analysis

All data preparation was undertaken in Stata/IC 16.1 and ArcMap 10.7.1. For each country the most recent DHS data were downloaded and prepared in Stata. Data preparation included:

- removing all households that use an unimproved drinking water source. These households were removed to ensure continuity with SDG target 6.1 and indicator 6.1.1 which focus only on improved/safely managed sources (United Nations 2021).

- removing all households that use packaged water (e.g. bottled and sachet water) or a delivered water source (e.g. tanker truck or cart with small tank) as their main source.

- removing all households that use a drinking water source that is not covered by the DHS's survey question on availability, for example a protected spring or well and rainwater. The DHS availability question is only asked to households that use a piped source at either their neighbour, yard or home or a tubewell/borehole (Croft *et al*. 2018).

- removing all households who reported 'not knowing' about the availability of their sources or where there was missing data for source availability.

- removing all households who were in household clusters that did not have GPS coordinates. The DHS marks all household clusters that cannot be georeferenced as missing (Burgert *et al*. 2013). For this analysis, missing GPS coordinates meant that the associated DHS geospatial data was also missing, and the household data could not be linked to the environmental data required for analysis.

The number of households removed for each country at each stage of data preparation is available in Table 5-5.

Following data cleaning, all variables were prepared for analysis. For each of the 10 countries, the outcome variable 'household reported availability of drinking water' and 12 additional explanatory variables were collated. All additional explanatory variables were chosen to represent variations in drinking water consumption that are experienced as a result of drinking water being unavailable when needed and environmental, social and physical WASH factors. These variables were at the household and household cluster level.

All household-level variables were sourced from the corresponding DHS. Where information was not available in the DHS household survey, it was taken from the DHS Men's questionnaire and Women's questionnaire and merged to create a new variable at the household level. Details of the DHS variables and the exact wording of the question households were asked are available in appendix B.1.

The preparation of variables included grouping each into different response categories. Where possible, the response categories were kept consistent across the 10 case study countries. Thus, for all countries, the outcome variable, household wealth, type of improved water source, number of household members, home ownership, type of place of residence, degree of urbanisation, change in urbanisation, neighbourhood wealth and age of neighbourhood all had the same response categories. All other explanatory variables had variations in their categories or were continuous variables.

Table 5-5: Total number of households included in final DHS dataset for all 10 countries (alongside reasons for excluding households)

Country	Total number of households (HHs) in DHS	Number of households removed and reason					Total number of HHs in final dataset (% of original HHs)
		They use an unimproved, packaged or delivered source	They use a source that is not included in the DHS availability question	They do not know the availability of their source	Availability of sources is reported in DHS as missing data	No GPS coordinates in DHS dataset	
Ethiopia	*16,650*	5136 (30.8%)	2445 (14.7%)	90 (0.5%)	0 (0.0%)	106 (0.6%)	**8,873 (53.4%)**
Gambia	*6,549*	378 (5.8%)	155 (2.4%)	78 (1.2%)	1 (0.0%)	0 (0.0%)	**5,937 (90.6%)**
Malawi	*26,361*	3440 (13.1%)	914 (3.5%)	49 (0.2%)	0 (0.0%)	268 (1.0%)	**21,690 (82.2%)**
Nigeria	*40,427*	15,610 (38.6%)	5732 (14.2%)	25 (0.1%)	137 (0.3%)	469 (1.2%)	**18,454 (45.6%)**
Sierra Leone	*13,399*	5630 (42.1%)	3170 (23.7%)	9 (0.0%)	9 (0.0%)	83 (0.6%)	**4,498 (33.6%)**
South Africa	*11,083*	1041 (9.4%)	133 (1.2%)	89 (0.8%)	10 (0.1%)	0 (0.0%)	**9,810 (88.5%)**
Tanzania	*12,563*	4529 (36.1%)	2067 (16.5%)	56 (0.4%)	22 (0.2%)	0 (0.0%)	**5,889 (46.8%)**
Uganda	*19,588*	4510 (23.0%)	3238 (16.5%)	81 (0.4%)	8 (0.0%)	309 (1.6%)	**11,442 (58.5%)**
Zambia	*12,831*	4040 (31.5%)	1894 (14.8%)	51 (0.4%)	0 (0.0%)	143 (1.1%)	**6,703 (52.2%)**
Zimbabwe	*10,534*	1939 (18.4%)	1656 (15.7%)	33 (0.3%)	0 (0.0%)	0 (0.0%)	**6,906 (65.6%)**

The following sections include justifications for the inclusion of each explanatory variable, as well as how each variable was defined, created and categorised.

5.2.4.1. Household Level Explanatory Variables

Type of Improved Source

Variations in drinking water availability exist due to the type of piped source as different types of supplies are prone to different types of interruptions, especially under conditions of water scarcity

(Luh and Bartram 2016). Households may also consume more water if it is piped to the yard or home, than if located further afield, such as at a neighbour, public tap/standpipe or borehole/tubewell (Cassivi *et al*. 2019). It may also be the case that boreholes/tubewells that are located on premises are better managed and used less intensely than those off premises and so are less prone to interruptions, or if interruptions do occur are repaired quicker.

Details of the type of improved source were used from the DHS household survey which includes five categories of 'piped into dwelling', 'piped to neighbour', 'piped to yard/plot', 'public tap/standpipe' and 'tubewell or borehole'. To overcome issues of small counts in some categories for some countries, these details were grouped to create a variable with five categories, including 'piped supplies on premise' which included piped into dwelling and piped to yard/plot, 'piped to neighbour', 'public tap/standpipe' and 'tubewell or borehole'.

Household Wealth

Wealth at the household level was included to account for the fact that wealthier households may be less prone to interruptions; they pay tariffs more regularly, there are less likely to be illegal piped connections or breakages within the local piped network, they are likely to be able to afford to consume more water (Kayaga and Franceys 2007) and to pay for storage tanks which may protect them from interruptions (Dungumaro 2007). Wealth also relates to the type of piped source used, for example, wealthier households are more likely to have piped supplies in their home or yard (Zoungrana 2020).

The DHS assume that the possession of observable assets, sources and amenities are related to the relative economic position of the household in the country (Rutstein 2008, p. 2). Unlike the DHS wealth index, which relates to national populations as a whole and has been criticised for being too urban in its construction, the newer urban/rural composite wealth index enables the poorest of the poor to be distinguished from other poor households(ICF n.d.). In doing so, it considers assets and sources that rural populations would have in conjunction with those of urban populations. For instance, type of flooring and roofing, water source and sanitation facilities, electricity, appliances, persons per sleeping room and having a bank account are all assets and sources used to calculate the wealth of households (see: Rutstein (2008) for a comprehensive list of assets and sources included).

We used the DHS's urban/rural composite wealth index for a household level wealth variable. This variable included categories of 'poorest', 'poorer', 'middle', 'richer' and 'richest'.

Type of place of residence

The DHS's classification of the type of place of residence households are located in was included. This variable includes categories 'rural' and urban' and uses the official urban/rural definition of enumeration areas used in each country's census. This variable was included as inequalities in drinking water availability exist between each type of location. Typically urban areas fare better than rural areas (WHO and UNICEF 2021). The ability to deal with breakages in water sources is greater in urban areas where skilled workforces, quicker responses and greater finances are generally more readily available. In rural areas, where water committees are often responsible for sources, the capacity to deal with interrupted supplies varies considerably with factors such as seasonality playing a key role (Kelly *et al*. 2018). Additionally, informal urban settlements can have highly intermittent supplies due to the pressures densely populated areas and overuse can cause.

Number of Household Members

The number of people in a household was included as it correlates with water consumption (Dungumaro 2007; Arouna and Dabbert 2010) and the risk of supplies breaking due to additional pressures on infrastructure. It also relates to choice of source type (Armand et al. 2012; Mulenga et al. 2017). The DHS collects information on the number of people in a household, which we grouped into five categories of '1 member', '2-3 members', '4-6 members', '7-9 members' and households with 'more than 10 members'.

Tenure

Home ownership is related to the choice of water source and the ability to deal with or fix a fault or interruption to a source. For example, a household that owns their home can choose to have a piped source in their home over a source in the yard, and if this source is interrupted, they can more readily and easily fix the issue than households who rent their home. Tenure also affects water tank ownership; water tanks are an important coping strategy to mitigating unavailable supplies (Staddon *et al*. 2018).

We used details of home ownership that are collected in the men's and women's DHS questionnaires. The men's and women's questionnaires interview all eligible men/women in each household, meaning that there are multiple responses for each household. To create the tenure variable the data was sorted so that responses were only used for the owner of the house, thus removing household duplicates. Data from both the men's and women's questionnaires were then merged with the household dataset using the household and household cluster IDs and categorised into 'does not own', 'at least partly owns' and 'no information'.

Housing Quality

In order to account for water source issues experienced in the household, a housing quality variable was created based on three variables available in the DHS: (1) type of roof material, (2) type of wall material and (3) type of floor material. These three variables include numerous materials that are classified into 'natural', 'rudimentary' and 'finished' materials. For instance, the Ethiopian DHS classifies earth/sand and dung as natural floor materials, wood planks and palm/bamboo as rudimentary and parquet/polished wood, vinyl/asphalt strips/plastic tile, ceramic tiles, cement and carpet as finished flooring materials. There were variations between each country's DHS in the roof, wall and floor materials that fell into each category. An additional category of 'other' was also present in the three variables.

In order to create the housing quality variable, for each roof, wall and floor material variable, any households that stated 'other' were assigned 1 (natural), 2 (rudimentary) or 3 (finished) based on the classification of the other two material types. For example, if a household reported having natural flooring, rudimentary walls but 'other' roof materials, the materials for floor and walls were used to assign a classification for their roof material. In order to decide which values should be assigned, we explored correlations between the three housing materials which found that if the material of roof were 'other', then the material for floor was to be used. If details of wall material were 'other', then the roof material was used and if the details of floor were 'other' then the roof material was used. If households reported 'other' for two materials or more, then housing quality was classified as missing.

Using details of the roof, floor and wall material we created a housing quality variable where we used count measures (Poirier *et al*. 2020), similar to those used to create an absolute wealth index (Hohmann and Garenne 2011). For each floor/wall/roof material variable, natural materials were classified as 1, rudimentary materials 2 and finished materials 3. We summed these together to create a housing quality scale of 3-9. These were grouped into 3 categories, where 3-5 included households who classified at least one of the roof/floor/wall materials as natural, 6-8 included households who reported a mixture of rudimentary, natural or finished roof/floor/wall materials and households with a housing quality score of 9 had finished roof/floor/wall materials.

5.2.4.2. Household Cluster Level Explanatory Variables

Water Stress

Water stress was included as it may restrict the availability of supplies, especially in African countries where seasonal variations and drought are common (Kelly et al. 2018; McNally et al. 2019). Variations in groundwater, due to climatic and human induced pressures, affect borehole yields thus limiting groundwater fed supplies. Whilst variations in rainwater result in water shortages in rivers, dams and reservoirs that feed piped source networks.

Using ArcPro, a water stress value for all months was calculated for each DHS household cluster in each country. The water stress data consisted of a global shapefile where each hydrological sub-basin has an associated water stress value for each month. In ArcPro a spatial join between the DHS household clusters and water stress data was undertaken. This enabled features from each dataset to be joined based on their spatial relationship. In all cases a one-to-one join was undertaken, this ensured that in instances where multiple hydrological sub-basins were found that had the same spatial relationship with the DHS clusters, attributes were aggregated. Thus, if a DHS cluster fell within two hydrological sub-basins the water stress value of the two basins was aggregated. To account for the DHS displacement of household clusters, for all urban household clusters a search radius of 2km was used, whilst for all rural household cluster a 5km radius was used. The results were exported from ArcPro and imported into Stata where they were merged with the household level DHS data using the household cluster ID.

Once in Stata, five water stress variables at the household level were created based on the month of interview. The first directly corresponded with the month in which each household was interviewed. The second included a one-month lag time, thus included water stress values for the month prior to being interviewed. The third, fourth and fifth versions included 2-month, 3-month, and 6-month lag times and therefore had the water stress values for 2, 3 and 6 months prior to the month of interview. Conditions of water stress are unlikely to implicate household water availability immediately, hence the calculation of three water stress values two of which included lag times.

Blue Water Scarcity

In addition to the WRI's water stress data, we also used the WFN's BWS data. The annual average monthly BWS was used, where it is said to be moderate if it is in the range 1.0-1.4, significant if it is in the range 1.5-1.9, and severe if >2.0.

Using ArcMap, a BWS value was calculated for each DHS household cluster for each country. The BWS data consists of a global raster layer where each grid cell has an associated BWS value. To account for the DHS's displacement of household clusters (undertaken to maintain anonymity) we first created buffers around each cluster, these were 2km in size for urban, and 5km for rural, household clusters.

We then sought to use the zonal statistics tool in ArcMap to calculate the modal BWS for each buffer. A recurring error in ArcMap meant however, that where HH cluster buffers overlapped a value was only calculated for the top buffer. To overcome this, we exported the data from ArcMap and used RStudio to calculate the most common BWS value for the pixels in each buffer. The results of which were imported into Stata and merged with the DHS household data using the household cluster ID.

For Tanzania there were 478 households that did not have an associated BWS value. Further exploration found that these households were all located in clusters on Pemba Island. All clusters were located less than one grid cell from a cluster with a BWS value, therefore, the same value (1.73) was used for all households with missing data.

Change in Urbanisation

Recently urbanised areas may have water infrastructure that has undergone development and thus be less prone to maintenance-related interruptions. Given this, a variable that accounted for change in urbanisation was created at the household cluster level. As with the degree of urbanisation variable, the DHS's pre-prepared geospatial covariate for GHSL settlement data was used for 1990 and 2015 (Pesaresi and Freire 2016). To create the change in urbanisation variable, the difference in urbanisation between 1990 and 2015 was calculated and merged with the household data. This variable was then categorised into the following: 'less urbanised', 'more urbanised' and 'no change' between 1990 and 2015.

Neighbourhood Wealth

Neighbourhood wealth represents a range of societal factors such as crime levels and disorganised and disadvantaged communities (Winter *et al*. 2018), which in turn affect water infrastructure and the capacity to deal with faulty or interrupted supplies that result in supplies being unavailable. The DHS's urban/rural wealth index was used to create this variable at the household cluster level. An average wealth score for all households within a cluster was created using the continuous urban/rural wealth index factor score. This was then grouped into three quantiles, 'poor', 'middle' and ‘rich’, to create a categorical variable. Whilst the resultant variable was not representative, as it is based on unrepresentative data, it was the best information/data available for neighbourhood wealth.

Age of Neighbourhood

Newer neighbourhoods are less likely to have water infrastructure that is prone to failure due to general aging of materials and poor upkeep (Bellaubi and Visscher 2014; Robles-Velasco et al. 2020). Conversely, in some cities newer urbanisation can include informal settlements that generally have poor water sources. To account for both instances, age of neighbourhood was included as a variable. The men’s and women’s DHS questionnaires ask respondents their length of residence in their current home. This information was used as a proxy for the age of a neighbourhood, on the premise that if a respondent reported living in their home for 49 years, the neighbourhood must be at least 49 years old.

To create an age of neighbourhood variable, all respondents who stated that they were a visitor were first removed from the men’s/women’s questionnaire. For those that reported having ‘always’ lived in their home, their current age was used as a proxy for length of residence. The data was collapsed to the household cluster level and the highest value from the men’s/women’s questionnaire for each household cluster was taken. For example, if the length of residence in a household cluster was 15 years in the men’s questionnaire but 35 years in the women’s questionnaire, the value from the women’s questionnaire was used as the proxy for neighbourhood age. The data was merged with the household dataset using the household cluster ID.

Finally, the variable was grouped to create a categorical variable with the following categories: neighbourhood is ‘<30 years old’, ‘31-40 years old’, ‘41-50 years old’ and ‘>50 years old’. The resultant variable therefore represents the maximum length of residence within each household cluster, and thus approximates the minimum potential age of the neighbourhood.

Population Density

This variable was included as more populated areas may experience more interruptions to their supplies. Piped networks source more people meaning lower water pressure and boreholes/standpipes are more prone to breakages or depleted groundwater as usage is higher. The DHS population count geospatial covariate was used and linked to the household dataset using the DHS cluster ID. The resultant variable, which represented the number of people per DHS buffer area, was divided by 10,000 and kept as a continuous variable at the household cluster level.

5.2.5. Statistical Analysis

Initial analysis included bivariate analysis between the outcome variable, household reported availability, and all explanatory variables in order to collate descriptive statistics and calculate 95% confidence intervals. Chi-squared tests were also run in order to explore associations between the outcome variable and all categorical explanatory variables. This was conducted using Stata 16.1 and for each country survey weights were used. Provided at household level by the DHS, their inclusion helps to improve representativeness, correct for non-response and minimise the problem of unequal selection probabilities that can occur during surveys that use multistage sampling (Pfeffermann *et al*. 1998). The use of Stata's *svy* command ensures their use and subsequently takes into consideration stratification and clustering. In addition, binary logistic regression models were run for each country in order to test for collinearity and missingness. These included the outcome variable and all explanatory variables. No issues of missingness or multicollinearity were found.

Comparison of a single-level unconditional model and a two-level variance components model quantified the clustering in the dataset and showed that multilevel models were the most appropriate method for the data. Multilevel logistic regression models were therefore undertaken to account for the complex clustered sample design of the user data, and the additional complexity of the explanatory variables available at the higher household cluster and provider levels. The clustered nature of the data may reduce independence between household-level observations due to unobserved shared sources of variation within household cluster. This needed to be accounted for to ensure that standard errors were not underestimated and the significance of some variables was not overestimated (Aarts *et al*. 2014).

Sensitivity analysis was undertaken in order to assess which of the five water stress variables to use. This included running five rounds of multilevel logistic regression models for each country (see appendix B.2, B.2.1-B.2.10). Each round including only one of the water stress variables (no lag, 1-month 2-month, 3-month, and 6-month lag) alongside all other explanatory variables. By undertaking this sensitivity analysis, we were able to approximate how long water stress took to have an effect on household drinking water availability. Following this analysis, we chose the variable that had the greatest effect, water stress with 1-month lag, across the majority of the study countries and included this in the final multilevel logistic regression models.

For the main effect models, all explanatory variables were kept constant across each study country. Where a variable was not significant at the 5% level ($p < 0.05$) in any country it was removed from the model. Survey weights were not used for the multilevel modelling as the DHS does not source them at the household cluster, due to concerns about disclosure risk level (Elkasabi *et al*. 2020), as would have been required.

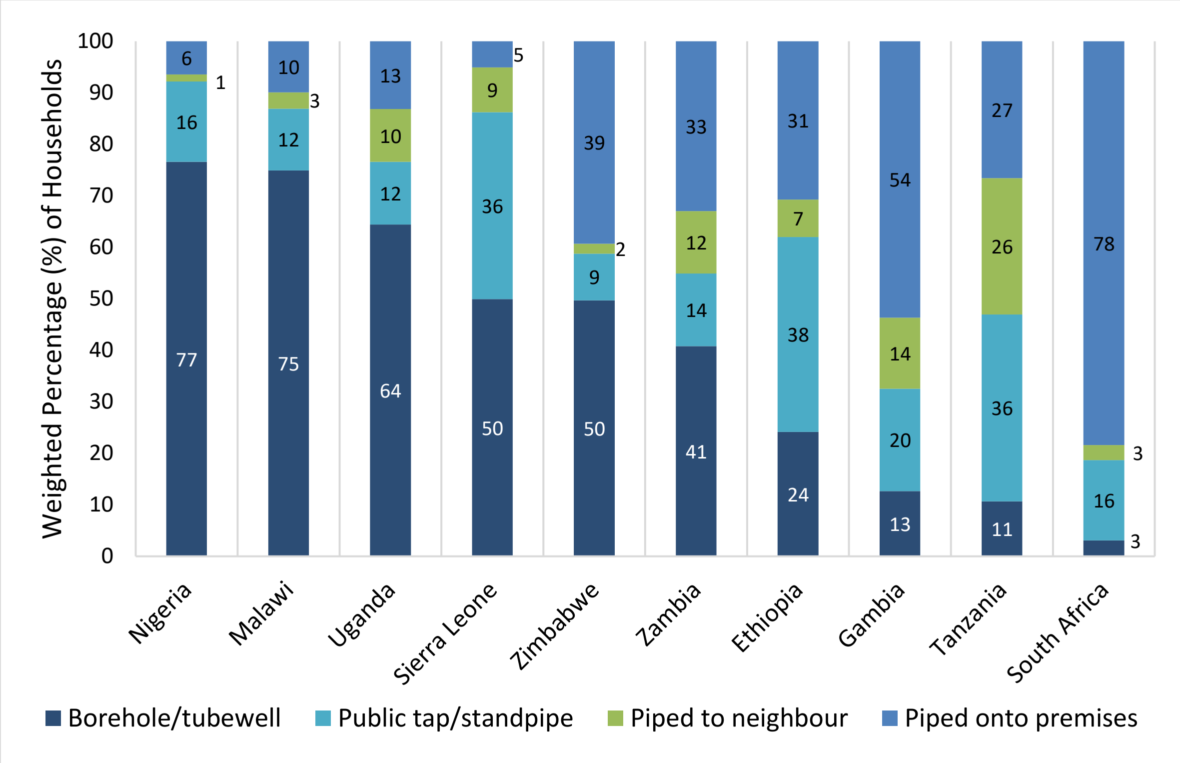
We also explored interaction terms between explanatory variables. These were only explored when deemed meaningful and informed by prior knowledge. We explored the following interactions: type of source and household wealth; type of source and water scarcity; type of source and water stress; type of source and housing quality. No meaningful or significant (at the 1% level) interactions were found, therefore they were dropped from our analysis.

5.3. Results

The total number of households surveyed by the DHS that used an improved drinking water source, reported the availability of their source and had locational data ranged from 4498 in Sierra Leone, to 21,690 in Malawi (Table 5-5). In Sierra Leone, this sub-sample represented only 34% of all households surveyed by the DHS, whereas in South Africa and Gambia this sub-sample included 89% and 91% of households.

5.3.1. Characteristics of Improved Drinking Water Services

In Nigeria, Malawi and Uganda most households used a borehole or tubewell for drinking water (Figure 5-5). Use ranged from 77% (95% CI: 76%, 77%) in Nigeria, to 75% (95% CI: 74%, 76%) in Malawi and 64% (95% CI: 63%, 65%) in Uganda. In two countries, Sierra Leone and Zimbabwe, the use of piped supplies and boreholes was equal. In Sierra Leone however, public taps and standpipes were the dominant piped source, as used by 36% (95% CI: 35%, 38%) of households, whereas in Zimbabwe, piped supplies on premises were used by 39% (95% CI: 38%, 41%). In Zambia, 59% (95% CI: 58%, 61%) of households used a piped source, with piped onto premises the most common source type. Over 75% of households used a piped source in Ethiopia, Gambia, Tanzania and South Africa. In South Africa, 97% used a piped source, with sources on premises used by 78% (95% CI: 77%, 79%) of households.



<u>Figure 5-5:</u> Weighted percentages of households using each type of improved drinking water source, for all countries.

5.3.1.1. Rural-Urban Variations in Drinking Water Sources

In all countries variations exist between households in rural and urban localities and the most used type of source (see appendix B.3). In South Africa, in both urban and rural areas, piped supplies are the most commonly used, however in urban areas 89% (95% CI: 88%, 90%) of households use them whereas in rural areas only 50% (95% CI: 48%, 52%) do. In rural areas public taps and standpipes are used by 33% (95% CI: 21%, 35%) of households. In Nigeria, there is minimal difference between localities in the dominant source type, with 75% (95% CI:75%, 77%) - 77% (95% CI: 77%, 79%) of urban and rural households using tubewells or boreholes respectively.

In urban areas of Uganda, the type of source used by households is approximately the same, with 28% (95% CI: 26%, 29%) - 31% (95% CI: 29%, 33%) using tubewells/boreholes and supplies that are piped onto premises. In rural areas 81% (95% CI: 80%, 82%) of households use a tubewell or borehole. Similarly, in Malawi, 89% (95% CI: 88%, 89%) of rural households use tubewells/boreholes, whilst in urban piped supplies are predominantly used (44%, 95% CI: 41%, 46%), closely followed by public taps/standpipes (34%, 95% CI: 32%, 37%). In Sierra Leone, half of urban households use public taps or standpipes, whilst a quarter use tubewells or boreholes. In rural areas, tubewells/boreholes are used by three quarters of households.

In urban areas of Tanzania there is even use of supplies that are piped onto a premise and piped to a neighbour (38%, 95% CI: 36%, 41%), in rural areas however, over half of households use public taps or standpipes. In Gambia and Ethiopia, households in urban areas predominantly use piped supplies (66% (95% CI: 64%, 68%) - 69% (95% CI: 66%, 71%)), whereas households in rural areas use public taps and standpipes or tubewells and boreholes. Similarities are also present between Zambia and Zimbabwe where 52% (95% CI: 50%, 55%) - 70% (95% CI: 68%, 72%) of urban households use a piped source on premises, whereas in rural areas between 85% (95% CI: 84%, 86%) and 74% (95% CI: 73%, 76%) use a tubewell or borehole.

5.3.1.2. Variations based on Household Wealth

Similar variations exist in the type of source used by households with differing levels of wealth (see appendix B.4). In Ethiopia and Tanzania at least half of all households in the poorest wealth quintile use a public tap or standpipe. The poorest households in Malawi, Uganda, Zambia and Zimbabwe predominantly use a tubewell or borehole (52% - 95%). Additionally, in Zimbabwe however, 33% (95% CI: 30%, 36%) of the poorest use a piped source on premises. In Gambia, amongst the poorest households there is an even split between the four types of source, with 22% (95% CI: 19%, 25%) using a piped source on premises, 24% (95% CI: 21%, 28%) using a public tap or standpipe, 26% (95% CI: 23%, 29%) use a public tap or standpipe and 28% (95% CI: 25%, 31%) use a neighbour's piped source.

In half of the study countries, the most frequently used source in the wealthiest households are piped supplies on premises: Uganda 38% (95% CI: 36%, 41%), Ethiopia 40% (95% CI: 37%, 43%), Tanzania 49% (95% CI: 46%, 52%), Zambia 57% (95% CI: 54%, 60%), Gambia 84% (95% CI: 81%, 86%) and South Africa 91% (95% CI:90%, 93%). In South Africa there is minimal variation between wealth quintiles in the type of source used; piped supplies are consistently the most common. However, 40% (95% CI: 37%, 43%) of the poorest households use a public tap or standpipe.

Unlike any of the other countries, in Nigeria, 74% of the richest households use a tubewell or borehole, however, households in all wealth categories predominantly use a tubewell or borehole. For example, 78% (95% CI: 77%, 80%) of those with middle wealth and 80% (95% CI: 78%, 81%) of the poorest households.

In Malawi and Zimbabwe, the richest households use both piped supplies on their premises and tubewells or boreholes. In Zimbabwe usage is relatively equal, 45% (95% CI: 42%, 48%) use piped onto premises whilst 44% (95% CI: 41%, 47%) use tubewells or boreholes, whereas in Malawi there is greater disparity with 62% (95% CI: 61%, 64%) using tubewells or boreholes and 26% (95% CI: 24%, 28%) using piped supplies on premises. Similarly, in Sierra Leone 38% (95% CI: 34%, 42%) of the richest households use a public tap or standpipe, whilst a further 43% (95% CI: 39%, 46%) use a tubewell or borehole. The majority of the poorest households use a tubewell or borehole (62% (95% CI: 58%, 66%).

5.3.2. Experiences of Interruptions to Water Services

The proportion of households reporting an interruption to their improved drinking water source in the two weeks prior to being surveyed ranged from one quarter to over half of households. Figure 5-6 shows, for all countries, household clusters where at least one household reported experiencing an interruption to their improved drinking water source, as well as those where no household experienced interruptions.

As shown in Figure 5-7, the country with the highest reporting of interruptions was Tanzania at 55% (95%: CI: 53%, 56%). In Ethiopia, 48% (95%: CI: 47%, 50%) of households reported experiencing an interruption and 39% (95%: CI: 37%, 41%) in Sierra Leone. Interruptions were experienced by 31% (95%: CI: 30%, 32%) and 32% (95%: CI: 32%, 34%) of households in South Africa and Uganda respectively. Drinking Water was interrupted for <29% in five countries: Zambia, Zimbabwe, Nigeria, Gambia and Malawi. The lowest reporting of interruptions was in Malawi at 24% of households.

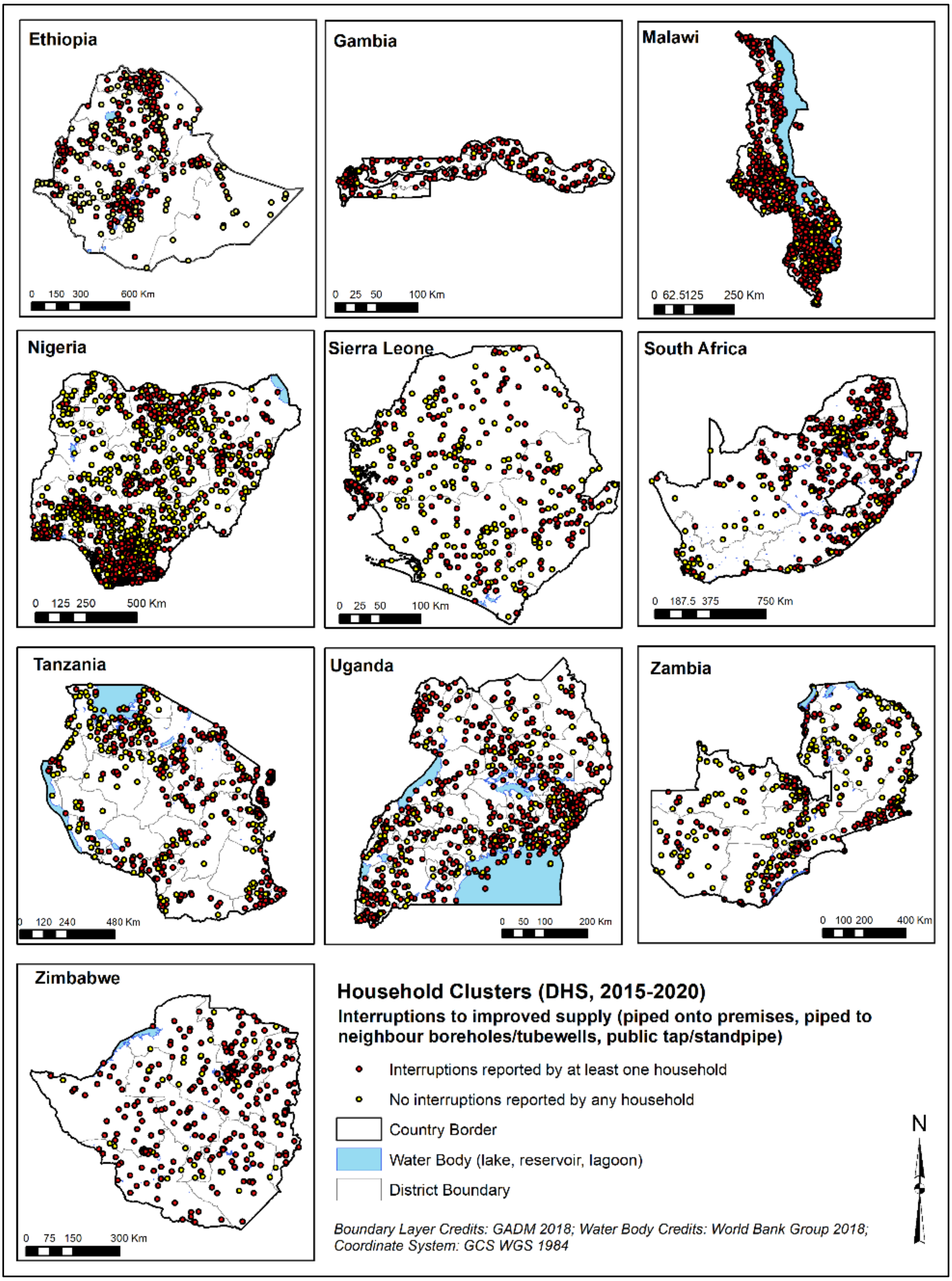


Figure 5-6: **Household clusters with an interruption, reported by any household, to their improved drinking water source (DHS data from 2015-2020 depending on the study country, see Table 5-3)**

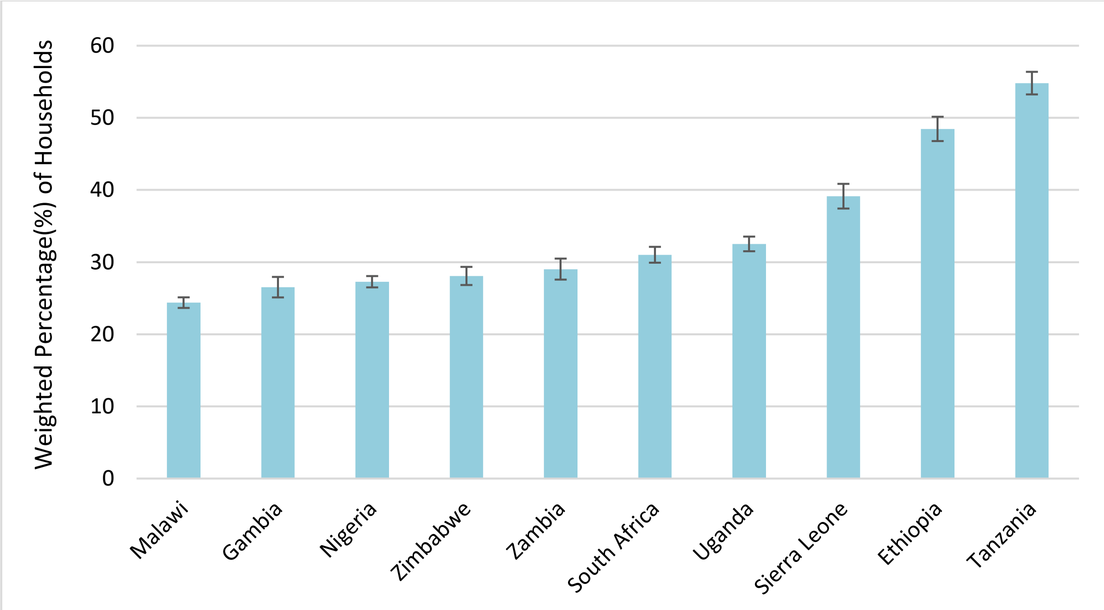


Figure 5-7: Weighted percentage of households reporting a full day's interruption in the two weeks prior to being surveyed, for all countries (2015-2020), with 95% confidence intervals

Interruptions based on type of improved source showed that in all countries more households using piped sources experienced interruptions than those using boreholes or tubewells (Figure 5-8). Uganda had the highest reported interruptions to piped sources at 61% of households (95%: CI: 59%, 63%), whereas Gambia had the lowest at 28% (95%: CI: 26%, 29%). In contrast, in Zambia, only 8% (95%: CI: 7%, 9%) of households using a borehole or tubwell reported an interruption compared to Tanzania's 28% (95%: CI: 26%, 33%), the highest in any country.

In all countries bar Nigeria, South Africa and Gambia, there was considerable variation in the number of households reporting an interruption based on the type of source. The greatest difference in reporting of interruptions between the two source types was in Uganda, with 61% (95%: CI: 59%, 63%) of households using piped sources reporting an interruption compared to only 17% (95%: CI: 16%, 18%) of those using a borehole or tubewell. Similarly in Malawi, where overall there was the lowest reporting of interruptions, 56% (95%: CI: 54%, 58%) of households using a piped source reported experiencing interruptions, compared to 14% (95%: CI: 13%, 14%) using a borewell or tubewell.

By comparison, in Gambia there was only a 11% difference in the number of households reporting an interruption based on type of drinking water source: 28% (95%: CI: 26%, 29%) of piped users versus 17% (95%: CI: 13%, 21%) of borehole and tubewell users. A similar situation was found in both South Africa and Nigeria. For all other countries, Zimbabwe, Zambia, Sierra Leone, Ethiopia and Tanzania, the variation in reporting between piped source users and users of boreholes and tubewells ranged from a 29% to a 36% difference in the number of households reporting an interruption.

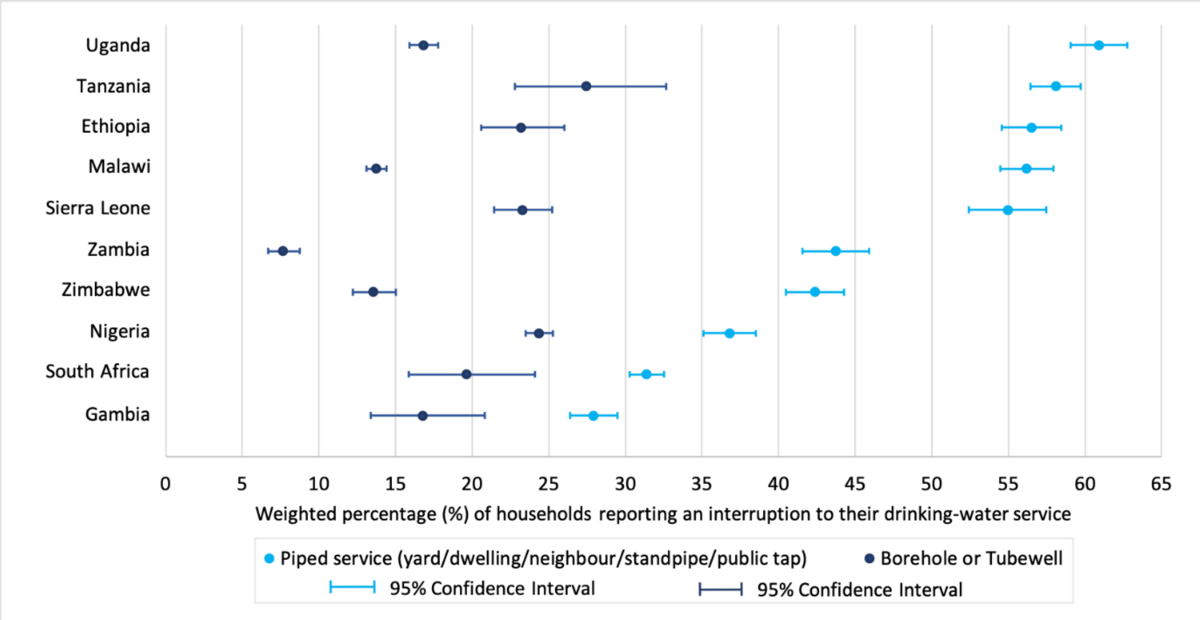


Figure 5-8: Weighted percentage of households reporting a full day's interruption based on type of improved drinking water source (piped sources versus boreholes or tubewells), for all countries (2015-2020), with 95% confidence intervals

5.3.3. Household Characteristics Associated with Interruptions

Table 5-6 presents descriptive statistics of all households reporting an interruption, for all study countries. Chi-squared results for the associations between household characteristics and reporting of source interruptions are also presented.

In all countries, at the household level, type of improved source is statistically significantly related to reporting of interruptions ($p < 0.001$). Households using a tubewell or borehole are the least likely to report an interruption in all countries. In Zambia, of those using a tubewell or borehole only 8% (n = 392) reported an interruption, whereas the highest reporting of interruptions of households using a tubewell or borehole is in Tanzania at 28% (n = 98).

Variations exist between countries in the piped source type with the greatest household-reported interruptions. For instance, in Ethiopia, Nigeria, South Africa, Tanzania and Uganda households using a neighbour's piped source are more likely to report an interruption (43%-75% of household). In Malawi 59% (n = 1416) and Gambia 38% (n = 659) of all households using a public tap or standpipe reported an interruption. In Sierra Leone, the most interrupted type of source is a piped source in the dwelling, yard or plot with 64% (n = 128) of households reporting an interruption. Similarly, in

<u>Table 5-6:</u> Proportion of households reporting an improved drinking water source interruption in the preceding fortnight by socio-economic characteristic, for all countries (2015-2020)

Explanatory Variable	Weighted Percentage (%) of Households (n) Reporting an Interruption																			
	Ethiopia		Gambia		Malawi		Nigeria		Sierra Leone		South Africa		Tanzania		Uganda		Zambia		Zimbabwe	
	%	(n)	%	(n)	%	(n)	%	(n)	%	(n)	%	(n)	%	(n)	%	(n)	%	(n)	%	(n)
Households with Interrupted Drinking Water Source	*48.5*	*4720*	*26.5*	*1602*	*24.4*	*5489*	*27.3*	*5040*	*39.1*	*1631*	*31.0*	*3267*	*54.8*	*3176*	*32.5*	*3513*	*29.0*	*1771*	*28.1*	*1967*
Type of Improved Source (chi-squared (df), p-value)	**1366.6 (3), p <0.001*****		**123.7 (3), p <0.001*****		**4018.3 (5), p <0.001*****		**265.1 (3), p <0.001*****		**483.9 (3), p <0.001*****		**336.1 (3), p <0.001*****		**291.8 (3), p <0.001*****		**2339.8 (3), p <0.001*****		**1034.0 (3), p <0.001*****		**719.1 (3), p <0.001*****	
Piped onto premises (dwelling/yard/plot)	71.2	2508	25.4	670	52.5	1477	37.8	553	64.3	128	27.3	2179	60.3	982	58.2	737	45.9	898	43.5	1331
Piped to neighbour	74.9	663	23.1	149	56.2	469	43.3	102	55.8	177	50.3	148	65.5	834	65.1	612	42.3	304	34.3	43
Public tap/standpipe	41.1	1031	38.0	659	59.3	1416	35.8	1143	53.4	730	48.4	863	51.1	1262	60.4	859	39.9	327	39.4	201
Tubewell/borehole	23.2	518	16.8	124	13.7	2127	24.4	3242	23.3	596	19.6	77	27.5	98	16.8	1305	7.7	242	13.6	392
Household Wealth *(chi-squared (df), p-value)*	**16.1 (4), p = 0.19**		**6.6 (4), p = 0.39**		**95.9 (4), p <0.001*****		**65.8 (4), p <0.001*****		**175.0 (4), p <0.001*****		**113.0 (4), p <0.001*****		**10.9 (4), p = 0.13**		**543.5 (4), p <0.001*****		**14.8 (4), p = 0.09**		**11.5 (4), p = 0.09**	
Poorest	44.6	653	26.1	356	21.3	968	23.0	574	24.5	203	35.2	670	58.6	359	16.2	483	24.9	281	31.0	372
Poorer	51.7	867	25.1	403	21.4	964	24.2	762	29.4	261	35.3	772	57.2	478	27.0	596	28.0	297	29.9	422
Middle	48.9	1117	25.1	314	25.5	1035	27.4	974	38.8	365	32.6	687	53.0	544	35.2	689	31.1	346	27.5	387
Richer	46.9	992	27.9	269	24.8	1117	30.4	1229	50.7	419	30.1	631	54.8	691	40.5	810	31.2	367	26.9	386
Richest	49.1	1091	28.8	260	29.0	1405	28.8	1501	46.8	383	22.1	507	52.8	1104	43.9	935	28.8	480	26.0	400
Type of Place of Residence *(chi-squared (df), p-value)*	**1034.9 (1), p <0.001*****		**24.9 (1), p <0.001*****		**2386.0 (1), p <0.001*****		**2.9 (1), p = 0.16**		**356.6 (1), p <0.001*****		**742.2(1), p <0.001*****		**151.5 (1), p <0.001*****		**780.8 (1), p <0.001*****		**939.9 (1), p <0.001*****		**461.2 (1), p <0.001*****	
Urban	69.3	3351	24.9	876	55.3	2341	27.8	2492	53.2	949	23.3	1563	62.6	1430	50.8	1549	43.6	1434	40.4	454
Rural	34.5	1369	31.7	726	17.8	3148	26.7	2548	25.7	682	51.9	1704	46.6	1746	24.3	1964	9.2	337	17.1	513
Number of Household Members *(chi-squared (df), p-value)*	**41.2 (4), p = 0.004****		**9.5 (4), p = 0.22**		**3.9 (4), p = 0.66**		**7.8 (4), p = 0.24**		**18.6 (4), p = 0.01****		**99.3 (4), p <0.001*****		**5.1 (4), p = 0.48**		**71.6 (4), p <0.001*****		**17.2 (4), p = 0.05****		**16.1 (4), p = 0.19**	
1 person	54.8	634	24.3	121	25.3	389	25.5	770	49.0	124	28.8	670	52.7	260	37.1	491	28.4	132	25.5	247
2-3 people	51.0	1581	24.5	173	24.1	1440	27.4	1252	41.8	369	28.7	1105	54.4	771	36.5	948	32.7	447	27.8	640
4-6 people	47.2	1846	26.1	410	24.7	2692	27.8	1950	37.9	699	31.2	1052	55.1	1337	31.6	1349	28.7	778	29.5	849
7-9 people	43.6	565	29.7	351	23.3	846	28.2	732	38.0	319	44.4	344	57.1	610	27.4	572	26.6	326	26.4	186
10 or more people	4.1	94	26.3	547	24.4	122	25.9	336	35.8	120	48.5	96	50.8	198	26.1	153	24.9	88	26.6	45
Tenure *(chi-squared (df), p-value)*	**128.5 (2), p <0.001*****		**0.7 (2), p = 0.81**		**84.0 (2), p <0.001*****		**2.9 (2), p = 0.40**		**24.4 (2), p <0.001*****		**0.7 (2), p = 0.79**		**16.26 (2), p = 0.005****		**80.3 (2), p <0.001*****		**111.1 (2), p <0.001*****		**14.9 (2), p = 0.01***	
Does not own	56.5	1511	27.4	243	33.1	612	28.5	711	44.1	335	31.4	557	60.9	372	42.6	294	35.6	753	30.2	758
At least partly owns	41.6	1223	25.9	352	21.5	633	26.4	587	32.3	245	32.0	276	49.2	254	24.9	399	21.6	456	24.8	430
No information	50.3	1986	26.5	1007	24.0	4244	27.2	3742	39.5	1051	30.8	2343	54.6	2550	32.9	2820	28.2	562	28.2	779
Housing Quality *(chi-squared (df), p-value)*	**277.1 (2), p <0.001*****		**4.4 (2), p = 0.11**		**1043.3 (2), p <0.001*****		**44.2 (2), p <0.001*****		**192.4 (2), p <0.001*****		**80.5 (2), p <0.001*****		**43.7 (2), p <0.001*****		**793.2 (2), p <0.001*****		**450.3 (2), p <0.001*****		**144.6 (2), p <0.001*****	
Natural	35.8	740	34.1	78	16.8	1837	20.6	308	23.8	245	59.1	73	47.0	424	17.0	735	10.1	189	16.0	142
Rudimentary	49.4	2805	2.6	276	23.4	1154	27.0	903	31.2	339	38.5	406	51.9	970	30.3	1028	20.9	272	18.2	125
Finished	69.3	1175	26.2	1248	39.3	2498	28.2	3829	47.7	1047	29.7	2788	58.3	1782	46.4	1749	38.6	1310	31.8	1697

p <0.05, **p <0.01, ***p <0.001

Note: n is an unweighted count

Zimbabwe and Zambia between 44% (n = 1331) and 46% (n = 898) of households using a piped source in their dwelling, yard or plot report experiencing an interruption.

In Ethiopia, Gambia, Tanzania, Zambia and Zimbabwe household wealth is not significantly associated with households reporting an interruption ($p > 0.05$). In all other countries, Malawi, Nigeria, Sierra Leone, South Africa and Uganda, there was a statistically significant association ($p < 0.001$). In South Africa, 35% (n = 670) and 35% (n = 772) of households in the poorest and poorer wealth quintiles report experiencing an interruption. In Malawi, Nigeria, Sierra Leone and Uganda however, between 29% (Malawi) and 51% (Sierra Leone) of households in the richer and richest wealth quintiles reported an interruption.

Type of place of residence is significantly associated with experiencing an interruption in all countries apart from Nigeria ($p < 0.001$). In Gambia and South Africa more households living in rural areas report experiencing an interruption. 32% (n = 726) of all rural households, compared to 25% (n = 876) of urban households, report experiencing an interruption in Gambia. In South Africa, 52% (n = 1704) of all rural household and 23% (n = 1563) of all urban households reported experiences of interruptions. By contrast, in Ethiopia, Malawi, Sierra Leone, Tanzania, Uganda, Zambia and Zimbabwe more interruptions were reported by those living in urban areas, with between 40.4% (n = 454) of all urban households in Zimbabwe and 69% (n = 3351) in Ethiopia reporting experiencing an interruption.

Considerable variations exist between countries in the association between household size and reporting of interruptions. In 50% of countries (Gambia, Malawi, Nigeria, Tanzania and Zimbabwe) no significant relationship was found. In Zambia, Sierra Leone and Ethiopia, household size is significantly associated with reporting experiencing an interruption ($p < 0.01$). In South Africa, 49% (n = 96) of all households with over 10 members reported experiencing an interruption. Of the households with fewer members, significantly less reported experiencing an interruption however- 29% (n = 1105) of all 2-3 people households and 29% (n = 670) of all one person households. In Ethiopia, Sierra Leone, Uganda and Zambia, the inverse was found and more households with a smaller number of members reported interruptions, than those with a larger number of household members. For example, in Ethiopia, 55% (n = 634) of all households with only one member reported experiencing an interruption, compared to only 4% (n = 94) of all households with more than 10 members.

In Ethiopia, Malawi, Sierra Leone, Tanzania, Uganda, Zambia and Zimbabwe tenure is significantly associated with reporting of interruptions. In all cases, more households that did not own their home, compared to those that at least partly own their home, reported interruptions. In Tanzania, 61% (n = 372) of the households that did not own their home reported experiencing an interruption, compared to 49% (n = 254) of all who at least partly owned their home. Overall, in all countries with a significant association, of the households that did not own their home between 30% and 61% reported an interruption. In contrast, among all households that at least partly owned their home, interruptions were experienced by between 22% and 49%.

Housing quality was associated with interruptions to drinking water supplies in all countries ($p < 0.001$), other than Gambia. In South Africa, 59% (n = 73) of all household with natural quality housing materials reported an interruption, compared to 30% (n = 2788) of all households with finished housing materials. The inverse was present in Ethiopia, Malawi, Nigeria, Sierra Leone, Tanzania, Uganda, Zambia and Zimbabwe, with proportionately more households with finished materials reporting interruptions than those with natural materials. For example, in Uganda of all the households with finished housing materials 46% (n = 1749) reported an interruption, whereas comparably only 17% (n = 735) of all those with natural housing materials did.

5.3.3.1. Multi-level Logistic Regression Results

Table 5-7 compares, for each study country, a single-level unconditional model with a variance components model. The former shows that the odds of a household reporting an interruption range from 0.34 in Malawi to 0.57 in Sierra Leone. When accounting for household clusters within each country, the two-level variance components models show that the intercepts vary about the means with a variance of between 2.04 in the Gambia and 6.55 in Sierra Leone. The statistically significant odds of reporting an interruption subsequently range from 0.17 in Nigeria to 0.81 in Ethiopia, when clustering is accounted for.

The intra-class correlation shows that in Ethiopia, Nigeria and Sierra Leone 55% - 67% of the variation in the propensity to report an interruption lies between household clusters, whilst 33%-45% lies within household clusters. By comparison, in the Gambia, Malawi, Tanzania, Uganda and Zimbabwe between 38% and 44% of the variation in the propensity to report an interruption lies between household clusters, whilst 56% to 62% lies within household clusters. In both South Africa and Zambia, results show that the propensity to report an interruption are as likely to be attributed to community-level factors between household clusters, as they are to household characteristics.

Table 5-7: Exploration of clustering in reported service interruptions - comparison of a single-level unconditional model with a two-level variance components model

Model	Parameter	Ethiopia		Gambia		Malawi		Nigeria		Sierra Leone	
		Estimate	Std. Err.	Estimate	Std. Err.	Estimate	Std. Err.	Estimate	Std. Err.	Estimate	Std. Err.
Single-level Unconditional Model	***Fixed-part***										
	Intercept	1.14***	0.02	0.37***	0.01	0.34***	0.01	0.38***	0.01	0.57***	0.02
	Deviance	12,264		6,924		24,539		21,640		5,892	
Two-level Variance Components Logistic Model	***Fixed-part***										
	Intercept	0.81*	0.08	0.26***	0.02	0.21***	0.01	0.17***	0.01	0.33***	0.05
	Random-part										
	Between PSU variance	4.02	0.37	2.04	0.24	2.46	0.16	4.93	0.34	6.55	0.79
	Intraclass Correlation Coefficient (ICC)										
	Intra-PSU correlation coefficient	0.55		0.38		0.43		0.60		0.67	
	Deviance	9,405		5,897		19,867		16,224		4,216	

**p<0.05, **p<0.01, *** p<0.001; PSU: Primary sampling unit (household clusters)*

Model	Parameter	South Africa		Tanzania		Uganda		Zambia		Zimbabwe	
		Estimate	Std. Err.	Estimate	Std. Err.	Estimate	Std. Err.	Estimate	Std. Err.	Estimate	Std. Err.
Single-level Unconditional Model	***Fixed-part***										
	Intercept	0.50***	0.01	1.17***	0.03	0.44***	0.01	0.36***	0.01	0.40***	0.01
	Deviance	12,484		8,127		14,113		7,741		8,252	
Two-level Variance Components Logistic Model	***Fixed-part***										
	Intercept	0.30***	0.02	0.93	0.08	0.32***	0.02	0.18***	0.02	0.23***	0.02
	Random-part										
	Between PSU variance	3.40	0.27	2.53	0.26	2.55	0.21	3.32	0.36	2.56	0.28
	Intraclass Correlation Coefficient (ICC)										
	Intra-PSU correlation coefficient	0.51		0.43		0.44		0.50		0.44	
	Deviance	9,987		6,917		11,478		6,165		6,737	

**p<0.05, **p<0.01, *** p<0.001; PSU: Primary sampling unit (household clusters)*

Table 5-8: includes the results of multi-level logistic regression models undertaken for each study country. Odds ratios and standard errors for selected household and household cluster factors that explain inequalities in piped-water interruptions are illustrated, whilst actual values are available in appendix B.5.

Across all countries, variations of household-level factors such as type of improved source, household wealth, type of place of residence, number of household members and tenure are significant. Housing quality is not significant at the 5% level ($p < 0.05$) in any country and was therefore dropped from all models. Additionally, at the household cluster level, water stress with a one-month lag, blue water scarcity, change in urbanisation, neighbourhood wealth, neighbourhood age and population density are all significant in at least one country.

Type of Improved Source

When accounting for all other explanatory variables, type of piped source is significantly associated with reporting experiencing an interruption in all countries except Sierra Leone. In the Gambia, households using a public tap or standpipe have 58% greater odds of reporting an interruption than those using a piped source on premises (yard/plot/dwelling) ($p < 0.01$). Similarly, in South Africa, households using a public tap or standpipe have 31% greater odds of reporting an interruption than those using a piped source on premises.

In 8 of the 10 countries (Ethiopia, Malawi, Nigeria, South Africa, Tanzania, Uganda, Zambia and Zimbabwe) households using a tubewell or borehole have lower odds of reporting experiencing an interruption, than those using a piped source on premises. In Ethiopia the odds are 53% less ($p < 0.001$), in Malawi 87% less ($p < 0.001$), Nigeria 45% less ($p < 0.001$), 83% less in South Africa

Table 5-8: Main effects multi-level logistic regression analyses of household reported interruptions to improved drinking water sources for each study country.

	Study Country									
	Ethiopia	Gambia	Malawi	Nigeria	Sierra Leone	South Africa	Tanzania	Uganda	Zambia	Zimbabwe
Households (n):	*8873*	*5937*	*21,690*	*18,454*	*4498*	*9810*	*5889*	*11,442*	*6703*	*6906*
Household clusters (n) :	*535*	*278*	*825*	*1088*	*396*	*732*	*464*	*594*	*452*	*381*
Parameter	*Odds ratio (standard error)*									
Intercept	2.86 (4.46)	0.11* (0.10)	1.07 (0.34)	1.98 (0.12)	0.14* (0.12)	0.20*** (0.08)	1.24 (0.61)	0.94 (0.28)	0.45 (0.39)	0.52 (0.49)
Household-level Factors										
Type of Improved Supply *(Ref: Piped onto premises)*										
Piped to neighbour										
Public tap/standpipe		**				**				
Tubewell/borehole	***		***	***		***	***	***	***	***
Household Wealth *(Ref: Poorest)*										
Poorer										
Middle										
Richer		**			*	*				
Richest		**		**		**				
Type of Place of Residence *(Ref: Urban)*										
Rural	***		***		***	***	**	**	***	
Number of Household Members *(Ref: 1 person)*										
2-3 people						**			*	
4-6 people	*					***	**			***
7-9 people	**			*		***	**	*		**
10 or more people						**	**			***
Tenure *(Ref: Does not own)*										
At least partly owns						*			*	
No information						*				
Household Cluster-level Factors										
Water Stress with 1-month lag *(Ref: Low)*										
Low-Medium	**	-			-					
Medium-High		-			-			-		
High	*	-		**	-	***	**			
Extremely High					-	*	**	-		***
Arid & Low Water Use		-	-	***	-		-			
Blue Water Scarcity	**			***		**		**	**	***
Change in Urbanisation *(Ref: More urbanised)*										
Less urbanised										-
No change	**			**	**					
Neighbourhood Wealth *(Ref: Poor)*										
Middle		*		*	**			*		
Rich			*	**	**	***		***	*	
Neighbourhood Age *(Ref: <15yrs)*										
15-30 yrs					-					
31-40yrs										
41-50yrs				*						
>50yrs				*			-			
No information	-	-	-	-	-			-	-	-
Population Density					*					
Random-effects Parameters										
Between PSU Variance	1.94	1.73	1.38	4.13	4.88	2.24	2.02	1.12	1.47	1.90
Intraclass Correlation Coefficient (ICC)										
Intra-PSU correlation coefficient	0.37	0.34	0.30	0.56	0.60	0.41	0.38	0.25	0.31	0.37
Log likelihood	-4555.82	-2912.05	-9369.11	-7972.46	-2059.20	-4798.85	-3367.41	-5473.96	-2908.07	-3197.79
Deviance	9112	5824	18,738	15,945	4118	9598	6735	10,948	5816	6396

[orange] : Odds ratio <1.00 [blue] : Odds ratio >1.00 [ ] : Not significant [*] : Significant, p<0.05 [**] : Significant, p<0.01 [***] : Significant, p<0.001 [-] : No data *PSU: Primary Sampling Unit*

($p < 0.001$) and Tanzania ($p < 0.01$), 79% lower in Uganda ($p < 0.001$) and Zambia ($p < 0.001$) and in Zimbabwe 84% less ($p < 0.001$).

Household Wealth

Household wealth has a significant association with reporting of source interruptions in only the Gambia, Nigeria, Sierra Leone and South Africa. In both the Gambia and Sierra Leone, wealthier households are more likely to report an interruption than those that are poorer. For instance, households in Sierra Leone in the richer quintile have 44% higher odds of reporting experiencing an interruption than those in the poorest wealth quintile ($p < 0.05$). In Gambia, richer households have 31% greater odds, and the richest households have 44% higher odds of having an interruption than the poorest households ($p < 0.01$). Conversely, in Nigeria the richest have 31% lower odds of reporting experiencing an interruption than the poorest ($p < 0.01$). Similarly, in South Africa the richest households have 34% lower odds ($p < 0.01$), and the richer 24% lower odds ($p < 0.05$), of reporting an interruption than the poorest households.

Type of Place of Residence

Type of place of residence is significantly associated with reporting experiencing an interruption in 7 of the 10 countries: Ethiopia, Malawi, Sierra Leone, South Africa, Tanzania, Zambia and Zimbabwe. In South Africa, rural households have 4.46 times the odds than urban households of experiencing an interruption ($p < 0.001$). In Zambia, Sierra Leone and Ethiopia, the odds are 75%, 78% and 81% lower in households residing in rural areas than those in urban areas ($p < 0.001$). By contrast, in Uganda the odds of reporting experiencing an interruption are 35% lower ($p < 0.001$) in rural households, in Tanzania they are 42% lower ($p < 0.01$) and in Malawi they are 51% lower ($p < 0.01$) than in urban households.

Number of Household Members

In 3 of the 10 countries, Gambia, Malawi and Sierra Leone, there is no association between household size and interruptions to improved supplies. In all other countries, generally speaking the bigger the household, the higher the reporting of interruptions.

In Ethiopia, households with 4-6 members have 1.28 times the odds ($p < 0.05$), and households with 7-9 members have 1.36 times the odds ($p < 0.01$), of reporting an interruption than those in a one person household. In Nigeria and Uganda only households with 7-9 members have significantly greater odds, 1.20 and 1.24 respectively, of reporting an interruption than those in a one person household ($p < 0.05$). Whilst households in Zambia with 2-3 members are 1.38 times more likely to report an interruption than one person households ($p < 0.05$).

In both Zimbabwe and Tanzania, households with 4-6 people, 7-9 people and more than 10 people all have greater odds of reporting an interruption than one person households. This is also the case in South Africa, however additionally 2-3 people households also have greater odds of reporting an interruption. Overall, as household size increases, so too do the odds. For example, in Zimbabwe, 4-6 member households have 1.56 times the odds ($p < 0.001$) than one person households, 7-9 member households have 1.57 times the odds ($p < 0.01$) and households with more than 10 members have 2.34 times the odds of an interruption.

Tenure

Home ownership is only statistically significantly associated with experiencing interruptions in South Africa and Zambia. In both cases, households that at least partly own their home have greater odds of reporting an interruption than those that do not own their home. In Zambia, the odds are 78% greater ($p < 0.05$) and in South Africa they are 92% higher ($p < 0.05$).

Change in Urbanisation

In Ethiopia, Nigeria and Sierra Leone there is a significant association between change in urbanisation and reporting of interruptions. In all instances, households living in areas where there has been no change in urbanisation have lower odds of reporting an interruption than those in areas that have become more urbanised. In Ethiopia the odds of reporting an interruption in an area that has not changed are 46% less than those in more urbanised areas ($p < 0.01$). Whilst in Nigeria the odds are 39% less ($p < 0.01$) and in Sierra Leone they are 55% lower ($p < 0.01$).

Neighbourhood Wealth

Neighbourhood wealth is significantly associated with reporting experiencing an interruption in all countries except Ethiopia, Tanzania and Zimbabwe. In South Africa, households in richer neighbourhoods have 57% lower odds ($p < 0.001$) of reporting an interruption than those in poor neighbourhoods. Whereas in Gambia, compared to households in poor neighbourhoods, households in mid-wealth neighbourhoods have 33% lower odds of reporting an interruption ($p < 0.05$).

In Nigeria, Sierra Leone and Uganda households in both middle and rich neighbourhoods have higher odds of reporting experiencing an interruption than those in poor neighbourhoods.

Households in rich neighbourhoods have 2.05 (p <0.01), 2.09 (p <0.001) and 3.90 (p <0.01) higher odds in Nigeria, Uganda and Sierra Leone respectively. In addition, households in rich neighbourhoods in Malawi had 1.30 time the odds (p <0.05) and in Zambia 1.56 times the odds (p <0.05) of an interruption than those in poor neighbourhoods. Households in mid-wealth neighbourhoods in Sierra Leone had 2.40 greater odds (p <0.01), in Uganda 1.36 greater the odds (p <0.01) and in Nigeria 1.51 higher odds (p <0.05) of experiencing an interruption than those in poor neighbourhoods.

Age of Neighbourhood

A statistically significant association between neighbourhood age and reporting of interruptions is only present in Nigeria. In older neighbourhood's households have lower odds of reporting an interruption than those in neighbourhoods that are less than 15 years old. For example, in neighbourhoods of 41-50 years households had 63% lower odds (p <0.05), whereas in those older than 50 years households had 64% lower odds (p <0.05) of reporting an interruption than neighbourhoods less than 15 years old.

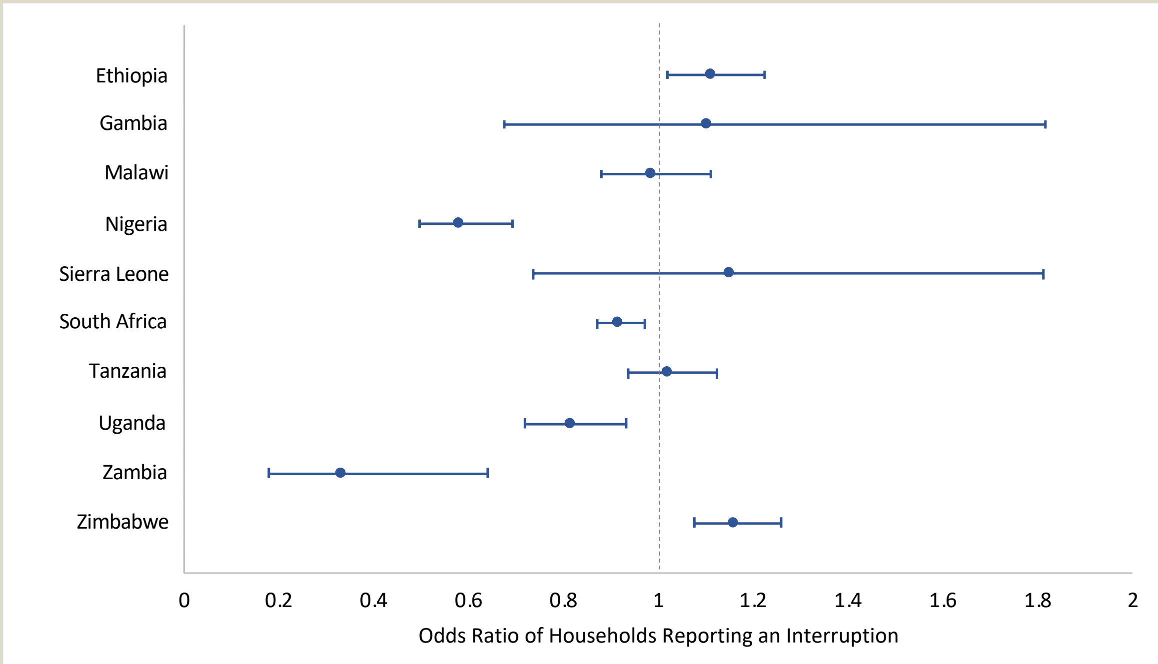
Population Density

Population density is significantly associated with reporting experiencing an interruption in only Sierra Leone. For each population increase of 10,000 people per DHS buffer area, the odds of reporting an interruption increase by 1.07 (p <0.01).

Blue Water Scarcity

The relationship between blue water scarcity and reporting of interruptions, for all countries, is shown in Figure 5-9. A statistically significant relationship is only present however in 6 of the 10 countries: Ethiopia, Nigeria, South Africa, Uganda, Zambia and Zimbabwe. In Ethiopia and Zimbabwe, as blue water scarcity increases so too does the odds of reporting an interruption. In Nigeria, Uganda, South Africa and Zambia the inverse exists, with the odds of reporting an interruption decreasing as blue water scarcity increases.

For every one point increase in annual average blue water scarcity the odds of reporting experiencing an interruption are 1.12 times higher in Ethiopia (p <0.01) and 1.16 times higher in Zimbabwe (p <0.001). In contrast, in Zambia and Nigeria for every one point increase in annual average blue water scarcity, the odds of experiencing an interruption are 66% (p <0.01) and 42% (p <0.001) less. In Uganda, the odds are even lower at 8% less for every one point increase in annual average blue water scarcity, whilst in South Africa the odds of reporting having an interruption are 18% less.



<u>Figure 5-9:</u> The odds of households reporting an interruption for each point increase in annual average blue water scarcity, where 0 = no water scarcity, 1.0-1.4 = moderate water scarcity, 1.5-1.9 = significant water scarcity, >2 = severe water scarcity

5.3.3.1. Water Stress with one-month lag

The association between water stress and source interruptions, for all countries, is shown in Figure 5-10. The odds, and standard errors, of households reporting an interruption under each water stress risk category, for all countries, are present in Figure 5-11 (a-e). There is no statistically significant relationship between water stress and interruptions to source in Gambia, Malawi, Sierra Leone, Uganda or Zambia.

In Nigeria, households in arid and low water use areas have 16.40 times the odds of reporting an interruption to their improved source than those in low water stress areas (p <0.001). Of all countries, Ethiopia is the only country where a significant relationship between households living under low-medium water stress (Figure 5-12a) and interruptions exists. Households living under low-medium water stress have 12.14 times the odds of reporting an interruption than those living in areas of low water stress (p <0.01).

In Ethiopia, Nigeria, South Africa and Tanzania households living in high water stress have greater odds than those in low water stress areas of reporting an interruption in their source. In Nigeria, the odds are 7.95 times greater (p <0.01), in South Africa they are 2.78 times greater (p <0.001),

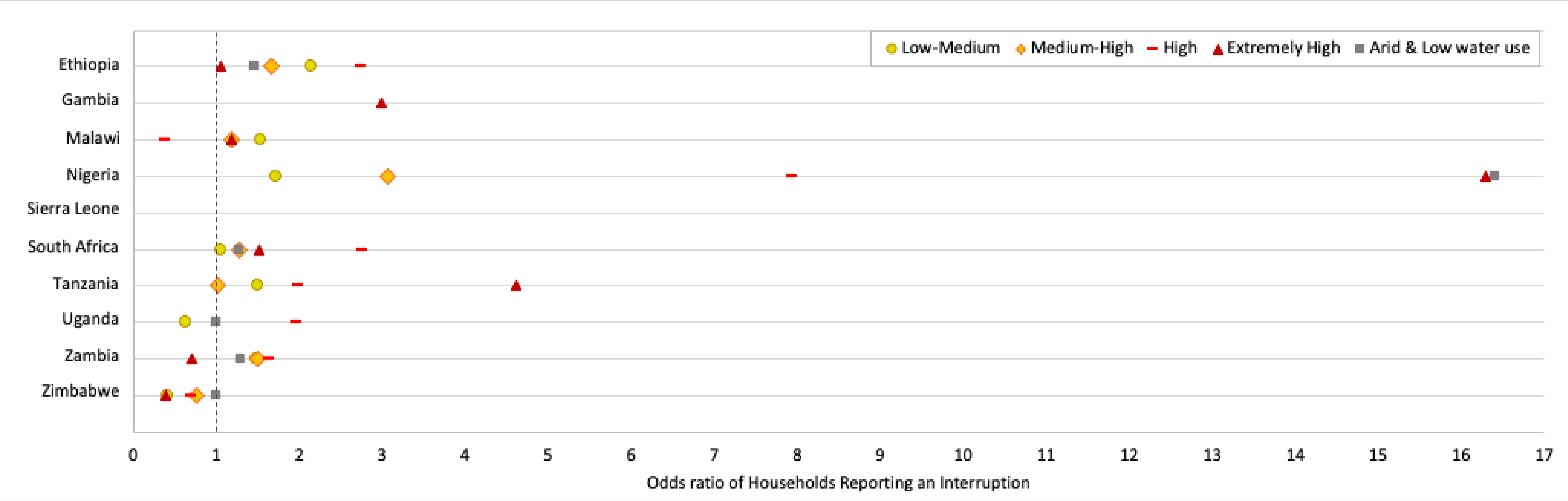


Figure 5-10: The odds of households, living in each water stress risk category, reporting an interruption compared to those living in areas of low water stress

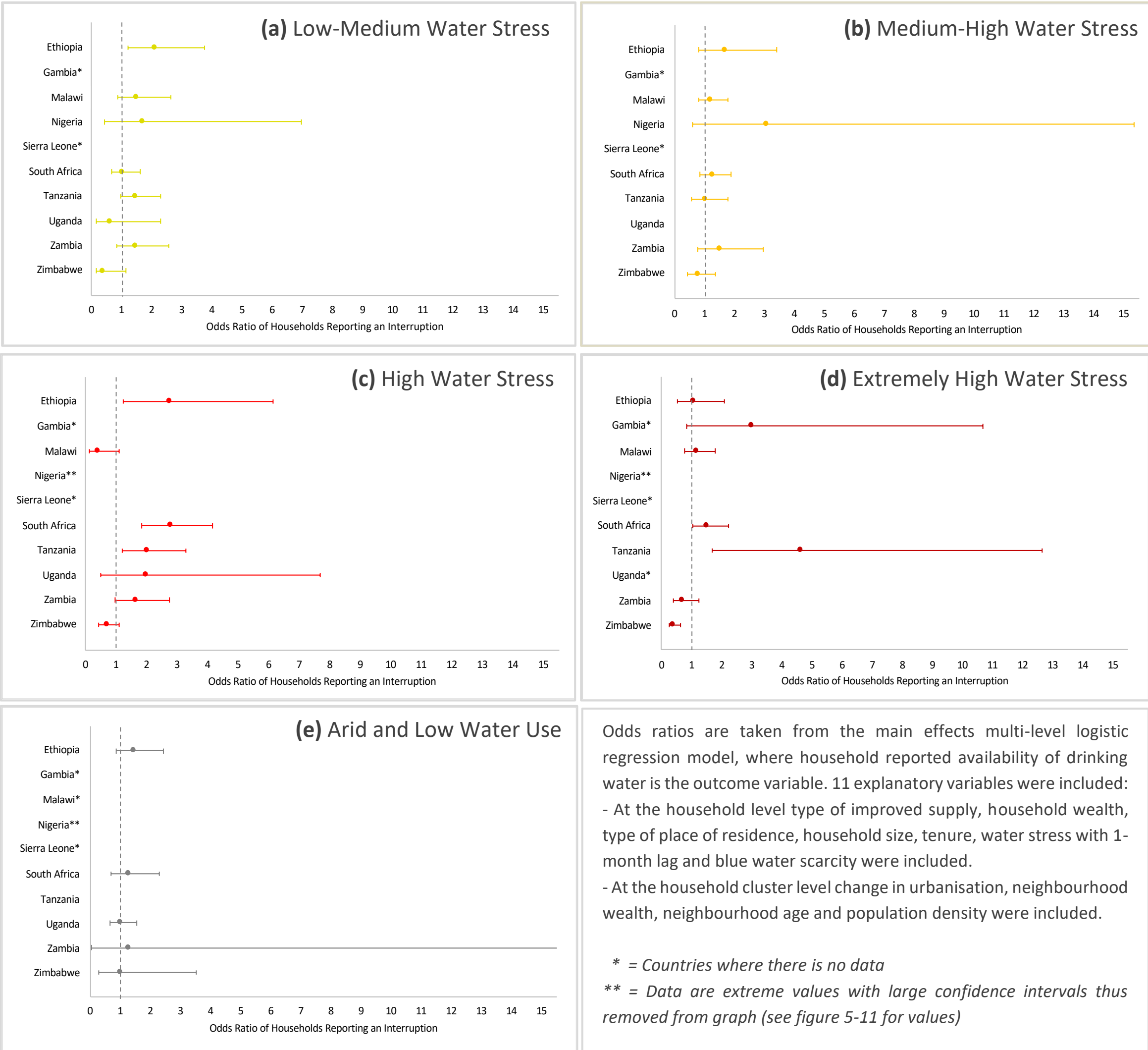


Figure 5-11 (a-e): The odds of households reporting an interruption in each WRI water stress risk category, compared to households living in low water stress areas (with 95% confidence intervals).

similarly in Ethiopia they are 2.76 times bigger (p <0.05) and in Tanzania they are twice as big (p <0.01).

The odds of households in extremely high water stress reporting an interruption are 60% lower than in low water stress areas in Zimbabwe (p <0.001). Conversely, in Tanzania and South Africa, households in areas of extremely high water stress have greater odds of reporting an interruption than those in low water stress. In South Africa, these odds are 4.62 times greater (p <0.01), whereas in Tanzania they are 1.52 times greater (p <0.01).

5.3.4. Variations in Water Stress

Variations in the association between water stress and interruptions exist depending on the lag-time used (Figure 5-12). These variations are present both within countries and between countries, both the odds ratios and their significance change depending on the country and lag-time in question (see B.2, Tables B.2.1-B.2.10). A one-month lag time was used as it is the best fit over all countries; in individual countries there were sometimes lags that explained a greater proportion of the variation in availability, as noted below.

Ethiopia

In Ethiopia, there is a significant association between water stress and reporting interruptions when using no lag, a 1-month lag and a three-month lag (Figure 5-12a). Between these three versions of the water stress variable there is minimal variation in the odds of reporting an interruption.

When using no lag and a 1-month lag, there is a significant relationship between households in low-medium water stress and those in low water stress, with the odds of reporting an interruption changing by 0.10. In addition, when using the 1-month lag households living in areas of high water stress have 2.75 times the odds of reporting an interruption than those in low water stress ($p < 0.01$).

For the water stress variables with a lag time of 2 or more months, the odds of households reporting an interruption drop to less than 2. The only significant association is when using a 3-month lag, where households living in medium-high water stress have 1.56 times the odds of reporting an interruption than those in low water stress ($p < 0.05$).

Gambia

For all water stress variables, in Gambia, there is no statistically significant relationship between water stress and reporting of interruptions (Figure 5-12b). Discounting significance, the longer the lag time, the lower the odds of reporting an interruption. As lag time increases, households transition from living in extremely high and high water stress, to low-medium and medium-high water stress.

Malawi

A significant association between water stress and reporting of interruptions only exists when using a 2 month or 3-month lag time in Malawi (Figure 5-12c). In both cases, the odds of reporting an interruption are lower than one, meaning households in low water stress are more likely to report an interruption. For example, when using a 3-month lag time, households living under extremely

(a)

Ethiopia					
	Water Stress Variable				
Water Stress Risk *(Ref: low)*	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Low-Medium	**	*			
Medium-High				*	
High		**			
Extremely High					
Arid/Low Water Use					

(b)

Gambia					
	Water Stress Variable				
Water Stress Risk *(Ref: low)*	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Low-Medium	-	-	-		
Medium-High	-	-	-		-
High	-	-		-	-
Extremely High				-	-
Arid/Low Water Use	-	-	-	-	-

(c)

Malawi					
	Water Stress Variable				
Water Stress Risk *(Ref: low)*	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Low-Medium			*		
Medium-High					
High					
Extremely High	-			*	-
Arid/Low Water Use	-	-	-	-	-

(d)

Nigeria					
	Water Stress Variable				
Water Stress Risk *(Ref: low)*	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Low-Medium				-	
Medium-High					
High	***	**	*		***
Extremely High	*o*	**	***	*	*
Arid/Low Water Use	***	***	***	***	***

(e)

Sierra Leone					
	Water Stress Variable				
Water Stress Risk *(Ref: low)*	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Low-Medium					
Medium-High					-
High	*o*	*o*	*o*	*o*	-
Extremely High					-
Arid/Low Water Use					-

(f)

South Africa					
	Water Stress Variable				
Water Stress Risk *(Ref: low)*	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Low-Medium					
Medium-High	**		*		**
High	*	***			
Extremely High	***	*	**		***
Arid/Low Water Use					

(g)

Tanzania					
	Water Stress Variable				
Water Stress Risk *(Ref: low)*	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Low-Medium					
Medium-High			**	*	*
High		**			
Extremely High	*	**	***		
Arid/Low Water Use	-	-	-	-	-

(h)

Uganda					
	Water Stress Variable				
Water Stress Risk *(Ref: low)*	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Low-Medium	*o*				*o*
Medium-High	*o*	-	*o*	*o*	
High			*		
Extremely High	-	-	-	-	
Arid/Low Water Use					

(i)

Zambia					
	Water Stress Variable				
Water Stress Risk *(Ref: low)*	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Low-Medium					
Medium-High				**	
High				**	
Extremely High					*o*
Arid/Low Water Use					

(j)

Zimbabwe					
	Water Stress Variable				
Water Stress Risk *(Ref: low)*	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Low-Medium	*				
Medium-High					
High					
Extremely High	***	***	***	***	*
Arid/Low Water Use					

Key	
	Odds Ratio
	>4.60
	2.00-4.59
	1.50-1.99
	1.01 -1.49
	1.00
	0.80-0.99
	0.60-0.79
	0.40-0.59
	<0.39
*	p<0.05
**	p<0.01
***	p<0.001
-	: No data
o	:Omitted

Results are taken from the main effects multi-level logistic regression models, with all 11 explanatory variables and each version of the water stress variable.

<u>Figure 5-12:</u> Odds of reporting an interruption for households with different water stress risks

high water stress have 70% lower odds of reporting an interruption than those in low water stress. Likewise, when using a 2-month lag, households living in low-medium water stress have 40% lower odds of reporting an interruption than those in low water stress. Households are only living under extremely high water stress when using a 1 month, 2 month lag time.

Nigeria

For all versions of the water stress variable, in Nigeria there is a significant association between water stress and reporting of interruptions for households living in arid or low water use areas, high and extremely high-water stress compared to those living in low water stress (Figure 5-12d).

The odds of reporting an interruption for households in high water stress compared to low water stress decrease as the lag time increases. For instance, when using no lag, the odds of households reporting an interruption are 20.12 times higher for those in high water stress compared to those in low water stress ($p < 0.001$), however, when using a 6-month lag, the odds decrease to 2.90 ($p < 0.001$).

The inverse happens for households living in arid or low water use areas compared to those in low water stress. When using water stress with no lag, households in arid or low water use areas have 17.17 times the odds of reporting an interruption than those in low water stress areas ($p < 0.001$). These odds increase top 24.24 when using a 6-month lag ($p < 0.001$).

Sierra Leone

Water stress is omitted from the models when using no lag, 1-month, 2-month or 3-month lag in Sierra Leone (Figure 5-12e), as all households in the sample are under low water stress. When using a 6-month lag, households under low-medium water stress are 3.74 times more likely to report an interruption than those in low water stress, however this is not statistically significant.

South Africa

In South Africa, for the water stress variables with no lag, 1 month and 2-month lag times there is minimal variation in the odds of reporting an interruption for households living with different water stress risks (Figure 5-12f). The odds of reporting an interruption are significant and range from 1.52 when using a 1-month lag ($p < 0.05$) to 1.83 when no lag is used ($p < 0.001$), for those in extremely high water stress compared to those in low water stress. Similarly, for households in high water stress compared to those in low water stress, the odds of reporting an interruption are significant and range from 1.61 when there is no lag ($p < 0.05$) to 2.78 when using a 1-month lag ($p < 0.001$).

The odds of reporting an interruption range from 1.50 ($p < 0.05$) to 1.69 ($p < 0.01$) when using a 2-month lag or no lag, for households in extremely high water stress compared to those in low water stress.

When using a 3-month lag time there is no statistically significant relationship between water stress and reporting of interruptions. Whereas the odds of reporting an interruption drop to less than one when using a 6-month lag time ($p < 0.01$).

Tanzania

When using no lag, a 1-month lag and a 2 month lag, the statistically significant relationship between water stress and reporting of interruptions in Tanzania is predominantly between households in extremely high or high water stress and those in low water stress (Figure 5-12g). There is some variation when using water stress with these three water stress variables, though this is minimal.

When using a 1-month lag time for water stress, the odds of reporting an interruption are at their highest for households living in high (OR: 2.00, $p < 0.01$) and extremely high water stress (OR: 4.62, $p < 0.01$). As the lag time increases to 3 months or 6 months, this significant relationship shifts to households in medium-high water stress compared to those in low water stress. The odds of reporting an interruption drop to less than one when using a 6-month lag time ($p < 0.01$).

Uganda

Variation in the odds of reporting an interruption is minimal when using the different water stress variables in Uganda (Figure 5-12h). The exception to this is the one statistically significant relationship between households living under high water stress and those in low water stress when using a 2-month lag. Here the odds of reporting an interruption are 5.19 times higher for those in high water stress ($p < 0.05$). Households are only living under extremely high water stress when a 6 month lag is used.

Zambia

In Zambia, for all water stress variables, the odds of reporting an interruption range from 0.52-1.64. The only statistically significant association between water stress and reporting of interruption however is present when using the variable with a 3-month lag (Figure 5-12i). Here, households living in high water stress have 72% lower odds of reporting an interruption than those in low water stress ($p < 0.01$), whilst households in medium-high water stress have 55% lower odds ($p < 0.01$).

Zimbabwe

Other than households living in arid or low water use areas, generally speaking in Zimbabwe for all water stress variables, the odds of reporting an interruption are lower than one regardless of the water stress risk category (Figure 5-12j). The association found in arid and low water use areas is not statistically significant, however.

For all water stress variables, there is a significant association between water stress and reporting interruptions for households in extremely high water stress compared to those in low water stress. The odds range from 0.34 when using a 2-month lag ($p < 0.001$), to 0.52 when using a 6 month lag ($p < 0.05$), lag time therefore has little effect on the odds of reporting an interruption.

Similarities between Countries

Comparison of the countries and odds ratios for each water stress variable are available in appendix B.6; B.6.1-B.6.5.

In Nigeria, South Africa, Tanzania and Zimbabwe, a significant association between water stress and reporting of interruptions when using a 6-month lag time is found. In Nigeria the odds are greater than 1 however, whereas in the other three countries, the odds are lower than 1 meaning households in low water stress are more likely to report an interruption than those in higher water stress.

There are similarities in the relationship between water stress and interruptions between Nigeria, South Africa and Tanzania, regardless of the water stress variable used. In all cases Nigeria consistently has the highest odds of reporting an interruption.

When using a 3-month lag, similarities are present between Zimbabwe, Zambia and Malawi, where again, the odds of reporting an interruption are less than one. Commonalities are also present between Ethiopia and Tanzania, where the only significant relationship is with households in medium-high water stress who have higher odds of reporting an interruption than those in low water stress.

5.3.5. Packaged Water Usage

Packaged water, including bottled and sachet water, was not included in this analysis as it is not always classified as an improved drinking water source. However, we are aware that the use of packaged water is a key coping strategy to intermittent and unavailable improved drinking water supplies. Closer examination of the households using an improved or packaged drinking water source (see Table 5-9) found that bottled water is used by less than 2% of such households in all countries. For sachet water, the majority of countries had no households that used it as their drinking water source, however, in Nigeria 10% of households used it and 5% of households in Sierra Leone relied on this source of water.

Of those that used a packaged drinking water source, in all countries 100% of households used an improved source as their secondary source for cooking and handwashing. Between 22% (South Africa) and 74% (Sierra Leone) of households using an improved water source as their secondary source reported experiencing an interruption in the 2 weeks prior to being surveyed.

Table 5-9: Interruptions of secondary water supplies for households that use packaged sources of drinking water

	Total number (n) of HHs in DHS using an improved/ packaged drinking water source	Percentage (%) of HHs using a packaged source of drinking water		Percentage (%) of HHs using packaged drinking water that also use an improved secondary water source (n)	Percentage (%) of HHs using packaged drinking water who reported experiencing an interruption in their secondary water source (n)
		Bottled water (n)	Sachet water (n)		
Ethiopia	9195	1.37 (126)	0.00 (0)	100 (126)	**71.43 (90)**
Gambia	6073	0.95 (58)	0 .00(0)	100 (58)	**36.21 (21)**
Malawi	22,013	0.03 (6)	0.00 (0)	100 (6)	**33.33 (2)**
Nigeria	21,204	0.84 (178)	9.80 (2078)	100 (2257)	**37.57 (848)**
Sierra Leone	4857	0.12 (6)	5.37 (261)	100 (267)	**74.16 (198)**
South Africa	9985	0.86 (86)	0.00 (0)	100 (86)	**22.09 (19)**
Tanzania	6032	1.41 (85)	0.00 (0)	100 (85)	**43.53 (37)**
Uganda	11,935	0.72 (86)	0.14 (17)	100 (103)	**57.28 (59)**
Zambia	6934	0.53 (37)	0.00 (0)	100 (37)	**43.24 (16)**
Zimbabwe	6986	0.67 (47)	0.00 (0)	100 (47)	**38.29 (18)**

5.4. Discussion

This analysis focuses on the currently under-researched area of drinking water availability in SSA. At the time of writing, we are unaware of any other multi-country study which explores the household and community causes of interruptions to improved drinking water sources. To the best of our knowledge, it is also the first to consider the association between such interruptions and local water scarcity and water stress in both the rural and urban context.

Household experiences of water service interruptions vary considerably between the SSA study countries included in this analysis. The results show that large proportions of the population are living with interrupted drinking water sources, regardless of the country in question. We find in some instances, such as Tanzania, over half of the population experienced an interruption of at least one full day in the two weeks prior to being surveyed. In comparison, in half of the countries included in this analysis the levels are much less, with up to one third of the population reported experiencing an interruption (Figure 5-7).

We find up to 67% of the variation in household reported service availability is explained by community-level contextual factors and where you live in Ethiopia, Nigeria and Sierra Leone. This likely reflects the standard of infrastructural upkeep and age of services. In South Africa and Zambia community and household factors equally explain the variation in reporting interruptions, whilst in all other countries, household-level factors are bigger contributors to service interruptions (Table 5-7).

Variations in service interruptions exist based on the type of water service used by households. This finding builds on existing research which, through its systematic analysis of previous studies, determined evidence of a relationship between source type and availability was inconclusive (Thomas *et al*. 2020). In all ten research countries, we find a significant association between reported interruptions and source type, with households using a tubewell or borehole least likely to have unavailable services (Table 5-6).

5.4.1. Key Household and Community Characteristics Associated with Interruptions

The results of this study show, across all countries, household and community characteristics including type of improved drinking water service, household size and rurality are consistently associated with reported interruptions (Table 5-8:). Variations exist between countries in the association between interruptions and population density. Whilst this study cannot confirm that tenure, neighbourhood age, change in urbanisation and home ownership were consistently related to service interruptions across SSA, it did partially substantiate this association, with evidence provided in several countries. One anticipated finding was that wealth would be related to reporting of interruptions. Contrary to expectations, this was not found to be the case at the household level. Furthermore, at the community level, we find the inverse to what was anticipated.

One of the most significant findings to emerge from this study is that in the majority of countries, more households using piped services report interruptions than those using a tubewell or borehole (Figure 5-8). Our findings support previous research which attributed interruptions of piped services to old and poor quality infrastructure and a lack of network expansion to meet increased population demand (Juma *et al*. 2018). The greatest differences in reported interruptions between the two source types was in Uganda and Malawi. In both cases, despite over half of piped service users reporting an interruption, less than 15% of households used a piped service (Figure 5-5). We find that interruptions affecting one service type are not correlated with interruption prevalence affecting other types of services (Figure 5-8), suggesting that the processes affecting interruptions vary considerably depending on the service in question.

Another major finding is that urban households are more likely to report an interruption than those in rural localities in most countries (Table 5-8:). South Africa is an outlier to this association however. This rural: urban disparity is greatest in Zambia, Sierra Leone and Ethiopia. In the latter, low capacity of water production due to surface water scarcity has been cited as a key cause of interruptions in urban areas (Adane *et al*. 2017). Given the use of piped services fed by surface water tends to be greatest in urban areas (Bain, Wright, *et al*. 2014), this correlates with the implications of water stress and the effects of climatic variability on surface water stores. These findings also support MacDonald *et al.'s*, (2011) calls for the increased use of motorised borehole pumps for more reliable urban water supply. There are, however, other possible explanations for this finding. Elsewhere causes of interruptions in urban areas have been cited as limited electricity provision, government water supplier failures (including unfair water rationing schedules) and unreliable pricing structures (Fisher et al. 2015; Smiley 2016), as well as leakages caused by above ground plastic pipes being broken by city traffic and intentional illegal connections (Rugemalila and Gibbs 2015). Low income urban areas are also often perceived as low political priority, meaning interruptions are longstanding (Chitonge 2014). In all instances, rapid growth in demand due to urbanisation which leads to rationing and non-revenue water are additional complicating factors (Simukonda *et al*. 2018a).

An important finding from our bivariate analysis, is that household wealth is associated with interruptions to drinking water sources in five countries (Table 5-6). In four of these countries, wealthier households report more interruptions. The inverse is found in South Africa, which could relate to the prevalence of piped water by wealth quintile. 53.0% of the poorest households in South Africa use a piped source on premises compared to between 0.3% and 2.0% in the other four countries (see appendix B.4). This difference between countries is likely however to be a selection effect as those included in the sample will be the poorest households using piped water. As a result, in the other four countries, Malawi, Nigeria, Sierra Leone and Uganda, the households in question are unlikely to be similar to the households in South Africa. In the multi-level models, household wealth has a significant association with reported service interruptions in only four countries. In two countries, Nigeria and South Africa - the richest in SSA with significant wealth inequalities (Fosu 2014)- poorer households are more likely to report an interruption than richer households, supporting recent evidence from Zoungrana (2020). In comparison, in the other two countries - the Gambia and Sierra Leone-, richer households are more likely to report an interruption than those that are poorer. This finding is consistent with Adeniji-Oloukoi, Urmilla and Vadi 's (2013) comments that wealthier households rely on technical strategies, such as water tanks, as coping strategies, compared to poorer households who have more entrenched behavioural related strategies, as they are more likely to repeatedly experience interruptions. Higher reporting of interruptions by the rich could also be attributed to the greater voice of richer households who are less likely to tolerate minor interruptions and have greater capacity and confidence to report them (Majuru *et al*. 2016).

Contrary to expectations, at the community-level, we find richer neighbourhoods are more likely to experience interruptions than poorer areas in half of the study countries (Table 5-8:). These results differ from Mehta (2014) and Chitonge's (2020) evidence of economic water scarcity which suggest populations experience water shortages due to a lack of investment in water services. There are likely to be different reasons for this association, especially given variations across the study countries in the most common type of water service used in rich neighbourhoods. South Africa and the Gambia are anomalies in this association, with poorer neighbourhoods experiencing more interruptions. These findings confirm those of Garrick, Hanemann and Hepburn (2020), who show drinking water infrastructure in poorer areas is often in a poorer state of repair and lacks the required funds for maintenance. For instance, communal supplies tend to be under greater pressure due to overuse and subsequently prone to breakages (Machingambi and Manzungu 2003).

Our analysis also suggests households with more members are more likely to experience an interruption (Table 5-8:). This could be a result of smaller, one-person households, being more likely to miss short duration interruptions when they are away from the home. Alternatively, in all countries apart from Nigeria and South Africa, use of communal sources, including public taps and standpipes, tubewells and boreholes, which are more prone to breakages, is higher in bigger households. Such households will also have greater water requirements, placing additional pressures on existing supplies (Dungumaro 2007; Arouna and Dabbert 2010). Moreover, a greater proportion of bigger households are located in rural areas, thus the drinking water sources being used are likely to be under greater pressure as they are communal supplies, and have fewer maintenance resources available to deal with breakages due to being in rural or remote locations (Kumamaru *et al*. 2011).

5.4.2. Association of Environmental Factors with Interruptions

We find water stress is consistently associated with household reported interruptions, whereas findings relating to water scarcity are more varied. Generally, more households in areas of higher water stress report more interruptions than those in areas of low water stress. Zimbabwe is the outlier to this however. In the countries where higher water stress is significantly associated with reported interruptions, piped water sources predominate. For instance, in South Africa, 75% of households in high or extremely high-water stress use piped supplies. This could suggest that water stress is affecting surface water stores, such as reservoirs, dams and lakes, which feed piped supplies more than it is affecting tubewells and boreholes that extract groundwater. The response of groundwater to climatic variability is known to be slower than that of surface water (MacDonald *et al*. 2011). Aquifers provide water supplies that can be maintained during periods of little to no rainfall, whilst surface water is more directly affected by higher rates of evapotranspiration and rainfall variability (MacDonald *et al*. 2011). There is no statistically significant relationship between water stress and water interruptions in five countries. However, there is little to no variation in water stress, and consequently no data in three of the ten countries (Table 5-8:).

Unexpectedly, in four countries, households in areas of greater water scarcity are less likely to report an interruption, thus challenging findings from the likes of Klingel (2012). Variations exist however, with households in higher blue water scarcity areas more likely to report an interruption in only Zimbabwe and Ethiopia (Table 5-8:). Differences between water stress and water scarcity results could be a result of WFN water scarcity data being an annual average which subsequently masks monthly variations and seasonality which the WRI water stress data accounts for. This is evident when comparing Figure 5-3 and Figure 5-4. Additionally, the WFN water scarcity data is narrower in definition and only focuses on consumptive blue water, thus fails to consider non-consumptive or green or grey water which the WFN water stress data does include (Mekonnen and Hoekstra 2011). Given this, the relationship with the seasonal water stress metric is more plausible than that with the water scarcity metric.

We attempted to control for the lag time between water stress and its impact at the household level. Whilst we used a 1-month lag time in the main effects models, we find pronounced differences in the association between water stress and household interruptions depending on the lag time and the country (Figure 5-12). We see plausible relationships between water stress and interruptions when using a lag time that is less than 3-months. Lag times of 3- and 6-months have less plausible associations with interruptions, especially in Uganda and South Africa. Groundwater responds more slowly to water stress than surface water (MacDonald *et al*. 2011). In contrast, the relationship between water stress and interruptions for supplies that rely on surface water stores is dependent on reservoir capacity relative to withdrawals and renewal. In places where large reserves are available, depending on demand, the rationing of supplies as a response to water stress will not be undertaken as immediately as those reliant on smaller surface water stores (Kumpel and Nelson 2016). There will therefore be a greater lag time between water stress and interruptions of supplies. Therefore, whilst on a preliminary basis we used a 1-month lag time, we show that depending on the country in question it may be more appropriate to use a different lag time. Moving forward, we need to consider the resilience of water supplies on a local scale, especially surface water stores.

It is important to note that both South Africa and Sierra Leone are consistent outliers in the associations found throughout this study's multi-level modelling. For example, compared to all other countries, in South Africa the inverse association is found with regards to household wealth and rurality and service availability. Community characteristics such as population density are only significant in Sierra Leone (Table 5-8:). Whilst for other variables, for instance type of supply and number of household members where there are consistencies across study countries, there is no association in Sierra Leone. The discrepancies found in South Africa are to be expected given its level of development compared to all other study countries. In Sierra Leone, we find that where you live is related to service availability most, however further research is required to explore in greater detail what is happening.

5.4.3. Limitations

The DHS question on drinking water service availability is necessarily restricted in its scope, however as a result, it has limited ability to truly represent household experiences of service interruptions. Such a complex issue, which has a multitude of interrelating factors affecting the outcome, can never be fully captured in one survey question. It is therefore important to recognise the limitations of the survey question and resultant quantitative data. For instance, the question is temporally limited with its focus on interruptions within a two-week window. Recall bias will likely exist (Boerma and Sommerfeltb 1993), with respondents failing to remember or misremembering interruptions in their supply. For instance, respondents may misclassify events that were 3-4 weeks ago, which could result in over or under estimation of supply availability (Overbey *et al*. 2019). The temporal limitations of the DHS question also mean annual variability (e.g. seasonality) in interruptions is not directly accounted for, nor does it identify whether the interruption reported by households is recurring. Depending on when the survey was undertaken relative to the time of year and seasons, the outcome of interruptions is likely to differ between households. The DHS question also only concerns piped water services, tubewells and boreholes, meaning it naturally limits the scope of households included to those that can afford such water services. Our findings relating to rurality must therefore be interpreted with caution, as low income urban/rural households will have been excluded during the data preparation.

There could be issues of data emission or item nonresponse as a result of the DHS surveying the head of household, and not the household member that is responsible for drinking-water and therefore is most knowledgeable. Similarly, gender related biases may exist in the DHS data as a consequence of the enumerator-effect and how the genders of the interviewer and interviewee effect interactions, levels of trust and willingness to be open (West and Blom 2017).

To maintain anonymity of households surveyed, the DHS randomly displace the GPS coordinates of households clusters by up to 10km in rural areas and 2km in urban areas (Mayala *et al*. 2018). Subsequently, when linking the DHS household clusters to the WRI water stress data and WFN water scarcity data in ArcPro, household clusters which fell on, or close to, the boundary of each water stress/scarcity classification may have been misclassified.

Additional limitations in the data used in this analysis exist. For instance, we account for type of improved supply and housing quality twice as it is included in the DHS's wealth index classification. Consideration was given to recalculating the wealth index, however it was decided that without details of water supply or housing quality the wealth index would be very weak. Similarly, by aggregating the DHS's household wealth variable to create a neighbourhood wealth variable, closely located extreme differences in wealth which are especially prevalent in urban areas (Miller 2022), are not accounted for.

Finally, we limited our analysis to focus on interruptions to drinking water services only. However, some households experiencing interruptions may adapt by drinking packaged water, including sachet and bottled water (Stoler 2017), though continue to rely on piped services for cooking and handwashing. As shown in

Table **5-9**, closer examination of the DHS data found that in Nigeria and Sierra Leone, households using sachet water for drinking water also used improved services for non-drinking water and experienced interruptions. We excluded these households, but as demonstrated, their inclusion could potentially alter our findings. Moving forward, consideration of interruptions to piped water used for both drinking water and for other needs, such as cooking and handwashing, would provide a more comprehensive analysis of the realities of service interruptions and water availability.

5.4.4. Future Research

As successive (DHS) surveys are published that include the drinking water availability question, it will be possible to examine trends in interruptions. The DHS introduced their question about drinking water availability from 2013, in DHS round 7 (Croft *et al*. 2018). The study countries included in this analysis therefore only had one DHS dataset with information on service availability. Our analysis could subsequently only explore intra-year variations in water scarcity and its implications for drinking water availability.

Future analysis could focus on predictors of borehole interruptions using functionality data from water point mapping alongside household surveys. The water point data exchange collect information on water point status, including which boreholes, standpipes and wells are most likely to fail in any given area (WPDx 2022). Exploration of hotspots of water point non-functionality around DHS household clusters could therefore be undertaken to better understand the reasons for service interruptions, especially in rural areas.

It is possible to examine alternative measures of water scarcity and/or stress that better capture the pressures on domestic water services reported in the DHS. For example, Ryan *et al.*, (2020) detect changes to water levels of reservoirs using remote sensing or alternatively WaterGAP data could be used (Müller Schmied *et al*. 2021). The latter quantifies water flows and storages, in addition to water withdrawals and consumptive uses. GRanD data could also be considered (London *et al*. 2021). This maps the location and attributes of dams that are greater than 15m high and reservoirs that are more than 0.1km and includes details such as the main use of each dam/reservoir, their storage capacity and long-term average discharge. Additionally, data from the GRACE satellite system which measures groundwater depletion via gravitational changes could be used (Richey *et al*. 2015).

There are risk factors for supply interruptions that are not measured in the DHS, such as social capital, which future work could include or focus on. Social capital is crucial in resource-limited communities, especially when overcoming issues relating to water insecurity (Bukachi *et al*. 2021). The role of social capital and connectedness on the ability to respond and request help when dealing with interrupted supplies is unknown. Whilst we considered using the DHS variables on mobile phone ownership and internet use/access as measures of connectedness, neither are good measures of social capital. For example, mobile phone ownership is not an accurate measure of connectedness, with it likely to be too high to be meaningful (Amankwah-Amoah and Business 2019). Future research could therefore investigate this via other household surveys or primary fieldwork.

Consideration of the impact of interruptions not just on drinking water, but on water used for agriculture and other economic purposes, would also be of value moving forward. Whilst competing water demands of agriculture, and the WEF nexus, implicate municipal water availability and result in interruptions for households (Albrecht et al. 2018; Rosa et al. 2020), little is known about the effect of unavailable supplies on other activities. The DHS does not include details of households small scale irrigation or water intensive agriculture, both of which relate to households having higher demands on water (Hamidov and Helming 2020), but does collect information on livestock ownership, and the amount of agricultural land households have. Neither variable sufficiently identifies the additional water needs that livestock ownership and agricultural land incur however. As such, better insights into this relationship, using other survey data that specifically includes water uses for livestock and agriculture, would be beneficial.

5.5. Conclusion

Our findings highlight the variability of drinking water service availability across SSA. Overall, the levels of disruptions to supplies are high in all countries, with over half of households reporting experiences of interruptions in their supply in some instances. As a result, populations are faced with wide ranging effects, including impacts to health, such as increased risk of diarrhoea or injury from carrying water as alternative unimproved services are turned to. Further to this, poor service availability results in an inability to engage in economic activities as daily schedules are changed to match water service schedules; reduced school attainment and absenteeism; knock on effects to hygiene and sanitation practices as water is limited; and invariably, undue levels of stress caused by the unpredictability of services.

Consistencies in the household and community characteristics related to reporting an interruption to an improved drinking water source are evident in households in Ethiopia, Gambia, Malawi, Nigeria, Sierra Leone, South Africa, Tanzania, Uganda, Zambia and Zimbabwe. With type of drinking water source, rurality, number of household members and water stress are impacting service availability. We also find considerable variations and inequalities between countries which leads to the mixed picture found with household and neighbourhood wealth, tenure, change in urbanisation, neighbourhood age and population density.

We demonstrate how the inevitable demands of ongoing population growth and urbanisation mean urban households are experiencing interruptions more than rural households. The challenges of maintaining and developing new water infrastructure to deal with these pressures is clear. Our findings illustrate boreholes and tubewells are faring better than both public and private piped water sources, and we suggest that this could be a result of surface water stores suffering the impacts of climate change and water stress more rapidly than groundwater stores. Given water stress consistently affects the availability of drinking water across study countries, with households in higher water stress reporting more interruptions, we provide evidence to suggest water stress could affect progress towards achieving SDG target 6.1 in Ethiopia, Nigeria, South Africa and Tanzania.

Given this, we recommend future work considers the resilience of water supplies on a more local scale, especially surface water stores. We also suggest research better considers temporal variations in the timing of survey data in relation to the reporting of interruptions and water stress, as well as additional risk factors not included in the DHS. The restrictions of the DHS survey question to two weeks brings limitations. Future analysis needs to more precisely account for real-time water stress and scarcity in addition to water services used for additional needs beyond purely drinking water. Overall, it is clear that the factors associated with drinking water availability and the presence of interruptions are complex. The ability of SSA countries to provide households with supplies that are available when needed is especially challenging with the pressing nature of population growth and urbanisation exacerbating the effects of fragile systems.

Chapter 6

Comparing Provider, Regulator and User reported Availability of Piped Drinking Water Services in Urban and Peri-Urban Zambia: A Cross-Sectional Analysis

6.1. Introduction

The sixth Sustainable Development Goal (SDG) aims to 'ensure the availability and sustainable management of water and sanitation for all' by 2030 (UN Water 2018). In line with this, target 6.1, which focuses specifically on drinking water, calls for universal and equitable access to safe and affordable drinking water. The associated indicator, 6.1.1, measures the progress towards this using the proportion of the population using safely managed water services, where the definition of safely managed drinking water services requires that drinking water from an improved supply is available when needed (WHO and UNICEF 2018a). Additionally, the World Health Organization (WHO) outlines a global drinking water availability benchmark which recommends that a minimum of 50 litres/capita/day (LPCD) is needed to meet domestic needs, including washing, personal hygiene and cleaning(Howard and Bartram 2003).

Between 2000 and 2020 the proportion of the sub-Saharan African (SSA) population using improved water sources that were available when needed increased by 14%, to 59% (WHO et al. 2020e; WHO and UNICEF 2021). Despite this, over 100 million people in SSA continue to be served by a piped water supply that at times is not available when needed, but is unreliable and prone to interruptions, water shortages and outages (Bivins *et al*. 2017b). Supplies that are not available when needed result in damage to water supply infrastructure (Rawas *et al*. 2020), compromise water safety (Kumpel and Nelson 2013), which adversely impacts health (Lechtenfeld 2012; Majuru et al. 2016), and leads to additional household expenditures on storage, treatment and supplementary supplies (Pattanayak *et al*. 2005), with the latter often sourced from informal service providers and unimproved supplies (Bellaubi and Visscher 2014).

Urban-rural and socio-economic disparities are evident, though patterns of inequality vary across countries. In 2020 only 13% of rural SSA supplies were safely managed compared to 54% of urban supplies (WHO *et al*. 2020e). With the SDGs seeking to '*leave no one behind',* recognising inequalities in water, sanitation and hygiene (WASH) services is critical. Inequalities may exist between socio-economic groups due to wealth, ethnicity or language, between individuals due to characteristics such as age, sex or disability or across geographical regions (WHO and UNICEF 2019b). It is imperative that closing gaps in services between disadvantaged groups and the rest of the population are considered in addition to improving overall rates of progress on WASH.

The transition from the Millennium Development Goals (MDGs) to the SDGs saw the specific addition of the availability of water to the international agenda, resulting in new demand for data sources for monitoring (Yu *et al*. 2016). Data on the availability of drinking water is provided by a range of sources, including users, utility companies (hereafter ‘providers’) and government regulators (WHO and UNICEF 2019b). This complex data landscape is further exacerbated by the challenges of measuring availability where to date there have been few standardised methods (Majuru *et al*. 2018). Quantification has been undertaken using multiple metrics, ranging from hours of supply a day alongside supply in the last week or month, to using household or per capita consumption per day, or the number of interruptions or breakages in a given time period (Thomas *et al*. 2020). In 2018, the Joint Monitoring Programme (JMP) of the WHO and United Nations Children’s Fund (UNICEF), who are responsible for international monitoring of SDG target 6.1, published a core question for incorporation into household surveys for monitoring of availability: *‘In the last month, has there been any time when your household did not have sufficient quantities of drinking water when needed?*’. Since this is a new question, the availability of related survey data currently remains somewhat limited internationally.

As a result of patchy data and the use of multiple metrics of availability, national and international monitoring has been reliant on numerous data sources. Under the MDGs, monitoring was primarily dependent on household surveys and census data (Bartram *et al*. 2014), whereas more recently under the SDGs, there has been a shift towards using information from regulators of providers alongside the more traditional sources (WHO and UNICEF 2017b). Regulators often produce annual reports which benchmark levels of service between different providers. An additional data stream on piped water service levels is also available directly from provider records (Rawas *et al*. 2020). Many providers report their performance data to the International Benchmarking Network for Water and Sanitation Utilities (IBNET). At present, IBNET provides the most systematic international data on water availability (Rawas *et al*. 2020). Critically, censuses and household surveys offer the household’s perspective and provide an alternative to provider and regulator reports.

Historic comparisons between household-level user data and national-level provider-based data on water services indicate substantial differences in coverage estimates, but with the direction and magnitude of differences being context-specific (Bartram *et al*. 2014). Differences may also exist between regulator and provider data on water services. Variations between data sources could be due to inaccurate reporting from users, or providers having limited knowledge of the actualities of water at the household level, instead knowing only about services at specifics points in the water system. Providers may also incur penalties from government regulators if supplies are inadequate and subsequently overreport on services in order to avoid such penalties. In one instance, a qualitative comparison from 2014 found that providers frequently over-reported hours of supply and service availability when compared to evidence from users (Bellaubi and Visscher 2014). Bellaubi and Visscher (2014) raised concerns that this overreporting, which shows progress and improvement over time especially in light of international development agendas such as the SDGs, could be to help to justify new investments in system extensions or justify funds from the donor community.

The JMP only makes estimates for safely managed drinking water when there are data available on water quality and at least one other element (accessibility or availability) that represents at least half of the population in question (e.g. country) (WHO and UNICEF 2017b). The development of methods which could help to reach this criterion threshold, for example by using data from multiple perspectives, will be critical in better analysing WASH for international agendas such as the SDGs. Improvements in data, coupled with a standardised process by which data are processed to give nationally-representative and internationally comparable insights into drinking water availability are needed, especially in order to understand inequalities between population groups (Bartram *et al*. 2014).

Moreover, while research is emerging which considers comparisons of user and provider-based data that are disaggregated at a sub-national level (Bellaubi and Visscher 2014; Rawas et al. 2020), limited evidence exists which compares all three data streams (user, provider and regulator) especially in the context of Africa, considers peri-urban areas and which specifically focuses on the availability of drinking water. This study addresses this gap by aiming to answer the following research questions:

- Are the three data streams, and metrics of water availability used, consistent with one another when analysing the availability of piped water and the population supplied?
    - If consistencies exist, can one data stream be used to represent all three perspectives, i.e. that of the user, regulator and provider?
- Can monitoring of piped water providers be enhanced by considering household survey data and the experiences of the user?
    - Do user-reported inequalities in piped water interruptions vary by provider coverage area?
    - To what extent are differences in the socioeconomic characteristics of users and the characteristics of water providers associated with user-reported availability of piped water supplies?

This study therefore aims to identify any underlying differences in data streams' representation of drinking water availability. It also goes on to use the data to identify, but not explain, the factors that may emerge as characteristics of water supply inequality amongst households, thereby setting the basis for more detailed investigations of why inequalities occur.

6.2. Methods

6.2.1. Study Site Selection

A systematic data audit was undertaken to identify the study country for this analysis. During the data audit, the following inclusion criteria were used:

- The study country must be an African Union country in line with Chapter 4 (Thomas *et al*. 2020).
- Data must be available for all three data streams: (1) user, (2) provider and (3) regulator.
    - The user data must be quantitative and could include household survey or census data in which consumers report on their water services.
    - Provider data includes water utilities' reports on their service provision levels, such as those reported in IBNET.
    - Regulator data includes national reports by water and sanitation governing bodies.
- For all three data streams there must be a metric of water availability (i.e., a measure of the quantity of household water supplied, or continuity of water service provision).
- All three data streams need to be geographically disaggregated to some degree (i.e., user data needs to be geographically disaggregated to sub-provincial level, whilst provider or regulator needs to be disaggregated sub-nationally to at least province level).
- All three data streams must be available for approximately the same year.

Extensive searches were undertaken in the JMP's 2019 country files which include 54 of the 55 African Union countries (JMP 2021b); a JMP country file was not available for Western Sahara. The country files include information on all available user and regulator data, as well as some provider data, including metrics of water availability and details of the relevant survey. The IBNET database was searched for additional provider data (IBNET 2021a). Results of these searches can be seen in Figure 6-1.

Initial assessment of the data available for all 54 African Union countries showed that 27 had no relevant data (Figure 6-2). Of the further 27 that had user data only 13 had a combination of user, provider and regulator data: seven countries had user and provider data, one country had user and regulator data and five countries (Kenya, Tanzania, Zambia, Mozambique and South Africa) had all three data streams. All 13 countries were shortlisted and closer analysis of the data available undertaken (see appendix C.1).

Closer examination of the 13 shortlisted countries found that the years in which data were available across all three data streams was highly variable (Figure 6-3). In total, across all data streams and all countries, 12 different metrics are used to quantify the availability of drinking water (Figure 6-4). The level to which the data are geographically disaggregated varied from local to district municipalities, rural to urban and coverage areas of utility companies (Figure 6-5).

Overall, of the five countries that had all three data strands, Zambia was chosen as the final study country. It m*et al*l the inclusion criteria and had provider, regulator and user data that was sufficiently disaggregated and matched temporally and spatially, it also had similarly defined metrics of availability. In contrast to the other four countries that met the inclusion criteria, Zambia also provided the most recent data and the least complicated drinking water landscape which proved crucial in achieving research question one and integrating all three data strands for comparison.

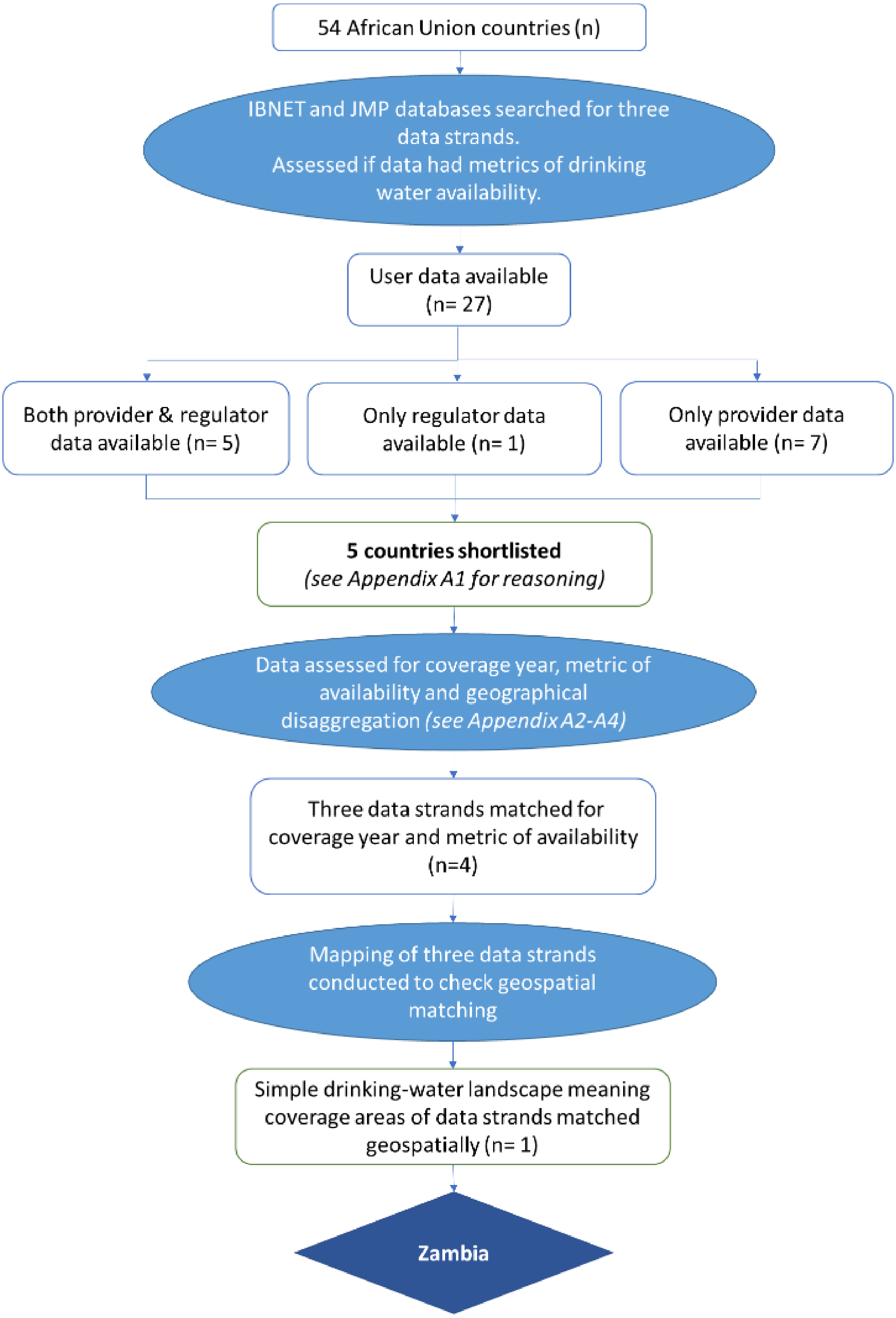


Figure 6-1: Flowchart showing inclusion criteria for identifying study country, with reasons for excluding African Union countries

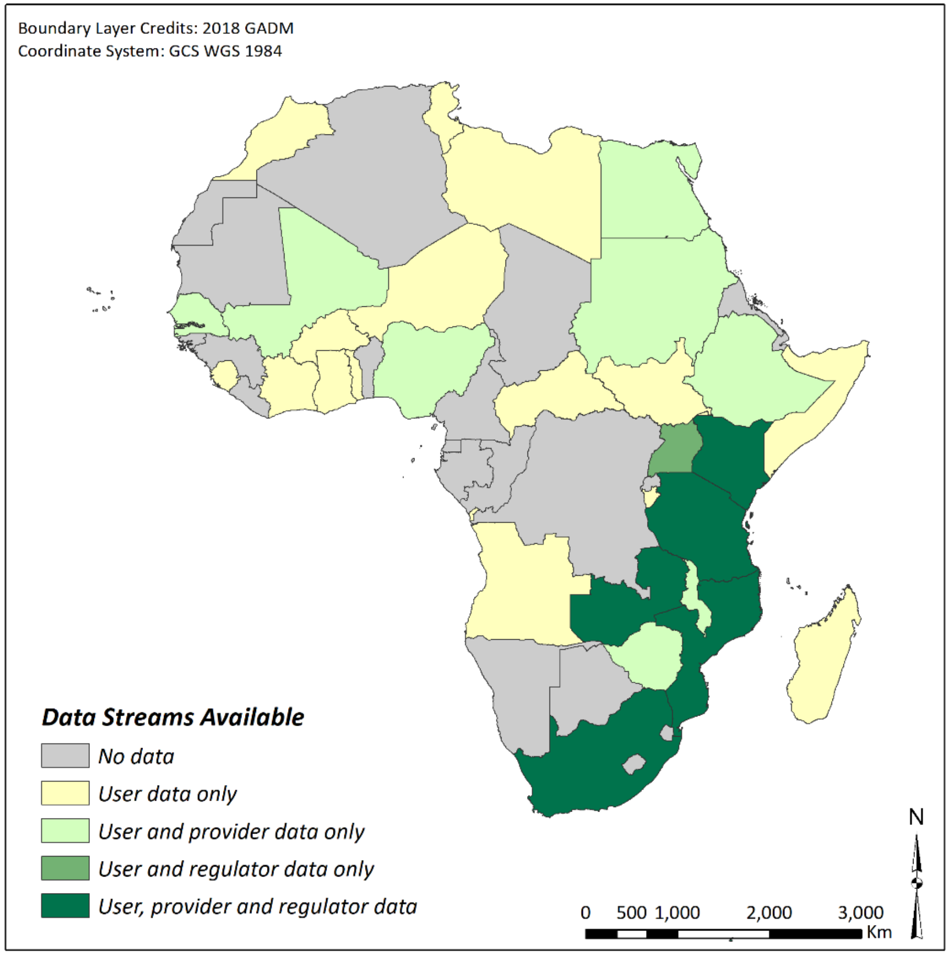


Figure 6-2: Available data for each of the 54 African Union countries

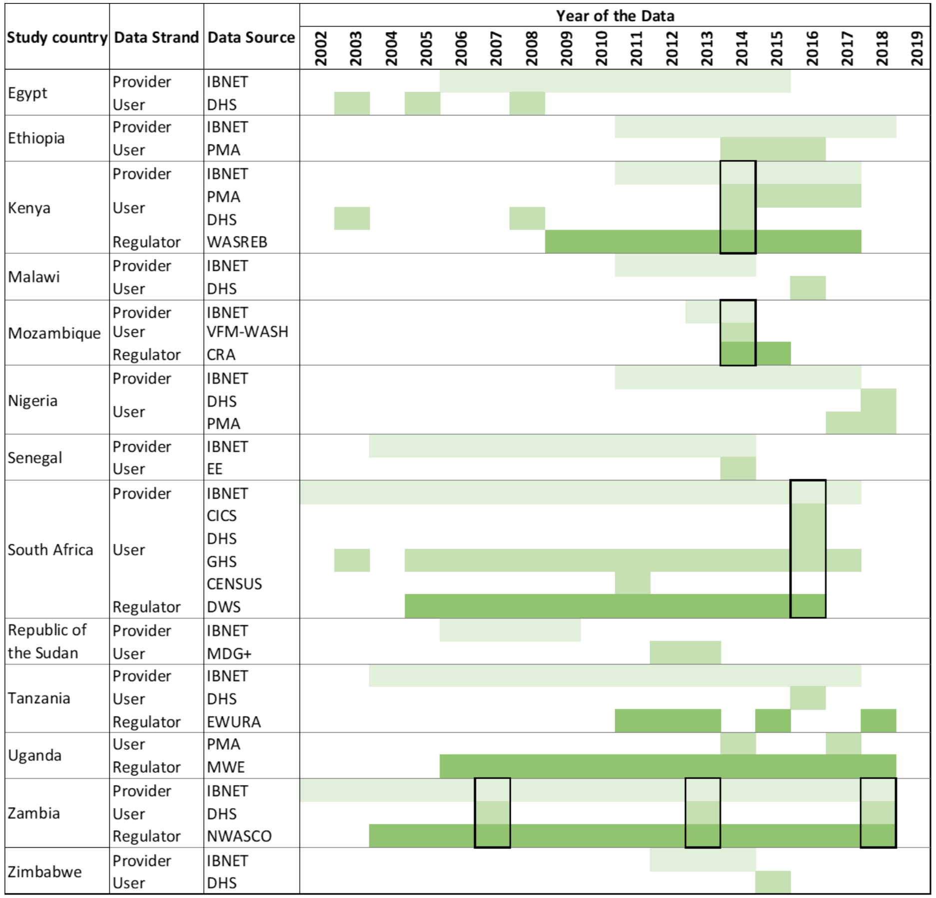


Figure 6-3: Year of all available data streams for the 13 shortlisted countries

(Colour depicts the data stream with dark green= regulator data, mid-green= user data and light green= provider data; black box indicates where data for all three streams is available for the same year)

Study country	Data Strand	Data Source	Metric of Availability										
			Coverage of water supplies (population directly served)	% Functioning water points	Litres per capita per day	Hours of supply a day	Interruptions longer >2 days in the last 12 months	Interruptions in last 2 weeks	Interruptions in last 3 months	Interruptions in last 12 months	Length of interruption (>15days cummulatively in last 12 months)	Months a year water is available	Predictability of interruptions
Egypt	Provider	IBNET											
	User	DHS											
Ethiopia	Provider	IBNET											
	User	PMA											
Kenya	Provider	IBNET											
	User	DHS											
		PMA											
	Regulator	WASREB											
Malawi	Provider	IBNET											
	User	DHS											
Mozambique	Provider	IBNET											
	User	VFM-WASH											
	Regulator	CRA											
Nigeria	Provider	IBNET											
	User	DHS											
		PMA											
Senegal	Provider	IBNET											
	User	EE											
South Africa	Provider	IBNET											
	User	CICS											
		DHS											
		GHS											
		CENSUS											
	Regulator	DWS											
Republic of the Sudan	Provider	IBNET											
	User	MDG+											
Tanzania	Provider	IBNET											
	User	DHS											
	Regulator	EWURA											
Uganda	Provider	IBNET											
	User	PMA											
	Regulator	MWE											
Zambia	Provider	IBNET											
	User	DHS											
	Regulator	NWASCO											
Zimbabwe	Provider	IBNET											
	User	DHS											

<u>Figure 6-4:</u> Metrics of availability used by all available data streams for the 13 shortlisted countries

(Colour depicts the data stream with dark green = regulator data, mid-green = user data and light green = provider data; black box indicates where the same metric of availability is used for multiple data streams for a given country)

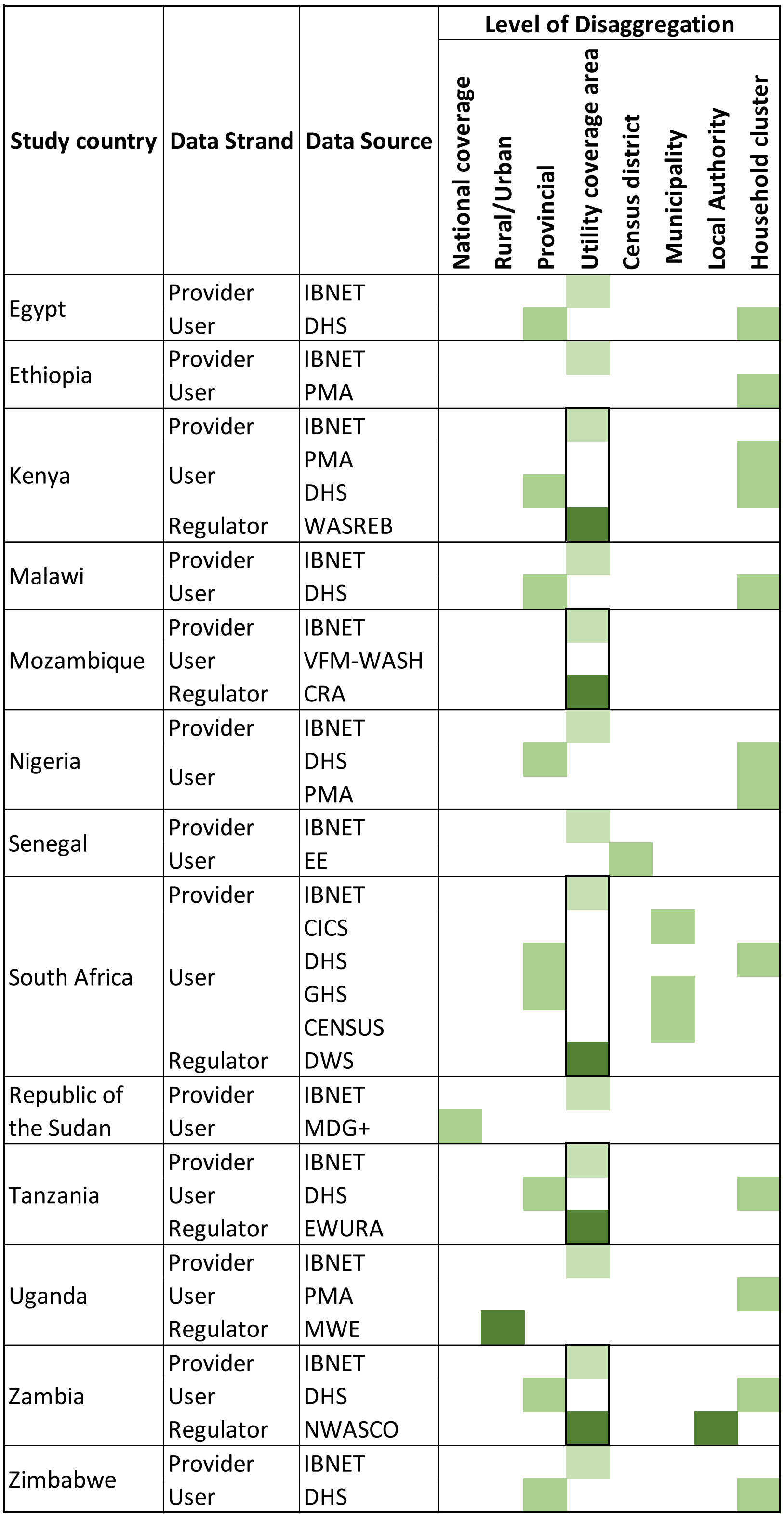


Figure 6-5: Level of geographical disaggregation of all data available for the 13 shortlisted study countries

(Colour depicts the data stream with dark green = regulator data, mid-green = user data and light green = provider data black box indicates where data is disaggregated to the same level for multiple data streams for a given country)

6.2.2. Study Site

Located in southern-central Africa, Zambia is a landlocked country with a 2019 population of nearly 19 million (World Bank 2019a); 45% live in urban areas (World Bank 2019b). Despite rapid economic growth (2019 GDP per capita, PPP (current international $) stood at US$3623 (World Bank 2019c)) and urbanisation, unemployment is high at 12% of the total labour force (World Bank 2018). 46% of the urban population are in the highest wealth quintile, measured by household durable consumer goods and housing characteristics, compared to 33% of the rural population who are in the lowest (Zambia Statistics Agency and ICF 2019).

Natural water supply is spatially variable in Zambia, in part due to many trans-boundary catchment areas. These result in fluctuations of surface water availability as a source for piped drinking water because of the varying water demands of neighbouring states (Hamududu and Ngoma 2020). Renewable water resources are affected by inconsistent seasonal rainfall, characterised by periodic drought (Libanda *et al*. 2019). Mismanagement and rapid urban growth have also caused considerable stress on groundwater supplies (Lapworth *et al*. 2017).

Urban and peri-urban piped drinking water is supplied to over six million people by 11 commercial Water and Sewerage Companies (WSCs) (NWASCO 2018a). Approximately 465,6375 piped water connections supply drinking water in 91 towns/centres (see appendix C.2). In total, 46% of the urban population have a safely managed water supply, that is available when needed (WHO *et al*. 2018). In rural Zambia, 35% have an unimproved supply compared to 9% of the urban population (WHO *et al*. 2018). The National Water Supply and Sanitation Council (NWASCO), a statutory body, is responsible for regulating water and sanitation services across Zambia (NWASCO 2018b).

6.2.3. Data Sources and Availability Metrics

One aim of this study is to compare the availability metrics from three different data sources: the user, the provider and the regulator. The specific sources for each of these are noted below.

User data: we used nationally representative data from the Zambian Demographic and Health Survey (DHS), implemented as a multi-stage cluster household survey (The DHS Program 2020b). The latest 2018 Zambian DHS was conducted from 18 July 2018 to 24 January 2019. All interviews were undertaken concurrently across the provinces, using a stratified two-stage sample design (Zambia Statistics Agency and ICF 2019). We used geospatial data that are georeferenced to cluster level (The DHS Program 2018); the mean location of GPS coordinates for all participating households are given as the centre of the sampling cluster from which the household was selected, displaced within 2km (for urban areas) to retain anonymity (Burgert *et al*. 2013). No sampling clusters were displaced outside of their administrative district. Details of the availability of drinking water are collected through asking households '*In the last two weeks was the water from your main source not available for at least one full day?'*. Only households that indicated in the DHS they used a piped supply (in their dwelling, yard or plot or from a neighbour) or a public tap/standpipe were included in this analysis.

Provider data: provider-reported availability of piped supplies for all 11 WSCs was obtained from IBNET. This includes metrics of availability, such as continuity of service, as yearly average hours of service per day (hrs/day) (IBNET 2020a), and yearly average residential consumption in LPCD (IBNET 2020b). Details of non-revenue water, that is the difference in water supplied and sold as a percentage of net water supplied (IBNET 2020c), were also of interest as it accounts for illegal use of piped networks, water that has been stolen and water that has leaked from the system. Provider data for 2017, the most recent year, were exported from the IBNET online database (IBNET 2020d).

Regulator data: since 2001 NWASCO have produced annual reports disseminating each WSC's performance based on nine key indicators (NWASCO 2018a, p. 71). Hrs/day, defined as the average duration of water supply at the customer connection, and the average amount of water consumed in LPCD are used as a metric of water availability and an annual average is reported for each WSC. Regulator data were extracted from the 2018 NWASCO report which was publicly available from NWASCO's online library (NWASCO 2020).

In both instances, the quality of the provider data from IBNET and regulator data from NWASCO reports depends greatly on the accuracy of the data reported by each WSC (Majuru *et al*. 2018). Generally speaking, data supplied by providers may be of limited reliability as they could be self-reported by the provider and lack any form of independent verification (UNICEF 2021c).

6.2.4. Integrating Provider, Regulator and User Data

Data integration was undertaken in ArcMap 10.7.1. Compared to the household-level DHS user data, regulator and provider data were reported by provider service area. Provider service areas approximately matched provincial boundaries in Zambia. Chama district was the main exception to this as it is located in the Eastern Province but water is provided by the same WSC as that in Muchinga Province. District administrative boundaries for Zambia were downloaded from the database of Global Administrative Areas (GADM) (GADM 2020) and joined to the provider and regulator data using the WSC and district names. Details of provider and regulator reported hrs/day, LPCD and provider non-revenue water were also joined to the user data.

The DHS household clusters were mapped alongside the provider and regulator data. 16% of households using piped water in the Zambian DHS were in rural areas. Any household clusters that were located in rural areas were removed (n = 347) (Figure 6-6), in order that the household data matched that of the provider and regulator who only provide urban and peri-urban piped water.

The DHS classification of urban/rural household clusters is adopted from the 2010 Zambian Census where each enumeration area is identified as rural or urban (The DHS Program 2018). As per this classification, an urban area must have at least 5000 people, of whom at least 50% should not be engaged in agriculture and should have attributes such as piped water, schools, hospitals, paved/tarred roads and electricity (Republic of Zambia Central Statistical Office and Sikanyiti 2019). 47 households in two clusters which had missing GPS coordinates were also removed.

The resultant dataset, with all three data strands, was exported from ArcMap and imported into Stata/IC 16.1. The final dataset therefore included information on the provider and regulator perspective of water availability at the provider coverage-area level (henceforth 'provider-level') and the user perspective at household-level.

6.2.5. Collating and Preparing Data for Analysis

Following the integration of all three data strands, the outcome variable 'user reported availability of piped water supplies', provider- and regulator- reported availability and 12 additional explanatory variables were collated. The additional explanatory variables were chosen to represent differentials in consumption that are experienced when a supply is not available when needed (Ramulong *et al*. 2017), environmental factors, social characteristics and physical WASH characteristics. These variables were at the household, household cluster and provider level (see appendix C.3).

All household-level variables were sourced from the 2018 DHS (Zambia Statistics Agency *et al*. 2019). Details of the DHS variables and the exact wording of the question households were asked are available in appendix C.4. Households that did not use any type of piped water supply (in dwelling, yard/plot, neighbour or public tap/standpipe) were removed (n = 1574) from the dataset as the question about availability of supplies did not apply (Croft *et al*. 2018), as were those that did not know about the availability of their piped supply (n = 46) (Figure 6-6). See appendix C.5 for factors associated with households not knowing their service availability.

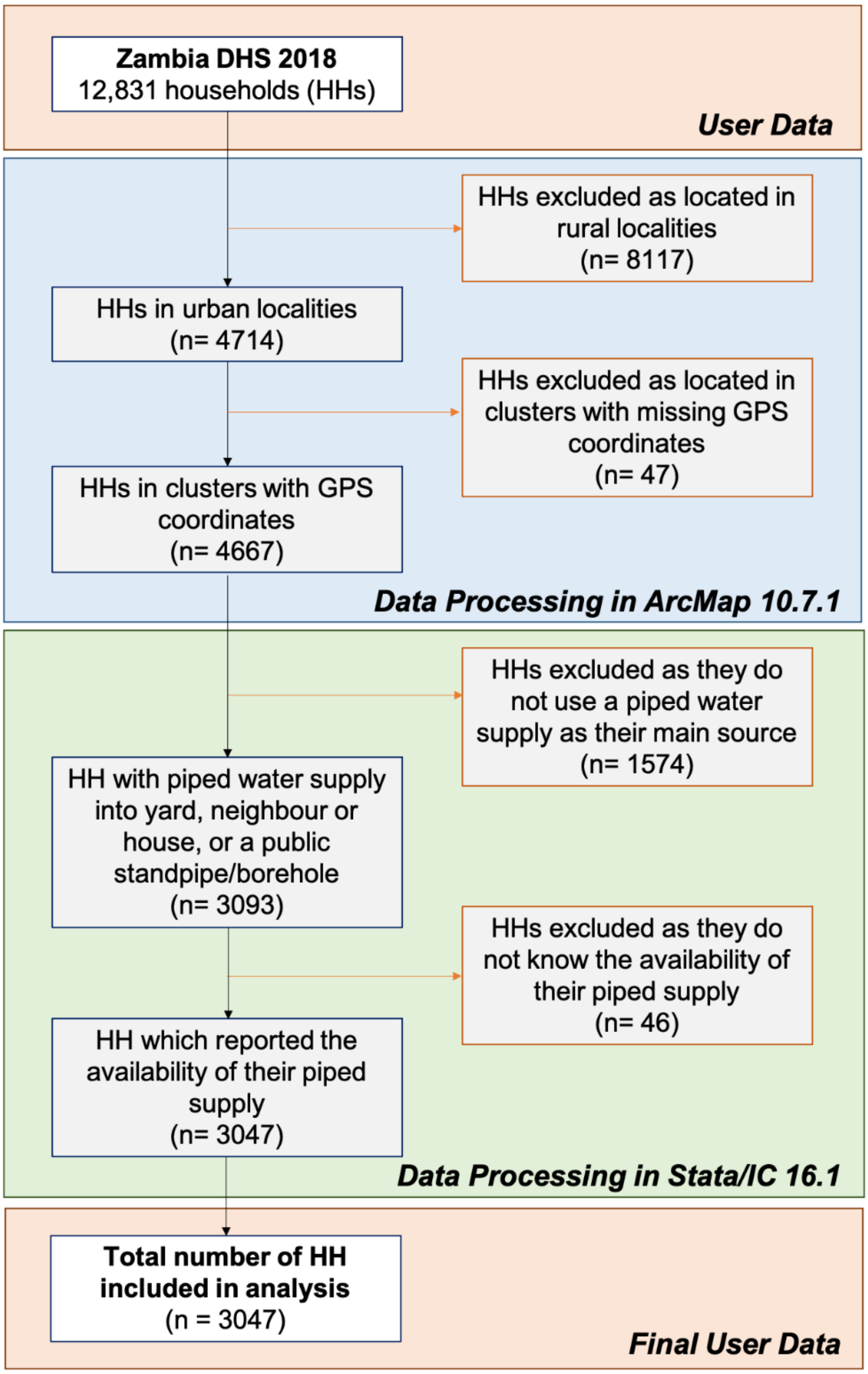


Figure 6-6: Flowchart, showing reasons for excluding households participating in the 2018 Zambian Demographic and Health Survey from analysis (n = number of households)

Several variables were only collected in the DHS men's and women's questionnaires, namely details of length of residence and home ownership. The men's and women's questionnaires were undertaken alongside the household survey. The men's questionnaire collected information from all men aged between 15 and 59 in each of the selected households, totalling 12,132 men, whilst the women's questionnaire collected information from all women aged 15 to 49 in the selected households, totalling 13,683 (Zambia Statistics Agency and ICF 2019).

The following sections include justifications for the inclusion of each explanatory variable, as well as how each variable was defined, created and categorised.

Type of Piped Supply

Details of the type of piped supply were used from the DHS and regrouped into three categories of 'piped into dwelling', 'piped to neighbour' and 'piped to yard/plot or public tap/standpipe'. Variations in drinking water availability exist due to the type of piped supply as different types of supplies are prone to different types of interruptions (Luh and Bartram 2016). Users may also consume more water if it is piped to the yard or home, than if located further afield, such as at a neighbour or a public tap/standpipe (Cassivi *et al*. 2019).

Household Wealth

Wealth at the household level was included to account for the fact that wealthier households may be less prone to interruptions; they pay tariffs more regularly, there are less likely to be illegal piped connections or breakages within the local piped network, they are likely to be able to afford to consume more water (Kayaga and Franceys 2007) and to pay for storage tanks which may protect them from interruptions (Dungumaro 2007). Wealth also relates to the type of piped supply used, for example, wealthier households are more likely to have piped supplies in their home or yard (Zoungrana 2020).

The DHS assume that the possession of observable assets, services and amenities are related to the relative economic position of the household in the country (Rutstein 2008, p. 2). Unlike the DHS wealth index, which relates to national populations as a whole and has been criticised for being too urban in its construction, the urban/rural wealth index enables the poorest of the poor to be distinguished from other poor households (ICF n.d.). In doing so, it considers assets and services that rural populations would have in conjunction with those of urban populations. For instance, type of flooring and roofing, water supply and sanitation facilities, electricity, appliances, persons per sleeping room and having a bank account are all examples of assets and services used to calculate the wealth of households (see Rutstein 2008 for a comprehensive list of assets and services included).

We used the DHS's urban/rural wealth index for a household level wealth variable. This variable included categories of 'poorest', 'poorer', 'middle', 'richer' and 'richest'.

Month of Interview

Month of interview was included as a proxy for seasonality. During the dry season there is a significant decrease in water availability (Kelly *et al*. 2018). The groundwater table may drop, lowering borehole yields and thereby restricting groundwater-fed piped supplies, while rainwater fed surface water such as rivers, dams and reservoirs that supply piped networks also experience fluctuations (Simukonda *et al*. 2018b). Supplies are also more prone to breakages during the dry season due to greater use and times where sources become more restricted.

To create this variable, the dates of DHS interviews were grouped into categories that aligned with the dry and rainy seasons experienced in Zambia. Zambia has a clearly defined rainy season (Libanda *et al*. 2020), with Libanda *et al*. (2019) recognising it as October-March, while April-September is the dry season. These seasons corresponded with the on-ground situation in 2018/19 (International Research Institute of Climate and Society and World Bank 2021), the period of this study, though longer-term there is variation and changes in monthly rainfall timings as a result of climate change (Makondo and Thomas 2020). The resultant variable therefore comprised four equal sized categories of 'September 2018' and 'July-August 2018' which aligned with the dry season, and 'October-November 2018' and 'December 2018-January 2019' as rainy season categories.

Native Language

Native language was included as a proxy for ethnicity. Belonging to a minority ethnic group may restrict water access, since for example, locations of public standpipes and household connections to mains supplies often disproportionately favour majority ethnic groups (Jackson 2013). The native language variable from the DHS was grouped into six categories to reflect ethnic groups and to ensure a large enough sample size in each group: 'English', 'Bemba', 'Lozi', 'Tonga', 'Kaonde, Lunda, Luvale' and 'other'.

Number of Household Members

The number of people in a household was included as it correlates with water consumption (Dungumaro 2007; Arouna and Dabbert 2010) and thereby the risk of piped supplies running dry. It also relates to choice of supply type (Armand et al. 2012; Mulenga et al. 2017). The DHS collects information on the number of people in a household, which we grouped into five categories of '1 member', '2-3 members', '4-6 members', '7-9 members' and households with 'more than 10 members'.

Tenure

Home ownership is related to the choice of water supply and the ability to deal with or fix a fault or interruption to a supply. For example, a household that owns their home can choose to have a piped supply in their home over a supply in the yard, and if this supply is interrupted they can more readily and easily fix the issue than households who rent their home. Tenure also affects tank ownership; tanks are an important coping strategy to mitigating unavailable supplies (Staddon *et al*. 2018).

We used details of home ownership that are collected in the men's and women's DHS questionnaires. The men's and the women's questionnaire interviews are conducted with all eligible men/women in each household, meaning that there are multiple responses for each household. To create the tenure variable the data was sorted so that responses were only used for the owner of the house, thus removing household duplicates. Data from both the men's and women's questionnaires were then merged with the user dataset using the household and household cluster IDs and categorised into 'does not own', 'at least partly owns' and 'no information'.

Degree of Urbanisation

In order to account for the known correlation between water availability and urbanisation, we included a variable at the household cluster level that accounted for degree of urbanisation. Less urbanised areas typically have lower levels of WASH infrastructure and consequently less water is available (Thomas *et al*. 2020).

To create the variable at the household cluster level, settlement data for 1990 and 2015 from the Global Human Settlement Layer (GHSL) project (Pesaresi and Freire 2016), made available via the DHS's pre-prepared geospatial covariates, was merged with the user data using the household cluster ID. The settlement data provided an urban-rural classification using four categories (1) urban centres/cities, (2) urban clusters/towns/suburbs (3) rural localities and (4) unpopulated, thus offering a finer scale classification than is available through the DHS household survey. Classifications are provided for the area within each displacement buffer surrounding the DHS household clusters (Mayala *et al*. 2018). Given this displacement, some household clusters are located in areas classified as rural or unpopulated despite all rural households being removed from the dataset.

Change in Urbanisation

Recently urbanised areas may have water infrastructure that has undergone development and thus be less prone to maintenance-related interruptions. Given this, a variable that accounted for change in urbanisation was created at the household cluster level. As with the degree of urbanisation variable, the DHS's pre-prepared geospatial covariate for GHSL settlement data was used for 1990 and 2015 (Pesaresi and Freire 2016). To create the change in urbanisation variable, the difference in urbanisation between 1990 and 2015 was calculated and merged with the user data. This variable was then categorised into the following: 'less urbanised', 'more urbanised' and 'no change' between 1990 and 2015.

Neighbourhood Wealth

Neighbourhood wealth represents a range of societal factors such as crime levels and disorganised and disadvantaged communities (Winter *et al*. 2018), which in turn affect water infrastructure and the capacity to deal with faulty or interrupted supplies that result in supplies being unavailable. The DHS's urban/rural wealth index was used to create this variable at the household cluster level. An average wealth score for all households within a cluster was created using the continuous urban/rural wealth index factor score. This was then grouped into three quantiles, 'poor', 'middle' and 'rich', to create a categorical variable.

Age of Neighbourhood

Newer neighbourhoods are less likely to have water infrastructure that is prone to failure, due to general aging of materials and poor upkeep (Bellaubi and Visscher 2014; Robles-Velasco et al. 2020), hence the inclusion of a variable that accounted for this. The men's and women's DHS questionnaires ask respondents their length of residence in their current home. This information was used as a proxy for the age of a neighbourhood, on the premise that if a respondent reported living in their home for 49 years, the neighbourhood must be at least 49 years old.

To create an age of neighbourhood variable, all respondents who stated that they were a visitor were first removed from the men's/women's questionnaire. For those that reported having 'always' lived in their home, their current age was used as a proxy for length of residence. The data was collapsed to the household cluster level and the highest value from the men's/women's questionnaire for each household cluster was taken. For example, if the length of residence in a household cluster was 15 years in the men's questionnaire but 35 years in the women's questionnaire, the value from the women's questionnaire was used as the proxy for neighbourhood age. The data was merged with the user dataset using the household cluster ID.

Finally, the variable was grouped to create a categorical variable with the following categories: neighbourhood is '<30 years old', '31-40 years old', '41-50 years old' and '>50 years old'. The resultant variable therefore represents the maximum length of residence within each household cluster, and thus approximates the minimum potential age of the neighbourhood.

Provincial Wealth

Wealth at the provider-level was used as a proxy for development (Felice 2016), which effects investment in WASH infrastructure (Luh and Bartram 2016). To create a wealth variable at the provider level, 2015 provincial GDP (current prices, Zambian Kwacha (ZMK), millions) (Republic of Zambia Central Statistical Office 2017) data were used and edited in MS Excel. For providers which cover provincial areas, such as Luapula WSC, Lukanga WSC, Lusaka WSC, North Western WSC, Southern WSC and Western WSC, the GDP data were converted to GDP per capita using 2015 provincial population statistics (Republic of Zambia Central Statistical Office 2018). Both the total GDP and GDP per capita were converted to USD$ using the 2015 exchange rate of ZMK1: USD$11 (Focus Economics 2020).

For providers which do not cover specific provincial areas, GDP per capita was calculated using population statistics at the district level, available from the 2010 census (Republic of Zambia Central Statistical Office 2012). An approximate population was calculated for 2015 using the population growth rate for each district, as reported by the Zambian Central Statistical Office (Republic of Zambia Central Statistical Office 2020). These population estimates were used in conjunction with the GDP for the province in which each district is located. For example, Nkana WSC covers Kaluluishi and Kitwe districts which are located within the Copperbelt Province. The GDP per capita for the Copperbelt province was used alongside the total populations of Kitwe and Kaluluishi districts to calculate GDP. In each case this was converted to USD$.

Finally, Eastern WSC approximately covers the Eastern Province while Chambeshi WSC approximately covers both the Northern Province and Muchinga Province. The exception is Chama district, which is located in the Eastern Province but served by the Chambeshi WSC. Therefore, to calculate the GDP for Eastern WSC and Chambeshi WSC, the population of Chama district was estimated for 2015 and used to calculate GDP per capita using the GDP for the Eastern province. The resultant GDP for Chama district was then deducted from the total GDP for Northern and Muchinga provinces to calculate the GDP for Chambeshi WSC. The GDP for Chama district and

Eastern province were added together to calculate the GDP for the Eastern WSC coverage area. The relevant population sizes were used to calculate the GDP per capita.

The resultant MS Excel spreadsheet with GDP and GDP per capita for each provider (see appendix 0) was imported into Stata, merged with the user dataset using the providers name and divided by 1000.

Non-revenue Water

Non-revenue water was included at the provider level in order to account for water theft, leakage or illegal use of piped networks (Simukonda et al. 2018b; Liemberger and Wyatt 2019). The most recent data for 2017 was downloaded from IBNET and merged with the user data in ArcMap (see: section 6.2.4). The IBNET non-revenue water variable takes into account the difference between water supplied and water sold that is 'lost' before it reaches the consumer, expressed as a percentage of net water supplied (IBNET 2021b).

Provider and Regulator Availability

Following data integration in ArcMap (see: section 6.2.46.2.4), provider and regulator hrs/day and LPCD were treated as continuous variables.

6.2.6. Statistical Analysis

Preliminary analysis, including bivariate analysis, tests for collinearity and missingness, and calculation of 95% confidence intervals, was undertaken in Stata version 16.1. Survey weights were employed during preliminary analysis, including descriptive statistics, the comparison of user, provider and regulator availability and bivariate analysis. The DHS survey weights are provided at household level. Their inclusion helps to improve representativeness, correct for non-response and minimise the problem of unequal selection probabilities that can occur during surveys that use multistage sampling (Pfeffermann *et al*. 1998), such as the DHS. Missingness was tested for by running a binary logistic regression between the outcome variable, user reported availability, and all explanatory variables.

Comparison of a single-level unconditional model and a two-level variance components model quantified the clustering in the dataset and showed that multilevel models were the most appropriate method for the data. Multilevel logistic regression models were therefore undertaken to account for the complex clustered sample design of the user data, and the additional complexity of the explanatory variables available at the higher household cluster and provider levels. The clustered nature of the data may reduce independence between household-level observations due to unobserved shared sources of variation within household cluster and provider coverage area. This needed to be accounted for to ensure that standard errors were not underestimated and the significance of some variables was not overestimated (Aarts *et al*. 2014). Despite there being three clear levels to the data (Figure 6-7), the small number of clusters in the third level (<25 clusters) meant it was not appropriate to include providers as a level in the model (Snijders 2005). Variation in the provider-level was accounted for by using providers as a dummy variable in one of the final multi-level models.

Backward elimination was used to select the final models. Each explanatory variable was sequentially removed following individual testing. Type of piped supply was included in the final models as a control. An interaction term was considered when deemed meaningful/necessary and where it was believed that the significant variables might have a different effect on household availability, depending on the categories of the other variable.

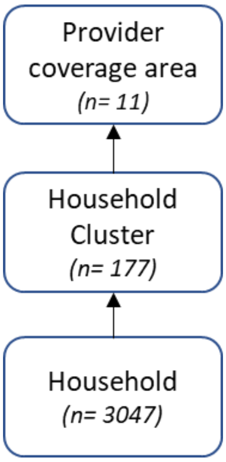


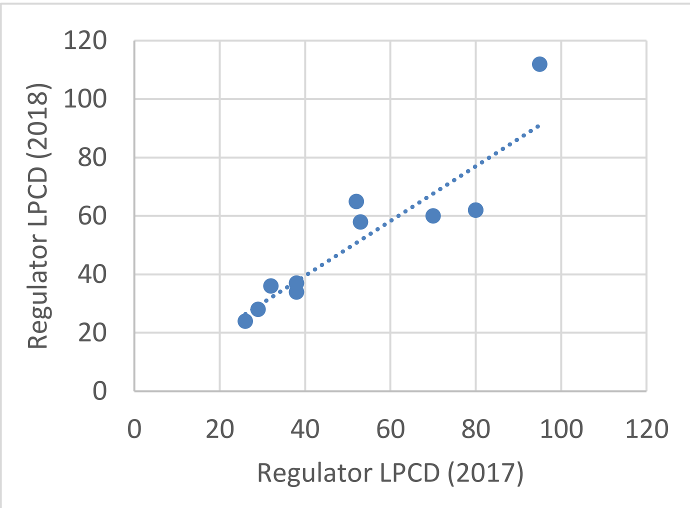
Figure 6-7: **Classification diagram of the three-level nested hierarchical structure of the data; households are within household clusters which are within provider coverage areas**

Survey weights were not used for the multilevel modelling as the DHS provides them at the household level, not the levels required for the model (i.e. household cluster/provider level), due to concerns about disclosure risk level (Elkasabi *et al*. 2020).

Issues of multicollinearity were found between regulator and provider reported LPCD/hrs/day. Analysis found regulator and provider reporting for the same year (2017) to be very similar for LPCD, whereas for hrs/day the data was identical. Providers report their performance data to the regulator; thus, the same source data are used explaining the similarities between the two perspectives.

More detailed analysis found a clear relationship between regulator LPCD in 2017 and 2018 existed (Figure 6-8), suggesting that if 2018 data were available for the provider, it would be very similar to the 2018 regulator figures. We therefore decided that when directly comparing regulator and provider perspectives during the descriptive analysis, 2017 data would be used due to consistencies of the year. Whereas for the modelling, given the issues of multicollinearity, it was decided that it was preferential to keep the regulator, rather than the provider, data in the model as it represents the same year (2018) as user reported availability. Therefore, provider data were removed from the model and 2018 regulator data were used to represent both the regulator and provider perspective. We also decided to use LPCD as the regulator/provider measure of availability rather than hrs/day.

Subsequently, data for providers was obtained from 2017, the latest year, while both 2017 and 2018 from the regulator was downloaded.



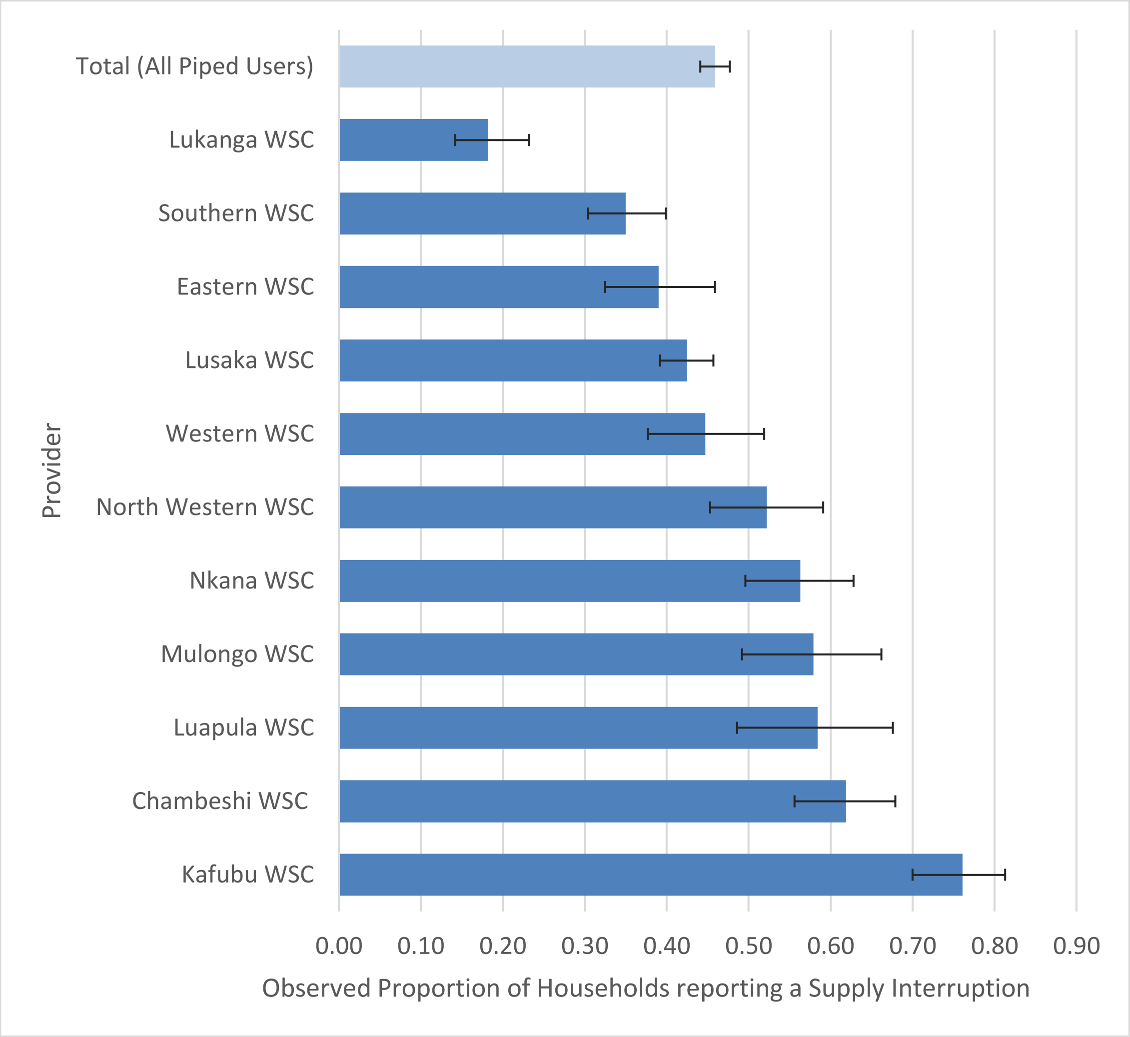
<u>Figure 6-8:</u> Scatterplot showing the similarities between 2017 and 2018 regulator reported LPCD

6.3. Results

6.3.1. Comparing Provider, Regulator and User availability

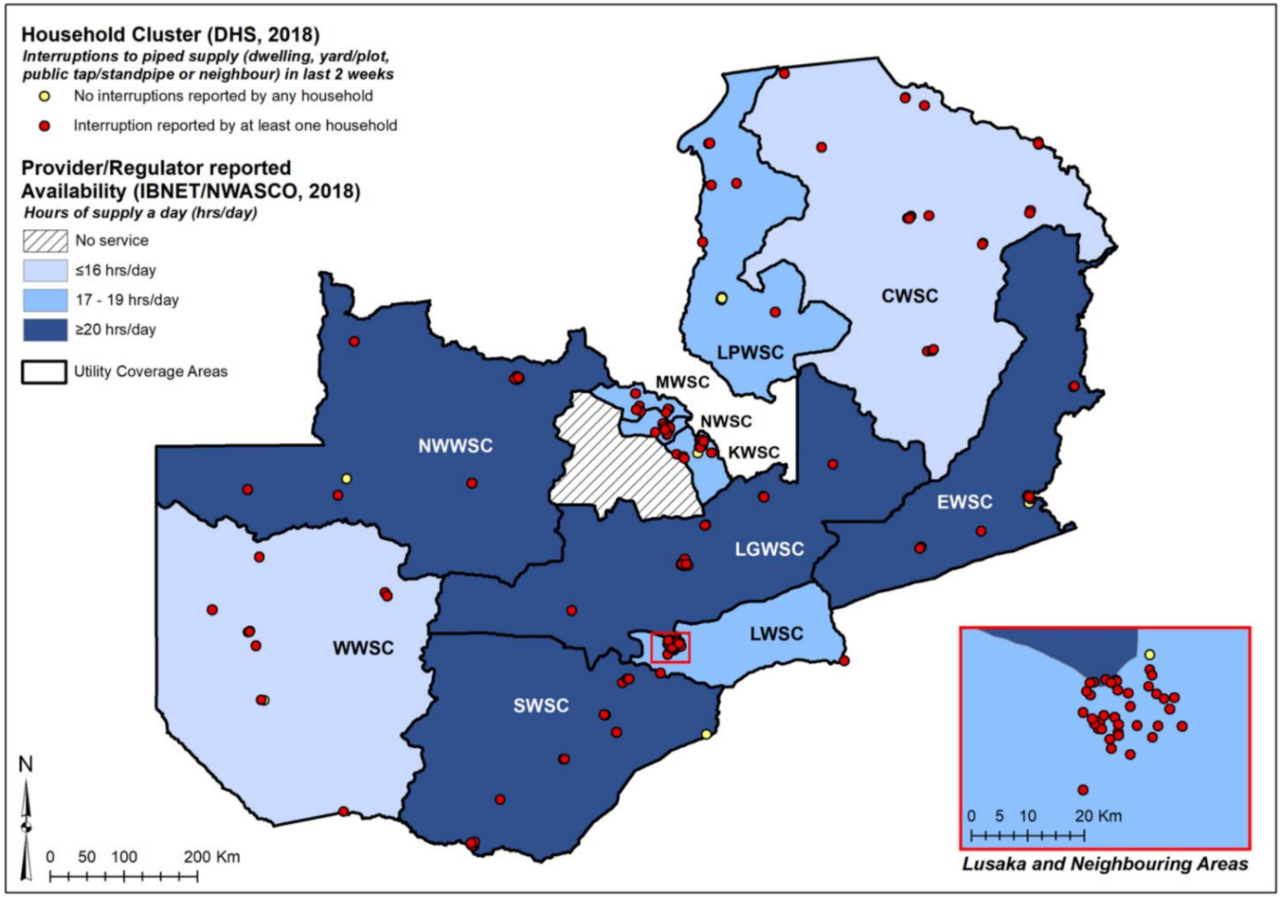
Overall, 47% (95% CI: 45%, 49%) of users reported experiencing at least one full day of interruptions in the two weeks prior to being surveyed in the 2018 DHS. Figure 6-9 shows the variation between providers in household reporting of interruptions in piped water supplies. The proportion of households reporting an interruption ranged from 76% (95% CI: 70%, 81%) in Kafubu WSC to 18% (95% CI: 14%, 23%) in Lukanga WSC. For all other WSCs, between 35% and 62% of households reported an interruption of at least one full day in the 2 weeks prior to being surveyed.

Figure 6-10 shows 2018 user-reported availability compared to regulator/provider reported hrs/day. Only six of 177 household clusters had no household reports of interruptions to supplies. Lusaka WSC supplied piped drinking water to 44% of households in the sample. Southern WSC supplied a further 14% of sampled households. All other WSCs provided drinking water to between 3% and 9% of sampled households.



<u>Figure 6-9:</u> The proportion of DHS households reporting a full day's interruption in piped water supply in the preceding fortnight per provider, with 95% confidence intervals

Comparison of regulator and provider data for the year 2017, found that for continuity of service (hrs/day) the data reported to IBNET by providers was the same as that reported to the regulator (Figure 6-11, 1a). On average households received piped water for 18.4 hrs/day (Table 6-1). The lowest supply hours reported within a WSC was 15hrs/day and the highest was 22hrs/day. No



<u>Figure 6-10:</u> Household and regulator/provider reported availability of piped water supplies in Zambia (2018)

Key to Utilities/Water and Sewerage Companies (WSC): NWWSC -North Western WSC; MWSC- Mulonga WSC; NWSC- Nkana WSC; KWSC- Kafubu WSC; LGWSC- Lukanga WSC; LPWSC- Luapula WSC; CWSC- Chambeshi WSC; ESWC- Eastern WSC; LWSC- Lusaka WSC; SWSC- Southern WSC; WWSC- Western WS

Table 6-1: Assessment of average annual piped water service delivery in urban and peri-urban Zambia in 2017/18 (n = 3047 HHs).

(*Note: s.d. = standard deviation, CI = confidence interval, all percentages reported are weighted*)

Perspective:	User (DHS, 2018)	Provider (IBNET, 2017)	Regulator (NWASCO, 2017)	Regulator (NWASCO, 2018)
Annual average reported availability:	46.66% (95% CI: 44.30%, 49.04%) of households experienced interruptions of at least one full day *(within the 2 weeks prior to the survey)*	Households receive piped water for 18.43 hours a day (95% CI: 18.33, 18.54) (s.d. 1.93)	Households receive piped water for 18.43 hours a day (95% CI: 18.33, 18.54) (s.d. 1.93)	Households receive piped water for 18.18 hours a day (95% CI: 18.12, 18.25) (s.d. 1.54)
		Average consumption of 74.9 LPCD (95% CI: 73.93, 75.99) (s.d. 27.13). 93% of households met or exceeded the WHO benchmark of >50 LPCD.	Average consumption of 53.1 LPCD (95% CI: 52.67, 54.75) (s.d. 20.33). 43% of households met or exceeded the WHO benchmark of >50 LPCD.	Average consumption of 47.7 LPCD (95% CI: 46.90, 48.55) (s.d. 18.96). 43% of households met or exceeded the WHO benchmark of >50 LPCD.

provider reported a continuous supply with average drinking water availability of 24hrs/day. Less than 3% of users had 15hrs/day, 9% had an average supply of 20hrs/day and 14% had 22hrs/day.

2017 regulator and provider reported LPCD were positively correlated (r_s= 0.86, p <0.001) (Figure 6-11, 1b), though higher average LPCD was reported by providers (74.9 LPCD) than regulators (53.1 LPCD) (Table 6-1). When comparing 2017 reported LPCD by providers and the regulator, the lowest report by the regulator was 26 LPCD in Luapula WSC whereas the lowest provider report was 33 LPCD in Eastern WSC. The highest reported LPCD for both the regulator and provider was in Mulongo WSC, where the regulator reported 95 LPCD and the provider reported 161 LPCD. Based on provider reports, overall, less than 3% of users received 33 LPCD, whilst 44% received 62 LPCD and 4% received 161 LPCD. By comparison, the regulator reported less than 2% received 26 LPCD, 50% received 38 LPCD and 4% received 95 LPCD.

Similarities were also evident in 2018 regulator and 2017 provider reporting of LPCD and hrs/day, with significant positive correlations evident (Figure 6-11, 2a/2b). Both reported similar average supply hours of 18.2 – 18.4 hrs/day, though greater variation is evident in reporting of average annual LPCD with a difference of 27.2 LPCD (Table 6-1).

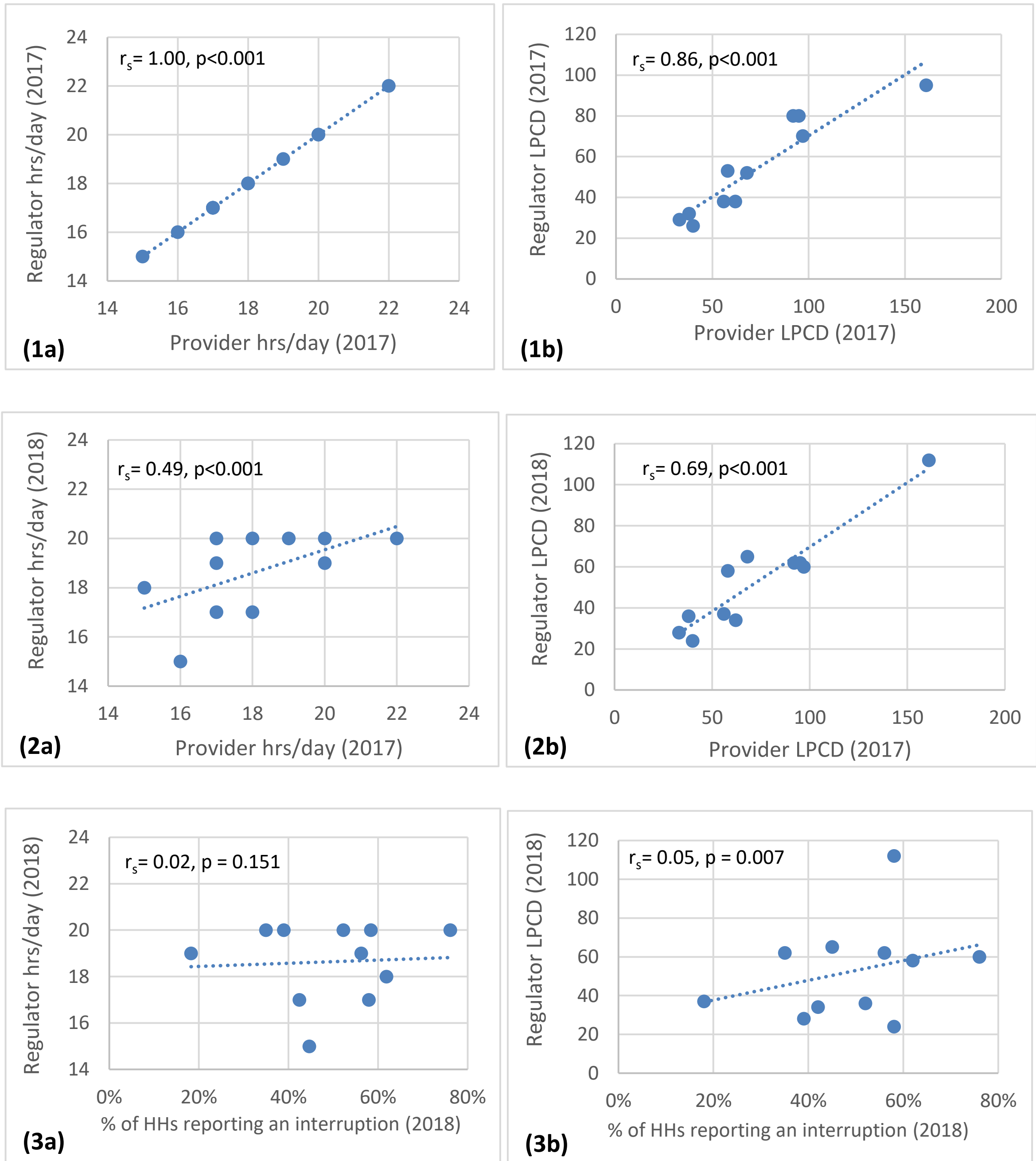


Figure 6-11: Comparison of perspectives (user/regulator/provider) of the availability of piped water supplies, with Spearman's rank coefficient, in urban and peri-urban Zambia in 2017/18

(n = 3047 HHs): **(1)** Regulator versus Provider (2017), **(2)** Regulator versus Provider (2017/2018), **(3)** Regulator versus User (2018). User reported availability represents the average percentage of households reporting an interruption per WSC.

An association was found between 2018 regulator hrs/day and user-reported availability ($\chi(4)$ = 56.04, p = <0.001), though a slight positive correlation was evident this was not significant (r_s = 0.02, p = 0.15) (Figure 6-11, 3a). 43% of users reported having an interruption when the regulator reported an availability of 15 hrs/day and 54% of users reported interruptions in the highest regulator-reported category of availability, 20 hrs/day.

When exploring 2018 regulator LPCD, the lowest report was 24 LPCD by Luapula WSC whereas the highest was 112 LPCD by Mulongo WSC. Based on regulator reports, less than 2% received 24 LPCD, 44% received 34 LPCD and 4% received 112 LPCD. 2018 regulator LPCD and user-reported availability are associated ($\chi(9)$= 220.63, p = <0.001), with evidence of a significant weak positive correlation (Figure 6-11, 3b). 58% of users reported an interruption where the regulator reported supplying 24 LPCD, whereas 59% of users reported an interruption where regulators supplied 112 LPCD. Where the regulator reported supplying ≥50LPCD and subsequently met the WHO benchmark, 55% of users reported an interruption to their supply.

Overall, provider and regulator reporting are similar (Figure 6-11), though there is some variation depending on the metric of availability in question (Table 6-1). The average number of supply hours reported by the provider and regulator in 2017 are the same, however when examining LPCD, differences are evident with providers' reports consistently higher than regulators. Similarities were also evident when comparing 2018 regulator and 2017 provider reported LPCD and hrs/day.

When considering the perspective of the user, discrepancies are clear. In light of the WHO benchmark, as reported by the provider, in 2017 eight WSCs met it and provided a minimum of 50 LPCD providing 93% of users with a sufficient supply. By comparison, in 2018 the regulator reported six WSCs met the benchmark, providing only 43% of users nationally with at least 50 LPCD. This discrepancy between perspectives in meeting the WHO benchmark is as a result of variations in reporting of LPCD for Lusaka WSC where 44% of households in the sample are. Here the provider reports an average of 62 LPCD whereas the regulator reports 38 LPCD; 42% of households in Lusaka WSC reported experiencing an interruption.

6.3.2. Bivariate Analysis of User-reported Water Availability

Table 6-2 presents descriptive statistics of the 1398 households that reported an interruption to their supply in the user data. Descriptive statistics of all 3047 households included in the user data are available in appendix C.7.

At the household level, neither household wealth, household size, tenure nor type of piped supply were statistically significantly related to supply interruptions ($p > 0.05$). Month of interview was significantly associated with interruptions to drinking water supply ($p < 0.05$), as was native language ($p < 0.05$).

As would be expected given its inclusion in how the DHS calculate wealth, type of piped supply was significantly associated with household wealth (p <0.01). 68% of households in the richest wealth quintile had a piped supply into their dwelling, compared to 2% in the poorest wealth quintile. 45% of those in the poorest wealth quintile used a public standpipe/tap whereas less than 1% in the richest wealth quintile did.

Table 6-2: Proportion of urban Zambian households reporting a piped water supply interruption in the preceding fortnight by socio-economic characteristic (n = 3047)

User Characteristics	Weighted Percentages (%) of Households (n) Reporting an Interruption	Chi squared (df), p-value
Household Size		3.537 (4), 0.472
1 person	42.6 (108)	
2-3 people	48.2 (358)	
4-6 people	47.2 (618)	
7-9 people	46.7 (250)	
10+ people	40.3 (64)	
Native Language		52.694 (8), <0.001**
English	25.8 (21)	
Bemba	50.3 (597)	
Lozi	49.1 (117)	
Lunda, Kaonde, Luvale	50.8 (137)	
Tonga	44.6 (142)	
Other	44.1 (384)	
Household Wealth Index		0.837 (4), 0.933
Poorest	45.5 (236)	
Poorer	44.3 (244)	
Middle	47.0 (273)	
Richer	48.8 (298)	
Richest	47.1 (347)	
Tenure		6.190 (2), 0.045
At least partly owns house	50.8 (477)	
Does not own	45.0 (855)	
No information	43.0 (66)	
Type of piped supply		1.396 (2), 0.498
Piped into dwelling	47.7 (322)	
Piped to yard/plot or Public tap/standpipe	47.0 (793)	
Piped to neighbour	44.7 (283)	
Month of Interview (Season)		17.545 (3), 0.001**
July-August 2018 (Dry)	49.8 (653)	
September 2018 (Dry)	43.8 (275)	
October-November 2018 (Rainy)	47.2 (349)	
December 2018- January 2019 (Rainy)	32.6 (121)	
Total households reporting an interruption	**46.7 (1389)**	

Note: n is an unweighted count
** p <0.05, **p <0.01*

Of the household cluster level explanatory variables only rurality and neighbourhood age were significantly associated with interruptions to drinking water supply (p <0.01) (Table 6-3). At the provider level, wealth, regulator- and provider-reported hrs/day, regulator- and provider-reported LPCD and provider non-revenue water were all also associated with supply interruptions (p <0.01).

Table 6-3: Association between user reported availability and all household cluster level and provider level explanatory variables in urban Zambia (n = 3047)

Explanatory variable	Chi-squared (df)	p-value
Household Cluster Level Factors		
Household Cluster Wealth	1.38 (2)	0.502
Neighbourhood Age	53.9 (3)	<0.001**
Change in Urbanisation	1.4 (2)	0.491
Rurality	15.6 (3)	<0.001**
Provider Level Factors		
Provider-level wealth	245.9 (10)	<0.001**
Regulator hrs/day	56.0 (4)	<0.001**
Provider hrs/day	144.3 (6)	<0.001**
Regulator LPCD	220.6 (9)	<0.001**
Provider LPCD	245.9 10)	<0.001**
Provider Non-Revenue Water	214.7 (10)	<0.001**

*Note: * p <0.05, **p <0.01*

6.3.3. User-reported Inequalities in Water Availability by Provider

Table 6-4 presents the socio-economic differences in household characteristics of those reporting interruptions to their supply, by provider. Ratios of those reporting an interruption are used as a measure of inequality within each WSC coverage area. Counts and weighted percentages of the number of households reporting an interruption for each inequality are presented in appendix C.8; C.8.1-C.8.6. Appendix C.9 presents household cluster inequalities in water availability by provider.

Inequalities in those experiencing an interruption between providers are sometimes large, though not necessarily significant, when considering household characteristics such as wealth, tenure, household size, type of water supply and month of interview. Inconsistencies often exist between WSC coverage areas in which household group reports the most interruptions. For instance, in most provider coverage areas more one-person households experienced interruptions than households with more than 10 members. Only in the coverage areas of Luapula WSC and Mulongo WSC did bigger households report interruptions more frequently than one-person households.

In all provider coverage areas, households using either a public standpipe or a supply in their yard had more interruptions than those with a supply in their dwelling. The degree of variation did however differ between provider coverage area. In particular, in Luapula WSC's coverage area, households using a public standpipe or a supply in their yard were 8.9 times more likely to

Table 6-4: **User-reported inequalities in piped-water interruptions by provider**

Provider	Percentage (%) (weighted) difference of households reporting an interruption between socio-economic characteristics						Ratio of households reporting an interruption between socio-economic characteristics					
	Partly Owns Home versus Does not Own	Richest versus Poorest HHs	One person versus >10 people HHs	Yard/ Public Standpipe versus Supply in Dwelling	Interviewed in Dry (July/Aug) versus Rainy Season (Dec/Jan)	Majority versus Minority Language in WSC Area	Partly Owns Home versus Does not Own	Richest versus Poorest HHs	One person versus >10 people HHs	Yard/ Public Standpipe versus Supply in Dwelling	Interviewed in Dry (July/Aug) versus Rainy Season (Dec/Jan)	Majority versus Minority Language in WSC Area
Chambeshi WSC	4.81	-29.49	0.78	21.42	16.54	92.99	1.16	0.30	1.11	1.59	1.91	65.84
Eastern WSC	20.56	-2.49	6.97	25.36	7.62	84.48	1.84	0.88	2.44	1.84	1.37	28.83
Kafubu WSC	32.25	20.79	3.66	19.16	45.24	63.05	2.64	2.88	2.05	1.85	6.25	45.43
Luapula WSC	15.65	-7.49	-5.41	62.63	32.63	84.36	1.61	0.77	0.19	8.89	4.45	21.02
Lukanga WSC	19.50	3.41	7.68	48.99	53.81	41.90	1.82	1.12	1.97	5.12	4.33	14.07
Lusaka WSC	39.01	20.95	3.69	44.92	48.81*	46.51	3.38	5.00	2.12	3.69	-*	116.11
Mulongo WSC	39.23	19.25	-1.04	55.87	29.76	73.70	3.31	4.05	0.80	7.02	8.81	69.37
Nkana WSC	44.00	15.36	1.02	55.91	55.63*	62.84*	4.00	3.40	1.16	5.83	-*	-*
North Western WSC	-0.10	17.90	6.45	40.10	51.98	53.50	1.00	2.26	3.70	3.28	10.14	44.39
Southern WSC	17.95	-19.52	10.73	16.19	63.35	47.58*	1.70	0.23	4.45	1.47	9.92	-*
Western WSC	21.63	-31.12	1.31	11.98	29.61	71.80*	2.43	0.36	1.25	1.31	2.21	-*

**Household did not report an interruption in one of the socio-economic categories being compared*

Note: Negative values show an inverse relationship between the groups of the socio-economic characteristic

experience an interruption than those using a supply in their home, whereas in Western WSC, the ratio is 1.3.

In all but one provider coverage area, households that at least partly owned their home were more likely to report an interruption than those that did not. Some variation exists between providers in the magnitude of this inequality. Households supplied by North Western WSC were the anomaly to this, with fewer reports of interruptions from those who do not own their home.

Variation in experiences of supply interruptions between provider coverage areas is evident when comparing the richest and poorest households. In six of the 11 provider coverage areas, the richest households experienced interruptions more than the poorest. For example, the richest households supplied by Lusaka WSC were five times more likely to report experiencing an interruption than the poorest. Similar differences are evident in Mulongo. Conversely, in Chambeshi the poorest are most likely to have an interruption, with interruptions occurring over three times the rate as the richest.

Differences in household interruptions between those speaking the majority and minority language are consistent between each provider coverage area. Those speaking the majority language were more likely to report experiencing an interruption, with the percentage difference ranging from 41.9% in Lukanga to 93.0% in Chambeshi. The ratio of households experiencing an interruption that were interviewed in the drier months of July-August was greater than those interviewed in wetter December-January, regardless of the provider coverage area they lived in. For example, in North Western WSC, households interviewed in the drier months were 10.1 times more likely to experience an interruption.

When considering the characteristics of each provider coverage area, namely wealth, population density and level of urbanisation, some patterns are evident in socioeconomic inequalities of households reporting an interruption (Figure 6-12). For instance, in more urbanised provider coverage areas, the ratio of those reporting an interruption in households speaking the majority language compared to those speaking the minority language is smaller than in less urbanised provider coverage areas (Figure 6-12a). When considering differences in tenure and household wealth, there is variation between provider coverage areas regardless of their level of urbanisation.

There is evidence that both population density and being a minority language speaker are linked to supply interruption risk (Figure 6-12b). Generally, the most populated coverage areas had the smallest variations in reported interruptions between households speaking the majority and minority language. For type of piped supply, there is some clustering of provider coverage areas that have mid-rank population densities, with a small difference in the reporting of interruptions between households using a yard/public supply and one in their dwelling. When considering the

(a)

Providers ranked by urbanisation *(1= most urbanised, 11= least)*		**Socioeconomic Characteristics of Households** *(percentage difference of HHs reporting an interruption)*			
Rank	**Provider**	**Home Owners vs. Not**	**Richest vs. Poorest**	**Yard/ Public supply vs. in Dwelling**	**Majority vs. Minority language**
1	Lusaka WSC				
2	Lukanga WSC				
3	Southern WSC				
4	Nkana WSC				
5	Kafubu WSC				
6	Chambeshi WSC				
7	Mulongo WSC				
8	Eastern WSC				
9	North Western WSC				
10	Luapula WSC				
11	Western WSC				

(b)

Providers ranked by pop. density (GDP) *(1= most populated, 11= least)*		**Socioeconomic Characteristics of Households** *(percentage difference of HHs reporting an interruption)*			
Rank	**Provider**	**Home Owners vs. Not**	**Richest vs. Poorest**	**Yard/ Public supply vs. in Dwelling**	**Majority vs. Minority language**
1	Lusaka WSC				
2	Southern WSC				
3	Lukanga WSC				
4	Chambeshi WSC				
5	Kafubu WSC				
6	Nkana WSC				
7	Eastern WSC				
8	Western WSC				
9	Mulongo WSC				
10	Luapula WSC				
11	North Western WSC				

(c)

Providers ranked by wealth (GDP) *(1= richest, 11= poorest)*		**Socioeconomic Characteristics of Households** *(percentage difference of HHs reporting an interruption)*			
Rank	**Provider**	**Home Owners vs. Not**	**Richest vs. Poorest**	**Yard/ Public supply vs. in Dwelling**	**Majority vs. Minority language**
1	Kafubu WSC				
2	Lusaka WSC				
3	Southern WSC				
4	Nkana WSC				
5	North Western WSC				
6	Lukanga WSC				
7	Mulongo WSC				
8	Chambeshi WSC				
9	Eastern WSC				
10	Western WSC				
11	Luapula WSC				

Legend:		
More interruptions in the first socio-economic group		*Darker blue indicates the greatest percentage difference in households reporting an interruption.*
		No difference
More interruptions in the second socio-economic group		*Darker red indicates the greatest percentage difference in households reporting an interruption*
Percentage (%) Difference: Group 1 - Group 2		

Figure 6-12: **Provider inequalities compared to differences in household socioeconomic characteristics, for households that reported experiencing an Interruption to their piped water supply**

(Provider inequalities are classed as follows: (a) Urbanisation as the number of household clusters classified as a city in each provider coverage area; (b) Population density as people per km^2; (c) Wealth as average GDP (US$ million) current prices (2015))

differences in experiencing an interruption based on household wealth and tenure, there is minimal evidence of there being a correlation with the population density of provider coverage areas.

For both tenure and household wealth, the richest provider coverage areas had the greatest variations in inequalities (Figure 6-12c). In Kafubu WSC and Luapula WSC, the two wealthiest coverage areas, the greatest differences were evident between those experiencing interruptions in households who at least partly owned their home and those that did not, and between the richest and poorest households. Conversely, when examining the differences between households using a yard or public supply and those with a supply in their dwelling, and between those speaking the majority and minority language, the richest provider coverage areas had the smallest differences in those reporting an interruption.

6.3.4. Multi-level Logistic Regression

In order to understand the main effects on availability at household, cluster, regional and water supply company level, a multilevel logistic model was estimated.

Table 6-5 compares a single-level unconditional model (model 1) with a variance components model (model 2). The former shows that the odds of reporting an interruption in an average household are 0.85 (p <0.001). Whereas in the latter (model 2), which accounts for the 177 household clusters in the dataset, the intercepts vary about this mean with a variance of 1.80. The Intraclass Correlation Coefficient (ICC) for model 2 shows that 35% of the variation in the propensity to report an interruption lies between household clusters, whilst 65% lies within household clusters. This indicates that it is where you live that is the greatest determinant of supply interruptions, rather than the actual household itself (although that still has a large effect).

Table 6-5: Exploration of clustering in reported supply interruptions through comparison of a single-level unconditional model with a two-level variance components model (n = 3047)

	Model 1 Single-level Unconditional Model		**Model 2** Two-level Variance Components Logistic Model	
Parameter	**Estimate**	**Std. Err.**	**Estimate**	**Std. Err.**
Fixed-part				
Intercept	0.85**	0.03	0.85	0.10
Random-part				
Between PSU variance	-	-	1.80	0.27
Intraclass Correlation Coefficient (ICC)				
Intra-PSU correlation coefficient	-		0.35	
Deviance	4203		3651	

*** p <0.001; PSU: Primary sampling unit (household clusters)*

We conclude therefore, that the variance-components model (model 2) is preferred as it provides a significantly better fit than the single-level model; the likelihood ratio is 552.28 which greatly exceeds the critical value of 3.84 ($p < 0.001$).

Table 6-6 includes the multi-level logistic regression results for two models. Model 3 presents odds ratios and their standard errors for selected household and household cluster factors that explain inequalities in piped-water interruptions, whilst accounting for provider via dummy variables. Model 4 does not account for the provider in this way but presents results that explore the association between socioeconomic characteristics at the household, household cluster and provider-level and the likelihood of households reporting an interruption.

When accounting for provider coverage area in model 3, tenure, native language and month of interview are factors associated with households reporting at least one full day of interruptions in their supply in the two weeks prior to being surveyed. Type of piped supply was not associated with experiencing an interruption, nor were any household cluster level factors. Similarly, model 4 finds household level factors such as tenure, native language and month of interview significant. In addition, type of piped supply is also significant. Wealth at the household cluster and provider level is associated with household supply interruptions, and at both levels there was a significant interaction between wealth and regulator reported availability.

Type of Piped Supply

The type of piped supply used by households is significantly associated with experiencing an interruption in model 4. Households using a neighbour's supply had 33% greater odds of reporting an interruption than those with a supply in their dwelling ($p < 0.1$). When provider is accounted for in model 3, type of supply is not significant.

Month of Interview

Results from model 3 show that, after controlling for other observed inequalities, those interviewed at the peak of the dry season (July-August) had 1.91 times the odds of reporting experiencing an interruption than those interviewed in the middle of the rainy season (December-January) ($p < 0.05$). When discounting providers in model 4, all households interviewed outside the wettest months of December-January had between 2.36 and 2.95 times greater odds of experiencing an interruption ($p < 0.05$).

Table 6-6: Multilevel logistic regression analysis of household reported interruptions to piped water supply in the urban and peri-urban population of Zambia 2018 (n = 3047, groups= 177)

Parameter	Model 3 Multilevel Logistic Model		Model 4 Multilevel Logistic Model	
	Odds Ratio	Std.Err.	Odds Ratio	Std.Err.
Intercept	0.18***	0.089	0.08***	0.05
Household-level Factors				
Native Language *(ref.: English)*				
Bemba	1.53	0.50	1.88*	0.60
Luvale, Kaonde, Lunda	2.06**	0.74	2.30**	0.81
Lozi	1.81	0.66	1.85	0.66
Other	1.60	0.52	1.77	0.57
Tonga	1.78*	0.62	1.73	0.59
Month of Interview (season) *(ref.: Dec 2018-Jan 2019 (Rainy))*				
Sept 2018 (Dry)	1.64	0.60	2.95***	1.12
Oct-Nov 2018 (Rainy)	1.61	0.53	2.36**	0.80
July-Aug 2018 (Dry)	1.91**	0.61	2.51***	0.84
Type of piped supply *(ref.: Piped into dwelling)*				
Piped to yard/plot or Public tap/standpipe	1.20	0.15	1.24	0.16
Piped to neighbour	1.32	0.20	1.33*	0.21
Tenure *(ref: Does not own)*				
At least partly owns	1.31***	0.13	1.32***	0.13
No information	1.10	0.23	1.10	0.23
Provider-level Dummy Variable				
Utility Company *(ref.: Lusaka)*				
Chambeshi WSC	2.43**	0.94	-	-
Eastern WSC	0.95	0.40	-	-
Kafubu WSC	8.02***	3.40	-	-
Luapula WSC	2.89**	1.45	-	-
Lukanga WSC	0.36**	0.15	-	-
Mulongo WSC	3.77**	1.85	-	-
Nkana WSC	2.24*	0.90	-	-
North Western WSC	1.39	0.65	-	-
Southern WSC	0.70	0.25	-	-
Western WSC	1.18	0.54	-	-
Household cluster-level Factors				
Neighbourhood Wealth *(ref.: Poor)*				
Middle	-	-	4.31*	3.29
Rich	-	-	3.22	2.31
Provider-level Factors				
Regulator LPCD	-	-	1.01	0.01
Provincial Wealth	-	-	0.51***	0.11
Regulator LPCD x Neighbourhood Wealth *(ref.: Poor)*				
Middle	-	-	0.97**	0.01
Rich	-	-	0.98*	0.01
Regulator LPCD x Provincial Wealth	-	-	1.02***	0.01
Random-effects Parameters				
Between PSU variance	1.21	0.19	1.47	0.23
Intraclass Correlation Coefficient (ICC)				
Intra-PSU correlation coefficient	0.27	0.03	0.31	0.03
Log likelihood	-1787.03		-1799.69	
Deviance	3574.00		3599.00	

****** p <0.01, ** p <0.05, * p <0.1; PSU: Primary Sampling Unit (household clusters)***

Tenure

In both models, household ownership is significantly associated with experiencing an interruption. In model 3, when accounting for provider, the odds of experiencing an interruption were 1.31 times higher for those that at least partly owned their home compared to those that did not ($p < 0.001$). Similarly, model 4 found that households that at least partly owned their home had 1.32 times greater odds of experiencing an interruption ($p < 0.001$).

Native Language

In both models, availability of supplies varies significantly with household native language. In model 3, where provider is accounted for, results suggest that the odds of experiencing an interruption were higher for households who speak Luvale/Kaonde/Lunda and Tonga. Compared to English speaking households, Luvale/Kaonde/Lunda speaking households had 2.06 times the odds of experiencing an interruption ($p < 0.05$) and Tonga were 1.78 times ($p < 0.1$).

Similar patterns are evident in model 4, though there is no longer a significant association with Tonga-speaking households. Bemba speaking households and those who speak Luvale/Kaonde/Lunda also have significantly greater odds of experiencing an interruption than English speaking households ($p < 0.05$).

Neighbourhood Wealth Status

Households in neighbourhoods classed as having middle levels of wealth had 4.31 times the odds of reporting experiencing an interruption than those in poor household clusters ($p < 0.01$), when disregarding provider level variation (model 4). Neighbourhood wealth was found to interact with regulator availability. When comparing households in mid-wealth household clusters to those in poor household clusters, for every one litre increase in regulator reported LPCD the odds of reporting having an interruption were 3% less ($p < 0.05$).

Provincial Wealth Status

Provincial wealth is the only provider-level factor associated with household availability (model 4). For each $1000 increase in provincial wealth, the odds of reporting having an interruption are 0.51 times less ($p < 0.01$). Provincial wealth was also found to interact with regulator LPCD. For every one unit increase in regulator reported LPCD and provincial wealth, the odds of having an interruption were 1.02 times greater ($p < 0.01$).

Differences between Provider Coverage Area

Variations between providers are evident when controlling for tenure, type of piped supply, month of interview and native language (model 3). When comparing the odds of households reporting an interruption to areas supplied by Lusaka WSC, households supplied by Lukanga WSC had 64% lower odds of experiencing an interruption ($p < 0.05$) whilst in Nkana the odds were 2.24 times higher ($p < 0.05$) and Mulongo WSC 3.77 times higher ($p < 0.05$). Similarly, in Chambeshi WSC the odds of having an interruption were 2.43 times higher ($p < 0.05$) and in Luapula they were 2.89 ($p < 0.05$). In Kafubu WSC, households have eightfold increased odds of reporting experiencing an interruption than those whose provision is from Lusaka WSC ($p < 0.01$).

Random Effect Results

The variability in household's likelihood of experiencing an interruption that could not be attributed to household and household cluster factors was tested. The ICC for model 3 shows that 27% of the variation in the propensity to report an interruption lies between household clusters, 73% lies within household clusters. By comparison, in model 4, 31% of the variation lies between clusters whereas 69% is within clusters. These results suggest that there are significant variations in the likelihood of interruptions due to unobserved household and household cluster characteristics.

6.4. Discussion

Urban and peri-urban piped water supplies in Zambia are not available when needed for significant proportions of the population. Almost half of users reported experiencing a full day's interruption in the 2 weeks prior to being surveyed, whilst the lowest mean annual availability of piped water as reported by the providers and regulators was 15 hrs/day. Based on Rawas *et al.*'s (2020) classification of an intermittent supply as <12hrs/day, which is consistent with the JMP's threshold for 'available when needed', providers and regulators are reporting a continuous supply. That said, given the 'gold standard' of supply continuity is recognised as 24 hours, 7 days a week of supply (Rawas *et al*. 2020), provider and regulator reported availability is insufficient.

In support of this, the WHO global drinking water benchmark recognises a minimum of 50LPCD is required to meet basic domestic needs (Howard and Bartram 2003), here we find variations in meeting this benchmark depending on the perspective considered. Reporting from regulators shows this benchmark is not being achieved, whereas provider data shows average LPCD as 63, marginally meeting this benchmark. Provider and regulator discrepancies in reporting of LPCD for Lusaka WSC are the cause of these variations between perspectives in meeting the WHO LPCD benchmark, however bearing in mind that 42% of users supplied by Lusaka reported experiencing an interruption, it is clear that the availability of piped supplies is far from the gold standard. In light of the SDGs, it is evident that irrespective of the perspective considered, considerable proportions of the Zambian population using a piped drinking water supply do not have a safely managed drinking water service that is available when needed (WHO and UNICEF 2018a).

6.4.1. Consistency of Data Streams

Variations between user reporting and regulator/provider reporting are evident. This could in part be because household-reported availability better captures water availability at the point of consumption, which may additionally be affected by localised breakages affecting small groups of consumer endpoints (Kumpel, Woelfle-Erskine, et al. 2017; Rawas et al. 2020). That said, comparison has included two very different metrics of availability: yearly mean service hours and the more specific measure of availability in the last two weeks. The regulator and provider data use the same metrics at WSC level and more or less match, whereas the household survey is based on a different, shorter-term metric. We do find that the household survey reporting is correlated with the provider/regulator reported availability (Figure 6-11).

The ability to make direct comparisons between user reported availability and provider/regulator reports is prohibited by the different metrics used. The modelling undertaken does indicate however that the three data streams are related to each other (Table 6-6). Moving forward, consistency between data streams is important. By 2030 the data landscape may change considerably and the JMP's estimates from household surveys could be challenged by data from outside of government, e.g. from providers. Were user and provider/regulator metrics consistent with one another, given the infrequency of household surveys but the regularity of annual regulator reports and provider monitoring, the latter could supplement information from household surveys. At present it is clear that the availability of data from all three streams is currently restricted to eastern and southern Africa (Figure 6-2). Were all three data streams to be consistent and available in other countries, the use of multiple data sources would be of great value for regular monitoring towards international development agendas such as the SDGs.

We found the availability of supplies reported by the provider and regulator to be consistent with one another (Table 6-1, Figure 6-11). Provider reporting in IBNET and the NWASCO regulator report were equally complete for Zambia, covering the same number of utilities. This is especially encouraging given that there is no legal obligation for providers to report to IBNET whereas there is for providers to report to regulators. Some differences between provider and regulator reports existed based on the metric in question. Our analysis suggests that were data to be available for 2018, provider and regulator LPCD would be even more similar as is shown when comparing 2017 figures (Figure 6-11, 1a-1b). These similarities in reporting are likely given that NWASCO's regulator reports use data supplied by the providers. That said, as found by Bellaubi and Visscher (2014), providers can frequently over-report performance data subsequently providing a more positive picture, thus may not be the most reliable source. Whilst there is therefore value in including the regulator's perspective alongside the providers, overall data from regulators is preferable and it is more appropriate for international estimates to be based upon.

6.4.2. Inequalities in Piped-water Availability

This nationally representative analysis of user data from the DHS show patterns of inequality in the availability of supplies (Figure 6-10) (WHO and UNICEF 2019b). This finding is especially pertinent given the SDGs aim to '*leave no one behind*'. In exploring inequalities in water services, as with previous comparisons (Bartram *et al*. 2014), we find substantial variations exist in user-reported interruptions between provider coverage areas. 19% of households reported an interruption in Lukanga, whereas 77% did in Kafubu. Our modelling also found that when controlling for household factors such as tenure, month of interview, native language and type of piped supply, significant variations in household interruptions are present within Chambeshi WSC, Kafubu WSC, Luapula WSC, Lukanga WSC, Mulongo WSC, and Nkana WSC when compared to Lusaka WSC (Table 6-6, Model 3). This suggests that the characteristics of providers impact household-reported availability of supplies. These results, which classify availability across a whole region, could however hide considerable differences within service areas (Bellaubi and Visscher 2014).

Provider and regulator data substantially oversimplify the complex reality of water supply at the household level by masking variations and patterns of inequality within provider coverage areas. Whilst data was unavailable for a finer resolution from the provider/regulator perspective, we have demonstrated the value of using household surveys to provide more detailed analysis. Variation at the household cluster, household- and provider-level is evident when exploring the descriptive analysis (Table 6-4 , Figure 6-12). Modelling shows however, that statistically significant inequalities at the household level are minimal (Table 6: Model 4) and that cluster- and provider-level variables are key predictors:

- Variations between households were evident based on native language, where we found English speaking households less likely to experience interruptions compared to households speaking all other native languages. This could also reflect the regional distribution of ethnicity in relation to supply availability. Ethnicity is an important factor contributing to water inequalities globally, with indigenous populations comprising 15% of the world's poor (UN Water 2018).

- Relatedly, households in mid-wealth clusters were less likely to experience an interruption than those in poor clusters. This could be a result of households in wealthier neighbourhoods being able to afford protective measures such as water storage tanks (Pattanayak et al. 2005; Oageng and Power Mmopelwa 2014) or because wealthier neighbourhoods have greater capacity to address supply network failures. Alternatively wealthier neighbourhoods experiencing less interruptions could be a result of greater development increasing availability of supplies as found by Thomas *et al*. (2020).

- Counter to our hypothesis, we also found that households who at least partly owned their home were more likely to experience interruptions than those that did not. Further exploration of the reason for this was inconclusive.

- Households using a neighbour's piped supply also had higher odds of experiencing an interruption than those with a supply in their dwelling, perhaps because households may be more resistant to selling their water to neighbours during times of water scarcity. As expected, availability of supplies was also affected by seasonal trends, with all bar those interviewed at the height of the rainy season reporting having interruptions (Rawas *et al*. 2020).

It is clear that the data landscape is complex and further exacerbated by the challenges of measuring availability (Majuru et al. 2018; Thomas et al. 2020). Whilst comparison has been possible between provider and regulator perspectives, it has not been possible to directly compare the perspective of the user. Thus, we have demonstrated the value that uniform metrics of measuring availability, across all three data streams, would provide in order to better streamline data comparison. This is especially important for international monitoring and benchmarking. In responding to calls for improvements in methods and data that include the different data sources (Bartram *et al*. 2014) we demonstrate the value of enabling comparable insights into drinking water availability in order to understand inequalities between population groups. That said, in the context of Zambia, comparison has been made possible by a relatively simple data landscape. Provider coverage areas match well to provinces, user data is not displaced over national boundaries and within each provider coverage area there are ample household clusters for analysis. In other countries such analysis may not be as straightforward due to more complex water governance landscapes and data variations. We therefore conclude that the transferability of methods is reliant on the data at hand.

6.4.3. Limitations

A number of limitations exist in the data used in this analysis. The provider data sourced from IBNET only includes the population served by reporting commercial utilities. It does not include supplies from private schemes/companies such as Kafue Sugar, Larfarge Cement-Chilanga or Konkola Copper Mines Plc (NWASCO 2021), whereas the DHS data will include the household's perspective of supply availability for these areas if they are included in the sample or cover enough of the population. Household reporting in the DHS could also be based on community piped supplies, which again IBNET does not capture (Rawas *et al*. 2020). In addition, whilst the survey question is successful in quantifying whether households experience interruptions, it is limited in its ability to truly represent household experiences of drinking-water availability because of its narrow scope. For example, only households who experience an interruption of at least one full day in the two weeks prior to being interviewed are captured, whilst information on how many full day interruptions there are in this period is not included. There are likely to be many more households, who experience shorter- and longer-term interruptions in their supply, that the DHS does not capture. There could also be issues of data omission or item nonresponse as the DHS surveys the head of household, and not the household member that is responsible for drinking-water and is most knowledgeable.

The analysis undertaken focuses on urban and peri-urban supplies as data were only available for these from the provider and regulator. Area definitional differences exist however. The regulator, NWASCO, define urban areas as '*developed parts of districts and where the district administration is located in*' and peri-urban areas as '*unplanned settlements within urban areas and these are densely populated with lower service levels than urban proper*' (NWASCO 2018a, p. 14). In contrast, the DHS's classification of urban is based on the 2010 Zambian census, and includes households that have basic amenities such as piped water. Given households were removed from the dataset based on the DHS's classification of urban/rural, these differences in definitions could mean that households were removed despite the regulator classifying them as urban. Additionally, given the DHS has used a classification of rurality that was determined eight years prior to the DHS being undertaken, it is likely that regions classed as rural may no longer be.

The issue of differing classifications of urban/rural is further exacerbated by the use of GHSL population data to create the rurality and change in urbanisation variables. This dataset has a finer scale classification of cities, suburbs/towns, rural areas and unpopulated areas (Dijkstra and Poelman 2014), meaning the location of households is classified differently to the DHS classification. As a result, despite having removed all rural households based on the DHS classification, for both the rurality and change in urbanisation variables some households are located in rural or unpopulated areas. This could also be a result of the DHS's displacement of household cluster locations where clusters are displaced into a location that is inconsistent with how they were classed for the DHS. For example, we found one cluster had been displaced into a lake, which could be a DHS mistake or due to inconsistencies with the GADM shapefile used.

Limitations also exist with the higher-level wealth explanatory variables included in the modelling. To create the neighbourhood wealth variable, we aggregated the DHS wealth quintiles to household cluster level however this will mean that closely located extreme differences in wealth will not be accounted for. The provincial wealth variable used provincial GDP data which is based on where industries produce their goods or where their head office is located. For industries such as railway systems, communication networks and power companies, services are provided nationally however. Therefore, the data may not be a true representation of wealth in the coverage area of each provider (Republic of Zambia Central Statistical Office 2017).

Additional explanatory variables were considered for this analysis, however there were either no available data or reasonable proxies did not exist. For example, 'voice' is a strategy that includes complaining and protesting to providers when supplies are inadequate (Majuru *et al*. 2016). It is hypothesised that those who have greater voice are more likely to have better supplies. No data could be sourced for this variable. We also sought to include the gender of the person collecting water as it is hypothesised that female respondents, whose role it often is to manage household water, may be more likely to report supplies as being unavailable due to increased knowledge (Jeil *et al*. 2020). This detail was not included in the DHS however. It also would have been difficult to include because it is not applicable to all piped supplies, for instance, supplies that are piped into the dwelling do not require someone to collect it.

Storage tank ownership was also considered for inclusion; tanks can be connected to household piped supplies and are often used as a coping strategy to enhance water quantity (Guragai *et al*. 2017). This can mean households are unaware of piped supplies being unavailable, leading to misreporting of the availability of their supplies. Neither tank ownership nor gender of water collector are included in the DHS. Blue water scarcity was also considered as it directly implicates drinking water availability, particularly in SSA where natural water sources vary greatly and are affected by drought and seasonal variations (McNally *et al*. 2019). However, exploration of the available data from the Water Footprint Network (Mekonnen and Hoekstra 2011) showed that there is limited variability with water scarcity being considered low across Zambia.

This analysis is limited to households in urban and peri-urban meaning that results are biased as they represent only a third of the population of Zambia. Recall bias will likely exist in the DHS (Boerma and Sommerfeltb 1993), with respondents failing to remember or misremembering interruptions in their supply. This may be further exacerbated by the two-week recall period used in the DHS question on the availability of supplies which could result in underestimation (Overbey *et al*. 2019). Respondents may also misclassify events that were 3-4 weeks ago. Gender related biases may exist in the DHS data as a consequence of the enumerator-effect and how genders of the interviewer and interviewee effect interactions, levels of trust and willingness to be open (West and Blom 2017).

6.4.4. Using Household Surveys for Assessing Inequalities within WSC Areas

Regulatory reports and provider performance databases such as IBNET do not differentiate the level of service provided to different household groups within their coverage areas. However, it is known that ethnic minorities, the poor, and other disadvantaged groups may receive poorer quality services (WHO and UNICEF 2019b). In this chapter, we integrated provider coverage area boundaries with household survey data to examine such inequalities. As discussed, we find some evidence of national inequalities in the availability of piped water supplies in relation to ethnicity (measured via first language), tenure and seasonality but not household wealth. We find no significant evidence that such inequalities vary between WSC coverage areas.

At present, exploring such inequalities elsewhere via this methodology would only be possible in countries where household surveys have measured supply interruptions and for WSCs serving large populations, with known geographic coverage areas (see: Figure 6-5). Such countries include Kenya and Mozambique, but analysis will become possible in more countries as data availability increases. Although currently possible for only a small number of countries, further analyses could enhance monitoring of provider performance via data gathered independently of service providers, such as from the households that rely on water services.

6.4.5. Improving Monitoring of Availability

Improving the understanding of user reported availability of drinking water through considering provider and regulator perspectives is of great value. Using all three perspectives together gives a more in-depth picture as to what is happening to households such as those in Zambia. However, at present, the varied use of the frequency of interruptions, hours of supply and LPCD makes direct comparison unnecessarily complex. One way to resolve this would be further uptake by national statistical agencies and user datasets, such as the DHS, of the JMPs expanded questions which include asking households *'how many hours per day is water supplied on average?'* (WHO and UNICEF 2018a). Whilst uptake and streamlining of these questions is reliant on the availability of resources (Thomas *et al*. 2020), it would enable direct comparison with regulator and provider reporting of supply availability.

Definitions of provider reported average service hours requires further clarity. For example, does it represent the hours a pump in a piped network is operated or the average duration of supply that households receive? Several suggestions have been made to address this, for instance regular random household surveys by providers or the use of sensors to detect outages (Rawas *et al*. 2020). At present, provider reporting of hrs/day is unclear and it is unknown what the number of days between supply is.

6.4.6. Future Research

We continue to recommend smaller scale studies of drinking water availability. Whilst our analysis bears similarities to Rawas *et al*. (2020) in its regional/provincial analysis, future work that resonates more closely with Bellaubi *et al.*'s (2014) finer scale case study analysis would give more detailed understanding of the availability of piped supplies. In order to achieve this, we call for providers and regulators to report availability for smaller geographical units so that households can be better matched with provider jurisdictions. This would also be enhanced by providers providing their supply areas as coverage area boundaries to IBNET in order to make data integration easier.

6.5. Conclusion

Overall, this analysis supports existing assessments of user and provider-based data that are disaggregated at a sub-national level (Bellaubi and Visscher 2014; Rawas et al. 2020) by comparing the perspective of the user, provider and regulator. A national-level comparison is provided in the context of Africa. Evidence shows user, provider and regulator reports of availability of supplies in Zambia are correlated, though direct comparison between perspectives is difficult due to the variations in metrics used to assess supply availability. Regulator and provider reporting are generally consistent with one another. Comparing data streams is of value, however data needs to be nuanced and consistent across perspectives in its measurements of availability, thus at present due to data limitations it may not be possible in all contexts. Using data from households could also help enhance monitoring of provider performance.

From our analysis we show the importance of providing finer-scale analysis that goes beyond what is possible when using only the regulator/providers perspective. Analysis has examined variations at the household and household cluster level and found inequalities to be minimal when adjusting for confounders. Of the inequalities that did exist, wealth was the only neighbourhood characteristic to influence supply availability, whereas at the household level tenure, month of interview, native language and type of supply had a modest effect. Overall, inequalities between provider coverage areas were found in household reporting of interruptions to piped drinking water supplies.

We outline recommendations for streamlining metrics of availability and highlight the importance of uniform geographical disaggregation of data which will enable the comparison of all three data streams. If achieved, more complex analysis of the availability of supplies will be possible. It will also allow easier comparisons of the perspectives of users versus providers and regulators across and within countries, and result in more frequent monitoring than is possible from using solely user data.

Chapter 7

Overall Conclusions

7.1 Overview

This research provides much-needed insight into the relatively newly established concept of water service 'availability', which could support the JMP's efforts in monitoring progress towards SDG 6. This thesis aimed to quantify factors that affect drinking water availability across SSA and associated geographic and socio-economic inequalities. It also aimed to evaluate the metrics used to assess service availability and the data currently available for monitoring progress towards SDG 6.

Specifically, it aimed to:

1. Assess how research has measured the availability of drinking water in SSA to date and examined its consequences.
2. Evaluate whether different data perspectives correlate and can subsequently be used in conjunction with one another in monitoring progress towards SDG 6.
3. Assess the environmental effect of water scarcity/stress on drinking water availability across SSA.
4. Explore variations and inequalities in drinking water availability across SSA and common contextual and compositional factors associated with user-reported service availability.

In this chapter, a summary of the main findings and contributions to the evidence base is given, alongside the conceptual and methodological contributions of this thesis, and the uncertainties within the research. The chapter concludes by highlighting avenues for future research and recommendations for policy and practice.

7.2 Main Findings and Contributions to the Evidence Base

Each of the empirical chapters extends previous research, advancing existing understanding of service availability and the realities of drinking water availability in SSA. Through the use of systematic review methods and multi-level modelling, the objectives of this thesis have been achieved and subsequently contribute to the existing evidence base through the following main findings.

To assess how research has measured the availability of drinking water in SSA to date and examined its consequences: Chapter 4 assessed literature from peer-reviewed journals, conference proceedings and theses published between 2000 and 2019 to establish how service availability has been measured to date and whether households have the drinking water required to meet their needs. Analysis found the methods used by existing research to assess service availability included a diverse range of metrics which were often limited in their scope. They include quantity of water available, measured predominantly using LPCD/LPHHD which is potentially difficult for respondents to recall, the frequency of breakdowns and the hours of service in a given time period. The review also confirms low coverage of safely managed water services in SSA as reported by the JMP, based on analysis of national household surveys.

Using evidence from 47 studies, this analysis found that for the 89% reporting LPCD or LPHHD, 91% of households reported their average drinking water availability as less than 50 LPCD, meaning significant proportions of the SSA population do not use a safely managed drinking water service that is available when needed. Evidence is provided to show that international benchmarks for service availability are not being met. Results also show a range of study methods including household surveys, unspecified interviews, and water-meters, all of which had considerable methodological issues, have been relied upon to date. Households associated the causes of interruptions with a multitude of factors, with seasonal water stress being the most frequently cited. As a result of poor service availability, households across SSA have developed an array of coping strategies. Of the 22 studies reporting coping mechanisms, rather worryingly, 30% reported use of unimproved sources such as surface water as a coping mechanism. Findings show current research to have a varied understanding of water service availability which is unnecessarily complicated by the diverse range of methods used in assessments and the lack of detail in reporting.

To evaluate whether different data perspectives correlate and can subsequently be used in conjunction with one another in monitoring progress towards SDG 6: Building on the evidence from Chapter 4, in Chapter 6 findings show different data perspectives also use different metrics of service availability. Data from service providers and regulators correspond in their use of annual average hours of supply a day to measure availability, whereas user data from DHS household surveys report ‘interruptions in the two weeks prior to being surveyed’. The latter in particular is subject to intra-annual variation arising from temporal issues due to its limited focus on a two-week window, meaning factors such as recurrence of interruptions and seasonality are not accounted for. Use of all three data sources is of great value given that regulatory reports can be cross-checked against those from providers. Provider reports can offer context about water availability in the specific year in which a survey was conducted relative to typical years; and household surveys enable quantification of socio-economic and other inequalities in water availability (see section 6.4.5). However, the capacity to integrate data from the user, provider, and regulators’ perspectives is somewhat prohibited by the different metrics of availability used.

To assess the environmental effect of water scarcity/stress on drinking water availability across SSA: Using evidence from published studies in Chapter 4, multiple linear regression results showed water scarcity was not associated with LPCD. In Chapter 5, analysis explored this in greater detail using household survey, WRI water stress and WFN water scarcity data at a greater spatial resolution, whilst controlling for selected household and contextual factors, and using a consistent water availability metric. The resultant multi-level logistic regression models for 10 SSA countries found water stress to consistently affect service availability and to be associated with household reporting of interruptions. The results obtained show the environmental effect of water stress on households across SSA and demonstrate piped water services, often reliant on surface water reservoirs, are more frequently affected than services supplied by improved groundwater sources. As such, progress towards SDG target 6.1 could be undermined by water stress. Findings regarding the effect of water scarcity on service availability vary across study countries, likely due to the annual water scarcity metric masking monthly variations and being more narrowly defined than water stress.

To explore variations and inequalities in drinking water availability across SSA and common contextual and compositional factors associated with user-reported service availability – In Chapter 5 variations in drinking water availability are presented for 10 SSA countries. Results found between a quarter and a half of all households that use an improved drinking water source experience interruptions, and those using piped services more frequently report poorer service availability than those using boreholes or tubewells. Exploration of the associations between household availability and contextual and compositional factors was achieved in all three empirical chapters. In Chapter 4, contextual factors such as GDP per capita (PPP) and rurality were positively related to LPCD when water is accessed via by improved and unimproved sources, as reported in published studies. However, the relationship between rurality and LPCD only held in urban areas. In Chapters 5 and 6, more complex analysis using multi-level models explored the effect of a multitude of household (contextual) and neighbourhood (compositional) characteristics on household reporting of service interruptions. In Chapter 5, where analysis focused on improved sources, rurality, household size and type of service are most commonly associated with service interruptions across the SSA study countries. Analysis of urban piped service interruptions in Zambia in Chapter 6 finds neighbourhood wealth to be the only contextual factor associated with interruptions. Household tenure, month of interview, respondent's native language and water source type are compositional factors associated with service availability. Overall, the results obtained show the factors affecting service availability to be complex and intertwined, both household and context specific, and inherently reliant on the type of service used.

7.3 Conceptual Contributions

In achieving this thesis's objectives, several key conceptual contributions have been made:

To evaluate whether different data perspectives correlate and can subsequently be used in conjunction with one another in monitoring progress towards SDG 6: throughout this thesis the investigations show that the contrasting measures of service availability resemble those used to measure health in public health. Self-reported health and clinical measures of health, or healthcare use, are often used in public health research (Short *et al*. 2009). In Chapter 6 in particular, this public health analogy has been utilised with household-reported availability offering a 'self-reported' viewpoint, whilst provider- and regulator-reported availability offer a perspective similar to clinical measures of health or healthcare use. This analogy is also depicted in Chapter 2 through the use of Sadana *et al.*'s (2002) empirical model for the measurement of health. In using this to conceptualise the assessment of service availability in Figure 2-2, it has enabled the different perceptions of availability, and their implications for depicting *true* service availability, to be considered.

To assess the environmental effect of water scarcity/stress on drinking water availability across SSA: analysis addressing this research objective links drinking water service availability to the WEF nexus concept, unlike most literature on this topic. Contextualised within the WEF nexus, previous studies have explored how water scarcity impacts on agriculture and irrigation and subsequently results in competition over water for domestic use. For instance, Hamidov and Helming (2020) focus on water needs of irrigated agriculture and highlight issues of competing demands under water scarce conditions across the WEF nexus.

Chapter 2, section 2.5.3, builds on this through discussion of the impacts of overexploitation of water for agriculture on municipal services and the resultant effect on household drinking water availability. In doing so, attention is given to how the WEF nexus may further affect service availability through the competing demands of other sectors and impact water scarcity. For example, cross-sectoral demands for electricity result in power outages that affect water processing plants, causing water service interruptions (see for instance Figure 2-16). Finally, through this conceptual contribution, the need for research which considers how interruptions in water services affect other sectors that are equally important is identified in Chapter 5. This is essential as progress towards SDG 2.3 could affect SDG 6, especially as water scarcity worsens.

Additionally, Chapter 5's assessment of the environmental effects of water scarcity and stress on service availability illustrates the conceptual links between drinking water availability and the WEF nexus. Whilst water scarcity concerns the physical lack of water, water stress, an outcome of water scarcity, accounts for the ability to meet human and ecological demand. Chapter 5 therefore provides evidence to show how human pressures and competing water demands affect water scarcity and subsequently availability, supporting the conceptual links with the WEF nexus.

To explore variations and inequalities in drinking water availability across SSA and common contextual and compositional factors associated with user-reported service availability: in achieving this research objective, a contribution of this thesis is the translation of public health concepts of context and composition into drinking water research in LMICs. While previous water-related research has used public health concepts, this has been conducted in high income countries such as Australia (Fielding *et al*. 2012) and the USA (Barnett *et al*. 2020), whereas this thesis is novel in its LMIC focus.

In section 2.5, context and composition (Diez-Roux 1998; Cromley and McLafferty 2011) were used to explore the complex web of interrelating factors that affect drinking water service availability and contribute to service interruptions. In doing so, the drivers of service availability are conceptualised at the individual, household, and neighbourhood level. Chapter 2's diagrams (Figure 2-15 and Figure 2-16) illustrate the contextual and compositional characteristics that affect service availability, thereby providing a key conceptual contribution. Chapter 4's systematic review proved important in facilitating the identification of critical factors which affect service availability that were subsequently integrated into the conceptual diagrams. Associations between the compositional biosocial, socio-cultural, and household-specific water-related factors are illustrated, as are the contextual drivers of the wider community and the interlinkages of broader concepts such as population change, urbanisation, the WEF nexus, and climatic variability. Similar conceptual diagrams are lacking in the literature, with those that do exist being much narrower in their scope and failing to specifically focus on *availability*. For instance, Fisher *et al.*, (2015) more narrowly illustrate the drivers affecting functionality of handpumps through their conceptual model. In contrast, the conceptual models provided in this thesis are applicable to a wider range of water source types. They can also be used as a baseline for exploring factors affecting the availability of different water services in different localities.

Chapters 5 and 6 build on the public health concepts of composition and context through modelling, reinforcing their applicability and providing empirical evidence to support the conceptual diagrams created in Chapter 2. The causes of interruptions reported by SSA households in the papers included in the systematic review in Chapter 4 were then also accounted for in the quantitative modelling undertaken in Chapters 5 and 6. The multi-level models used allow for lower-level compositional household factors and higher-level community and environmental contextual factors to be accounted for. Crucially, in using multi-level models, contextual and compositional effects have not been completely separated but considered in conjunction with one another and interactions allowed for, whilst ensuring all relevant levels of analysis are considered simultaneously (Duncan *et al*. 1998). As such, this has enabled differences in experiences of service interruptions to be considered beyond one level and for variations to be accounted for (*ibid.*). Using the concepts of context and composition has proven especially valuable in establishing the variations between countries in the factors associated with the external environment and those within households that affect service availability.

7.4 Methodological Contributions

In addition to these conceptual contributions, a number of methodological contributions are made, identified below in relation to the relevant objective.

To evaluate whether different data perspectives correlate and can subsequently be used in conjunction with one another in monitoring progress towards SDG 6: in achieving this objective, one of this thesis' most significant methodological contributions is the spatial integration of user, provider, and regulator data. In Chapter 6, ArcMap was used to join household survey data with data from providers made available through IBNET and regulator data. This spatial linkage, compared to administrative record linkage (e.g. by matching individual identifiers such as social security numbers or healthcare registration numbers) is particularly valuable in LMICs, where robust, digitised individual records are often lacking. While previous research has linked user survey data with provider data from IBNET (Rawas *et al*. 2020), methods of spatial linkage using GPS coordinates were not utilised. The novel analysis in this thesis additionally integrates regulator data. It is also the first study to connect household survey data with provider data from IBNET via multi-level modelling. For example, Rawas *et al*'s. (2020) analysis included simpler direct provincial-level comparisons of IBNET and household reported continuity, supported by sensitivity analyses.

In knowing the coverage areas of regulator reported data, and spatially matching this with provider data alongside household clusters, a more nuanced and complete dataset is created with multiple perspectives on drinking water services. As such, a method has been developed that could help the JMP to evaluate their minimum population coverage threshold for monitoring, which requires that when making estimates for safely managed drinking water data are available for at least 50% of the relevant population (WHO and UNICEF 2017b). Through this thesis's analysis and methodological contribution of integrating provider, regulator and user data, this threshold can be achieved where the data streams can be easily matched spatially, as is the case in Chapter 6. A plausible method has therefore been provided that the JMP could adopt moving forward. Moreover, in enabling user data from household surveys to be linked to regulator and provider data, it allows finer scale spatial and temporal analysis than if using only regulator or provider data which substantially oversimplify the complex reality of water supply at the household level.

To assess the environmental effect of water scarcity/stress on drinking water availability across SSA: in addressing this aim in Chapter 5, environmental water scarcity and water stress datasets were integrated with household survey data concerning service availability for the first time. The integration of datasets using spatial co-location is known for its power in developing rich spatially analytical research. This broadens the body of studies that has enriched DHS data through spatial linkage with infra-structure, environmental, and socio-economic map layers (Mansour *et al*. 2012).

Previous research has linked similar water scarcity data with data on domestic water use (Malley *et al.*, 2009), however this consisted of primary information where researchers have greater control and knowledge of the data collected. Similarly, Duchanois *et al.*, (2019) link WFN water scarcity data to household survey data on water continuity. However, in this instance, researchers collected the household survey data and GPS coordinates of the survey locations, again making data linkage easier. The methods used here are novel in their use of secondary household survey data on service availability and demonstrate the importance of international household surveys collecting geospatial data, which subsequently allows for linkage with additional datasets using GIS.

To explore variations and inequalities in drinking water availability across SSA and common contextual and compositional factors associated with user-reported service availability: to the best of our knowledge, Chapter 5 is the first multi-country study to assess the availability of drinking water services and prevalence of household-reported interruptions using household surveys. Whilst multi-country studies of WASH in household surveys exist (Fuller et al. 2015; Geremew and Damtew 2020; Dietler et al. 2021), they focus on domestic water treatment (Rosa and Clasen 2010), access to improved water services (Armah *et al*. 2018), socioeconomic factors which affect service access (Gomez *et al*. 2019), monitoring of drinking water quality in household surveys (Bain *et al*. 2021) and the burden of disease from inadequate WASH (Prüss-Ustün *et al*. 2014).

7.5 Transferability and Scalability of Research

The preceding section discusses how the analysis undertaken throughout this thesis could be transferred and up-scaled to alternative geographic areas and populations. The methodology and modelling undertaken in Chapter 5 could be applied to different contexts, within and beyond SSA, so long as appropriate underpinning data exist. The data scoping review undertaken in Chapter 6, Figure 6-4, indicates SSA countries where survey data, other than DHS data, are available that include metrics of water service availability. Using this, Chapter 5’s analysis could be transferred to other countries in SSA through employing data from other household surveys. For example, georeferenced PMA data is available for Kenya and includes information on the months water is available within a year (Performance Monitoring for Action 2022).

Additionally, alongside the PMA, both the DHS and MICS data have coverage beyond SSA. The DHS currently covers over 90 countries worldwide (The DHS Program 2022) and MICS have been conducted in over 110 countries (Khan and Hancioglu 2019). MICS data in particular include information on the availability of water in sufficient quantities, source availability and the number of household members unable to access water in sufficient quantities when needed (UNICEF 2022). However, geospatial data of household clusters is currently unavailable for MICS (Khan and Hancioglu 2019). For analysis from this thesis to be fully transferable to the MICS it would require household cluster GPS coordinate. Overall, the wider availability of data means analysis could be extended to Asia or South America for example. As the JMP continue to roll out and implement their core question on drinking water availability to different countries, methods will become transferable to more countries.

More specifically, the methods undertaken in Chapter 6 to integrate provider, regulator and user data are transferable to other countries and could be scaled beyond Zambia. They could also be applied to other regions and conducted at a larger scale than in this research. Transferring and scaling the methodology is heavily reliant on the availability of data, however. Data must be available for all three perspectives in order to replicate the analysis undertaken in Chapter 6. Alternatively, if data is available from two of the three perspectives, such as the user and the provider, then it may emulate analysis undertaken by Rawas, Bain and Kumpel (2020), or build on their findings if regulator data is available as at least one of the perspectives. The DHS has extensive coverage as previously mentioned, whilst IBNET has data from providers in over 170 countries (IBNET 2022a). Regulator data availability is varied with no central repository, though there are regional associations of national water regulators, for instance in South America see ADERASA (2022). Limited information about regulators is available through RegNet (WHO 2022) and the JMP's country files provide details on datasets from some country regulators (JMP 2021b), though data is generally accessible through annual regulatory reports such as that used in Chapter 6.

With ample data available from the three perspectives, should the national water service landscape be sufficiently simple and allow for the matching of geospatial units, the methods undertaken in Chapter 6 are easily scaled up and transferred. Methods are not scalable in contexts where water services have been nationalised and provided by one supplier, such as in Ghana, as regulator and provider data would match and show no spatial variation across provider coverage areas. In contexts where the national water service landscape is more complex, such as in South Africa and Kenya, methods could also be transferred. However, analysis would no doubt be more complex and require the development of methods to link provider and regulator data as this was not required in Chapter 6's analyses.

7.6 Limitations and Uncertainties

Detailed limitations of each empirical analysis have been stressed in the corresponding discussion sections of each chapter. More general limitations of the data used, measurement of availability and the methodology undertaken are outlined in this section.

There are numerous limitations in household reporting of service availability when the JMP's core question is used. These are especially applicable to the analysis undertaken in Chapters 5 and 6 where DHS data is used, which relies on the JMPs core question, to collect experiences of service interruptions. These limitations include:

- **Temporal limitations:** the question does not account for the number of full day interruptions a household experiences within the specified 2-week window. Subsequently, it does not allow for the identification or differentiation of short- or long-term interruptions. It also prevents information regarding the recurrence or regularity of interruptions to be collected. For example, intermittent services as discussed in section 2.3.3.2, can be irregular and potentially a result of mechanical failure, illegal breakages of pipelines or problems obtaining spare parts, or they can be regular as water demand exceeds supply and the provider attempts to manage the problem through rationing of supplies. As such, temporal data limitations mean it is unknown if interruptions are a result of water rationing being practiced or irregular intermittences. Interruptions following seasonal patterns also cannot be accounted for directly because of the cross-sectional nature of the DHS surveys. As such, they can only be identified indirectly by analysing household survey implementation months in relation to reported interruptions. Given a country's DHS can take up to a year to conduct, in some cases, some households will be surveyed during the rainy season and some the dry season, although this can only be identified by linking household survey GPS cluster locations and implementation months to climatological map layers.

- **Telescoping and errors of omission:** due to the temporal specificity of the question, and 2-week recall period, respondents may misclassify interruptions that were 'around 2 weeks ago' but in reality, were 3-4 weeks ago, a phenomenon referred to as telescoping an event (Gaskell *et al*. 2000). Alternatively, respondents may completely forget an interruption, especially if it was short term, though the length of the interruption and the likelihood of this occurring is likely dependent on the perception of an *inconvenient* interruption. Interruptions that occur throughout the night or whilst the respondent is out of the house are also likely to be omitted as the respondent is unaware of all, or any, interruptions that have occurred.

- **Recall and response bias:** as a cross-sectional survey, the data from the DHS is subject to biases (Boerma and Sommerfeltb 1993). When a household reports on water service availability, the respondent surveyed may not be the household member that is responsible for drinking water. This is particularly the case as the DHS interviews the head of household where possible, however this may not be the household member responsible for water collection or management. Responses may also be biased if respondents think they could get better services if they tell the enumerator their services are insufficient, or conversely, they may claim to have piped water / borehole water if this is seen as socially desirable, creating additional bias.

- **Gender bias:** in surveying the head of household, rather than the household member that is responsible for water provisioning (which is typically a woman (Pouramin et al. 2020)), women's perspectives are generally excluded from the DHS data. There will also be gender related biases as a result of the enumerator effect and social interactions between the interviewer and interviewee (Di Maio and Fiala 2020). In some instances this could result in failure to honestly report on the realities of drinking-water availability (Weber *et al.* 2021).

- **Missingness and non-response bias:** as with any household survey, the DHS is prone to issues of non-response bias (Marston *et al*. 2008). For example, sampled respondents may have declined to participate in the DHS completely, or they may specifically decline to answer certain questions within the survey. This item non-response may have occurred if the respondent did not understand the question being asked. Survey non-response, on the other hand, could have occurred due to refusals to participate or as a result of absenteeism and an inability to make contact with the sampled household. In all instances, this may have led to case-wise deletion of households from the modelling undertaken throughout this thesis.

- **Reliance on verbal responses:** the DHS question on service availability is asked verbally through interviews, rather than observing the water source used by households. As a result, inaccurate responses may be given especially if the respondent has certain feelings regarding their reality. For instance, respondents may be embarrassed to admit using unimproved services when they know they are a health risk, and therefore report using safer protected sources instead (Wright *et al.* 2004). Such issues could be reduced if enumerators conducted observations of drinking-water sources, as is the case with MICS when collecting water quality samples (Bain *et al.* 2021). This would also allow a more accurate understanding of the availability of sources and the factors affecting continuity of services (e.g. broken or damaged infrastructure).

- **Narrow scope:** details of alternative sources used to meet requirements are unknown because of the limited nature of the survey questions. This is important as households may not report experiencing an interruption if their needs are being met by an alternative service. Conversely, if households are reporting an interruption but use multiple services it is unknown whether it is their primary or secondary service that is unavailable. This is especially important as in LMICs and across Africa, it is routine to use multiple services to meet water requirements and build resilience (Elliott *et al*. 2019). Similarly, details of water storage practices are unknown. Households using water tanks that are plumbed into their piped network may also be unaware of interruptions occurring in their piped service. This is important as households may not report experiencing interruptions if their water needs are being met through use of stored water.

- **Limited scope**: DHS data on service availability only includes households using piped services, boreholes, and public taps/standpipes (Croft *et al*. 2018). This subsequently limits the scope of the analysis as only the wealthiest of populations are able to afford these service types. This particularly affects findings relating to rural households in Chapter 6, where inadvertently only the wealthiest of rural populations will have been included in analysis.

- **Misclassification of water source typologies**: the survey question on availability relies on households correctly reporting the type of water source used, however variations in terminology can lead to errors. Classifying different types of water sources could, for instance, be affected by regional and country-level variations, with different typologies used to refer to the same source. Similarly, as an adaptation to intermittent services, rainwater which is collected in tanks and connected to household supplies with piped infrastructure, is commonly reported as being a piped supply (Okotto-Okotto *et al.* 2020). Evidence from Okotto-Okotto *et al.* (2020), has also shown low inter-observer agreement between field survey teams, who can struggle to differentiate between water sources when using a standard classification such as the JMPs improved/unimproved categories. The misclassification of sources is of particular concern as households being surveyed for the DHS only report their availability when using a piped supply, tube well or borehole (Croft *et al.* 2018).

- **Restriction to only drinking-water:** the focus of the JMP, and subsequently the core-questions, on only drinking-water means that water used for domestic purposes is not included in current reporting and monitoring. Subsequently, this does not reflect the Human Right to Water which states that water should be available for *'[…]drinking and personal hygiene, as well as of further personal and domestic uses, such as cooking and food preparations, dish and laundry washing and cleaning'* (Human Rights Council 2011). Additionally, water also has huge economic value and multiple use water services are crucial for supporting household livelihoods especially in rural areas (Van Koppen and Smits 2010). By excluding all other uses of water, it could mean that significant proportions of the population are being missed from monitoring as they are reporting having sufficient drinking-water, but in reality do not have the water required to meet *all* their needs.

The analysis undertaken in Chapters 5 and 6 is also affected by data related uncertainties and limitations as a result of combining datasets. Issues affecting the covariates used during analysis include:

- **Missed populations:** provider data only includes the population served by commercial utilities. In the context of the analysis in Zambia (chapter 6), this meant rural populations could not be considered, nor could populations supplied by private service providers.

- **Incompleteness:** there are no obligations for providers to report to their performance data to IBNET, rather it is reliant on providers opting in to reporting. Data can therefore be incomplete, patchy, and out of date, and restricts where analysis is possible.

Moreover, issues affecting the linkage of DHS and covariate data include:

- **Misclassification:** the geospatial displacement of household clusters that is undertaken by the DHS has impacts when linking datasets. For example, when linking the DHS data to the environmental data in Chapter 5, household clusters falling on the boundaries of each classified area of water stress/scarcity may have been misclassified as their actual location has been displaced. This may also have occurred in Chapter 6, when linking DHS data to provider and regulator data, the outcome of which may mean households have been wrongly classified in who their service provider is.

- **Scale mismatches:** DHS data is nationally representative whereas provider data from IBNET may not be because of the reliance on providers to report data. This means that variation in service interruptions is masked by provider data which concerns annual averages for their coverage areas.

- **Definitional differences:** classifications of rural and urban areas are highly varied and will have impacted analysis in both Chapters 4 and Chapter 6. Analysis of studies included in Chapter 4 comprised comparisons between rural and urban LPCD, however the studies included will have used different classifications of urban and rural areas. In Chapter 6, regulator classifications of urban areas differed to those used in user data. This had a knock-on effect when creating additional variables from datasets with finer scale definitions of cities, suburbs/towns and unpopulated areas.

Inevitably, and as outlined in this section, the results of this thesis are prone to uncertainties and limitations. Whilst the upmost caution has been taken to limit the effect of these, most are inherent to, and a result of, the data that has been used. Given the relative newness of research which considers drinking water service availability, as discussed, data is limited and as a result restricts the possibilities of analysis. This thesis has used the best and most appropriate data that is available, and whilst limitations are inevitable, results are valid and have a significant importance in their contributions to WASH related research.

7.7 Future Research

Future work could include analysis using other measurements of water scarcity and/or water stress and undertake comparison with water interruptions reported via household surveys. This would allow for more detailed analysis that better captures the pressures water scarcity/stress place on domestic water services. Analysis of the effect of water scarcity on surface water reservoirs could for instance use data on dam levels made available via the GRanD database (London *et al*. 2021). This would also enable more specific research into the effect on piped water services. Alternatively, data from the GRACE satellite system (Richey *et al*. 2015), which estimates the depletion of groundwater reservoirs by measuring associated local gravitational field changes, could assess the effect of water scarcity on boreholes. Given the coarse spatial resolution of these data, analysis would only be suitable for multi-country or continental analyses. Building on this, to further explore predictors of borehole functionality, water point mapping data could be used (WPDx 2022). Analysis could include assessing hotspots of non-functioning boreholes in relation to DHS household clusters and reporting of service availability. This would be of particular value for exploring service availability in rural areas, where borehole use tends to be most prevalent (Foster *et al*. 2019).

Moving forward, smaller-scale more detailed studies which explore in depth the risk factors associated with interruptions and patterns of household water use behaviour would be valuable. Such studies could use the conceptual frameworks outlined in Chapter 2 as a basis for their analysis and explore in detail specific risk factors that have not been considered in this thesis's research. For example, compositional factors, such as gender or disability, of the household member responsible for domestic water and the effect on water availability could be assessed, or the effect of contingency water supplies or mode of transport for water collection on the amount of water available to households. More broadly speaking, more detailed assessments of the effect of compositional factors on service availability would enable greater scope to assess synergies between SDGs and trade-offs that are made in relation to the WEF nexus.

The reality of interrupted and unavailable drinking-water services that households are faced with is complex and context specific. As a result, it is very difficult to capture and represent household experiences using secondary data that has been collected using only one survey question. Throughout this thesis, discussion has illustrated the shortcomings of survey data in its ability to capture details of service availability (Chapter 7, section 7.6). Variations in interruptions between weekdays and weekends; the effect of seasonality and recurrence of interruptions; details of multiple source use to deal with variations in service availability; and water storage methods and effects on experiences of service interruptions, are all unaccounted for when using secondary data from household surveys. Moving forward, studies which conduct primary data collection, would allow for these details to be captured whilst reducing biases in the data which are introduced through a reliance on respondents' capacity to recall events. Such studies could adopt the use of methods such as the HWISE (Young, Collins, *et al*. 2019) and HWIAS (Tsai *et al*. 2016), where resources allow, in order to provide more rigorous and nuanced estimates of availability. The household member that is responsible for water collection could also be accessed, subsequently reducing the gender related biases discussed in section 2.3.4.1, and observations of water sources could be undertaken by field teams. A greater understanding of the coping strategies and adaptations households have developed in response to poorly available and discontinuous supplies would also be possible. Such studies could complement the use of household survey data whilst allowing the limitations of the JMPs core question on availability to be overcome. In doing so, the shortcomings of existing research, as outlined in Chapter 4, can also be addressed by ensuring sufficient amounts of study methodology detail is reported, for instance the sampling strategy, missing data and measures of uncertainty.

The quantitative analysis in this thesis only focused on a subset of improved drinking water source types. Whilst this is vital given the policy impetus of the SDGs that safely managed water services comprise only improved water sources, almost one quarter of SSA households rely on unimproved and surface water sources of drinking water (JMP 2021a). Given the evidence of poor availability of unimproved sources found in Chapter 4, future work could focus on interruptions of these services. Research would subsequently include assessments of service availability in rural areas which remain understudied and have not been addressed in this thesis due to data limitations. Additionally, in line with the SDGs' focus on safely managed services, research could focus on improved sources which are not captured by the DHS question on service availability, for example, protected wells, protected springs and rainwater harvesting. The latter could provide interesting insights into the more immediate effects of climatic variability and change, whilst considering planetary health concepts (French *et al*. 2021). Understanding their availability could also be important in certain local contexts, for example, where there are many protected family wells or wetter climates where rainwater harvesting is widespread.

Building on this thesis's use of DHS data, comparison of the metrics of availability used by other major household surveys, including MICS and PMA, would be of value. The data scoping reviews undertaken in Chapters 5 and 6 found overlap in the survey data available in some study countries. For example, Uganda and Ethiopia both have DHS and PMA data, and Gambia, Sierra Leone, Zimbabwe and Nigeria all have DHS and MICS data available. In conducting such analysis, questions surrounding the similarities of national level indicators used in surveys could be answered. Moreover, national-level comparison of availability indicators used in each survey, and whether they depict similar levels of service availability, could be explored alongside spatial coincidence of local hot-spots in reporting at sub-national level.

As successive DHS survey data becomes available and includes details of service availability, longitudinal analysis will be possible. Crucially, this will enable studies to explore trends overtime in service availability and better account for the impacts of ongoing and longstanding issues such as urbanisation, population growth and water scarcity/stress. This will also allow for seasonality to be better accounted for and support adaptation measures in response to the effects of climate change on domestic water supplies, such as unpredictability of weather patterns (Masson-Delmotte *et al*. 2021).

Finally, to explore the provider and regulator perspective of service availability in greater detail, future work could include surveying a sample of micro-enterprises or community run service providers in small towns and/or rural areas. This is of particular importance as IBNET only focuses on bigger providers that have greater coverage and do not include private service providers. In rural areas of SSA however, micro-enterprises and community run providers are crucial suppliers of drinking water. Gaining a better understanding of their perceptions of service availability through surveys will allow for a more rounded perspective of service availability across SSA. In a similar vein, exploration of how regulators and providers collect their data through the use of interviews would allow the barriers to making data more widely available to be understood.

7.8 Policy and Practice Recommendations

7.8.1 Recommendations for Enhancing International Monitoring

This thesis provides support for the JMP's continued roll-out of a consistently worded question on water service availability (WHO and UNICEF 2018a). It demonstrates how this facilitates multi-country analysis that can provide insights into how water scarcity, amongst other factors such as urbanisation and population growth, are affecting service continuity. Moving forward, ensuring a standard question, such as the JMP's which asks '*In the last month, has there been any time when your household did not have sufficient quantities of drinking water when needed?*' (WHO and UNICEF 2018a), is continually used and rolled out will allow for ongoing country-level comparisons in service availability. Further to this, household surveys other than the DHS, for instance the MICS, could also release household cluster geocodes to facilitate such analyses across a wider range of surveys.

Where possible, international monitoring efforts should continue to encourage national governments to roll out the core questions on service availability to water providers and regulators alongside their current measures. In doing so, direct comparison between user, provider and regulator-reported availability will be possible and more comprehensive analysis of the consistencies between data streams can be undertaken. The difficulties in comparing reporting of availability faced in Chapter 6 could subsequently be addressed.

In conjunction, where resources allow, the use of the JMP's expanded questions on availability should occur. This will ensure supplementary details are collected which provide a more complete picture of service availability and address some of the limitations and uncertainties of this thesis. This would facilitate data availability on the regularity of service interruptions, reasons for unavailable services, service continuity (i.e. number of hours water is supplied on average per day) and discontinuity (i.e. number of days in the last month that water was unavailable when needed), use of storage tanks and smaller water storage vessels, and variations in source availability during wet and dry seasons (WHO and UNICEF 2018a). In collecting such information, a more complete picture of service availability will be possible, which is especially important when considering the effect at the household level and the implications to individuals' standard of living and health.

The JMP should consider making its expanded question on responsibility for water (number XW2) a core question. This asks '*who usually goes to this source to fetch water for your household?*' and is especially important as it identifies the gender of the individual responsible for water collection (WHO and UNICEF 2018a). Crucially, encouraging more consistent uptake of this survey question will allow for some of the limitations identified in Chapter 2, section 2.3.4.1, to be accounted for. In doing so, the JMP should encourage national governments and statistical agencies to include this question in their surveys and censuses, with particular emphasis given to its importance in allowing gender to be accounted for within survey data.

In rolling out its guidance on WASH surveys, the JMP should emphasise that the most knowledgeable household member and person who is responsible for water provisioning should be interviewed, rather than the head of household. Where this is not possible, as an alternative multiple members of the household could be interviewed, allowing for the most knowledgeable respondents to provide different pieces of information wherever possible (Demombynes 2013). In all cases, to overcome the potential for gender related biases, the gender of the interviewer and the respondent should be recorded within all survey paradata. This would allow researchers to account and control for potential biases in their analyses, thus minimising the potential for differentiated effects that are possible when different genders interact during interviews (Flores-Macias and Lawson 2008).

Finally, it is recommended that international monitoring shifts its emphasis to using regulator data alongside household survey data more consistently. At present, regulator and provider data are used when there is insufficient household survey and census data available to monitor service availability (WHO and UNICEF 2017c). However, findings from Chapter 6 show that timeliness and currency of data are crucial, which can be a limitation for household surveys as they are often outdated and represent only one point in time. Using data from routine monitoring undertaken by regulators is vital in strengthening surveillance of water supplies (Charles and Greggio 2021). Encouraging uptake of regulatory and/or provider data to meet the JMPs data threshold of half the research population, could enable a timelier data feed for the JMP. Evidence from this thesis therefore makes the case for greater support for regional regulator networks. This would be of great value to encourage and enhance the harmonisation of indicators across countries, whilst enabling more consistent checks on data supplied to regulators by providers. Were this to happen, it would help the JMP to fulfil their mission by drawing more on regulator data.

7.8.2 Recommendations for IBNET

Given IBNET's role in collating and harmonising provider data, several recommendations can be made based on how they collect information. When providers report to IBNET, a benchmarking toolkit is provided to ensure consistency in the data (IBNET 2022b). Moving forward, IBNET should redefine this benchmarking toolkit in order that reporting from providers includes specific details of their coverage area boundaries. If possible, it would also be beneficial for providers to supply information of their catchment areas as a shapefile. This would make integration of the different data streams more streamlined, efficient, and accurate. It would also align well with the New IBNETs (see section 2.2.1) intention to be an independent global information system (New IBNET 2022).

In redesigning their toolkit, it is also recommended that IBNET ask that provider reporting is undertaken at a finer spatial scale where practical to do so. Where such data are available, the use of geographic areas smaller than provider coverage area is recommended. If for example district level data were generated, it would enable more detailed analysis and greater potential for linking geographic data. IBNET could also include the JMP's core metric of availability in their benchmarking toolkit in order that reporting aligns with household surveys and censuses. Further to this, IBNET could encourage water regulators to collect information on water user experience similar to that collected in health, where 'patient satisfaction' is sometimes incorporated as a quality metric for service delivery. For example, the Quality and Outcomes Framework in the UK (Baker *et al*. 2009). In doing so, regulator or provider data could be more closely compared with DHS measures and triangulated. Given IBNET is currently redesigning and transitioning to a data service, these recommendations are particularly pertinent.

7.8.3 Recommendations for National Governments

The findings of this thesis can also be used to make recommendations to national governments, which is particularly important as these provide an avenue to link monitoring efforts to action at the household and community level. For instance, as has been shown throughout this thesis, mapping of household survey data enables the identification of spatial hotspots where water availability is a problem. In addition, the integration of household survey data with larger provider coverage area data has enabled inequalities in piped water availability within coverage areas to be highlighted. For governments, this is valuable as the adoption of such methods could allow for targeted interventions and resource allocation, as well as the capacity to sense-check and audit providers' reports of availability of their services.

The impetus to report performance data to IBNET could be strengthened by encouragement from national governments, which would facilitate more complete analyses moving forward. This is especially important as reporting to IBNET has declined since 2015, and the development of the New IBNET, and the inevitable new reporting system, may discourage some providers from reporting as they have to adapt to the changes made. National governments would also benefit, as this would provide clarity on areas that are under-performing and allow for resources to be better targeted and more directly distributed to those most in need, therefore reducing inefficient use of government finances.

National governments also need to continue to roll out the JMP's core question on service availability through household surveys and censuses. Varied use of the frequency of interruptions, hours of supply and LPCD makes direct comparison of the data streams unnecessarily complex, as has been shown in this thesis. Advocating the use of the JMP's core question will help to overcome this and were there to be a systematic change in the metric used which allowed for more direct comparison of reporting of service availability, this would enable analysis such as that undertaken in Chapter 6 to include country comparisons.

It is recommended that national governments continue to develop water services in urban areas, including peri-urban areas and informal settlements. This thesis consistently indicates households in urban areas have as bad, if not worse, experiences of service availability than in rural areas using improved services. Going forward, governments needs to ensure services in these areas are developed, especially given current rural to urban migration in LMICs and ongoing growth in informal settlements which places inevitable pressures on already limited services (Hutton and Chase 2016; Dos Santos et al. 2022). Without prioritising their development, the availability of services will inevitably worsen and as shown in Chapter 4, the use of unimproved sources to meet demands could increase, posing significant health threats.

National governments also need to ensure that policy interventions include the maintenance of existing services, rather than solely focusing on developing new services. Throughout this thesis, it has been shown that households using improved drinking water services across SSA are faced with interrupted services. As infrastructure ages and usage increases due to population change, it is inevitable that services will undergo periodic breakages. To lessen their impact, it is a priority that national governments ensure funds are allocated to allow for the maintenance of service infrastructure and for training skilled personnel.

Lastly, in investing and developing drinking water services, national governments must ensure that interventions include communities. This is especially important in rural areas, where, as Chapter 4 has shown, service availability continues to be insufficient. Community involvement is imperative to ensuring services a) meet the needs of communities; b) are less likely to be damaged or broken in the first place; and c) are fixed efficiently, especially in remote rural areas. Outsourcing of labour to skilled personnel is timely and costly, whereas inclusion of communities and investment into basic maintenance training can address both issues (Gleitsmann 2005). Investment in communities by national government therefore needs to include providing the equipment and skills required to address breakages and maintain services, whilst ensuring that communities are autonomous and have a clear choice in the management of their services (Hope 2015). The inclusion of women, to ensure service sustainability and effectiveness, should also be encouraged (Tsekleves *et al*. 2022).

7.9 Concluding Remarks

Extensive pressures, linked to population growth and urbanisation, are affecting the availability of scarce water resources and drinking water supplies across SSA. Households are subsequently dealing with services that do not provide the drinking water required to meet their needs. Findings from this thesis show that in SSA services are non-functioning, unreliable, intermittent, and inadequate. Variations in availability between urban and rural areas are evident, with the severity of inequalities dependent on the type of service assessed.

The breadth of methods and inconsistencies in metrics currently used to measure service availability undoubtedly has implications at the household level. Failing to adequately measure the availability of services disproportionately affects informal, minority, and poor populations, whilst preventing progress from being made. Nuanced and consistent data from providers, regulators and users, collected through streamlined metrics, is vital in ensuring the health and welfare impacts faced by those with unavailable services are minimised. Aligning measures of service availability is critical in ensuring the availability of drinking water can be tracked over time and the consequences be limited and better accounted for.

With increasing needs and demands placed on scant resources, the issue of drinking water availability will, without change, no doubt worsen. In line with the United Nations 2030 Sustainable Development Agenda, to ensure that no one is left behind and SDG 6.1 is met, it is vital that policies enhance international monitoring, where applicable hold providers accountable for poor services and identify inequalities in service availability. Without doing so, poor drinking water availability will continue to affect the day-to-day lives of households across SSA, resulting in adverse health, inadequate sanitation, and reduced standards of living.

Appendices

Appendix A Chapter 4 Supplementary Information

A.1 The JMP's Expanded Questions on Availability

Element of Availability	Expanded Question
Availability of water supply	'Is water always available from your main water source?'
Reason for unavailability	'What was the (main) reason you were unable to access sufficient quantities of water when needed?'
Continuity of water supply	'How many hours per day is water supplied on average?'
Discontinuity of water supply	'In the past month, for how many days was water from this source unavailable when needed?'
Storage tanks	'Does your household have a large storage tank?' If so, 'How many litres does the storage tank hold?' 'How many times has the storage tank been filled in the last week/month?' 'Has there been any time in the last week/month when you have not been able to store sufficient water to meet your needs?'
Storage vessels	'Does your household store drinking water in small containers?' 'Can you show me?' **Observe whether containers are covered or not.**
Seasonal variations in availability	'What is your main source of drinking water in the wet season and the dry season?'

A.2 Systematic Review Search Terms

Searches using the chosen search terms followed this structure:

[Continuity/interruptions/availability] AND [domestic water] AND [water supply type] AND [African country]

The below search terms were used:

(Availab* OR Reliab* OR Interrupt* OR Function* OR Predict* Or Shortage OR Break* OR Limit* OR Failure OR Efficient OR Effective OR Intermitten* OR Irregularit* OR Function* OR Continu* OR Ration* OR Disrupt* OR Restrict* OR “hours of service per” OR “hrs of service per” OR “days of service per” OR “supply hours” OR “supply hrs” OR “supply interruptions”)

AND

((Water AND Drink*) OR “drinking water”)

AND

(Household OR Homestead OR Domestic OR Neighbo*)

AND

(potable OR suppl* OR tap OR faucet OR pipe* OR utility OR reticulated OR standpipe OR spigot OR “distribution network” OR “household connection” OR “protected well” OR “unprotected well” OR hand* OR pump OR “rope pump” OR “dug well” OR bore* OR tubewell OR “tube well”

A.3 Systematic Review Geographical Search Terms

(“sub-Saharan Africa” OR “East* Africa” OR “West* Africa” OR “South* Africa” OR “North* Africa” OR “Southern African Development Community” OR SADC OR “East African Community” OR EAC)

OR

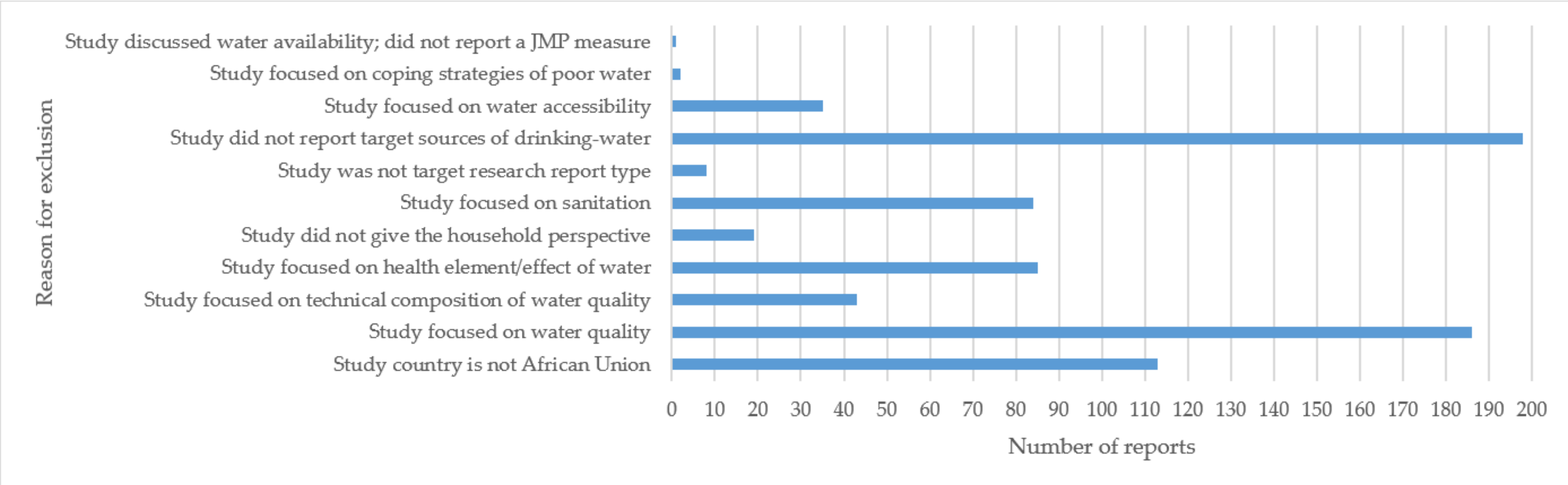
(Algeria OR Angola OR Benin OR Botswana OR “Burkina Faso” OR Burundi OR Cameroon OR Cameroun OR “Cape Verde” OR “Cabo Verde” OR Chad OR “Tchad” OR “Central African Republic” OR CAR OR “République centrafricaine” OR CAF OR Comoros OR “Côte d'Ivoire” OR “Ivory Coast” OR Djibouti OR DRC OR RDC OR “Democratic Republic of Congo” OR “Republic of the Congo” OR “Republic of Congo” OR Congo OR Egypt OR “Equatorial Guinea” OR “Guiné Equatorial” OR “Guinée équatoriale” OR “Guinea Ecuatorial” OR Eritrea OR Ethiopia OR Gabon OR “Gabonese Republic” OR “République gabonaise” OR Gambia OR Ghana OR Guinea OR Guinée OR “Guinea-Bissau” OR “Guiné-Bissau” OR Kenya OR Lesotho OR Liberia OR Libya OR Madagascar OR Malawi OR Mali OR Mauritania OR Mauritius OR Maurice OR Morocco OR Mozambique or Moçambique OR Namibia OR Niger OR Nigeria OR Rwanda OR Ruanda OR “Rwandese Republic” OR “Saharawi Arab Democratic Republic” OR “Sao Tome and Principe” OR “São Tomé e Príncipe” OR Senegal OR Sénégal OR Seychelles OR Sierra Leone OR Somalia OR “Somali Republic” OR “South Africa” OR “Suid Afrika” OR “South Sudan” OR Sudan OR Swaziland OR Eswatini OR Tanzania OR Togo OR “Togolese Republic” OR Tunisia OR “Tunisian Republic” OR Uganda OR Zambia OR Zimbabwe)

A.4 Study Quality Ranking and Criteria

Criterion			Explanation/Question	Calculated from Information Captured Elsewhere
Core criteria for *all* studies	(1)	Rationale for study stated	Do the authors describe the rationale for the investigation?	Y (where 'objective' is 'n/a')
	(2)	Rationale for chosen participants	Are the eligibility criteria (inclusion/exclusion) for study participants described?	
	(3)	Water supply characteristics documented	Water source/supply characteristics documented.	Y (where water source is 'n/a')
	(4)	Sampling strategy reported	Sampling strategy for study (e.g., purposive; simple random; multi-stage cluster, etc.) is described. For secondary studies; sources and dates of access are given (e.g., DHS).	
	(5)	Arithmetic error	Do all numbers/percentages reported in the descriptive statistics add up?	
	(6)	Limitations and bias	Limitations of the study are discussed, taking into account potential bias or imprecisions.	
Criteria for qualitative studies *only*	(7)	Participants recorded throughout	Have numbers of individuals at each of stage of the study been reported (e.g., those ineligible; declining to participate; unavailable for interview)?	
	(8)	Justification for methods	Has the choice of interviews, questionnaires, focus groups etc. been justified?	
	(9)	Replicability	Have methods been suitably described to enable their replication?	
	(10)	Extraction of data and themes	How have they reached the conclusions and are they justified?	

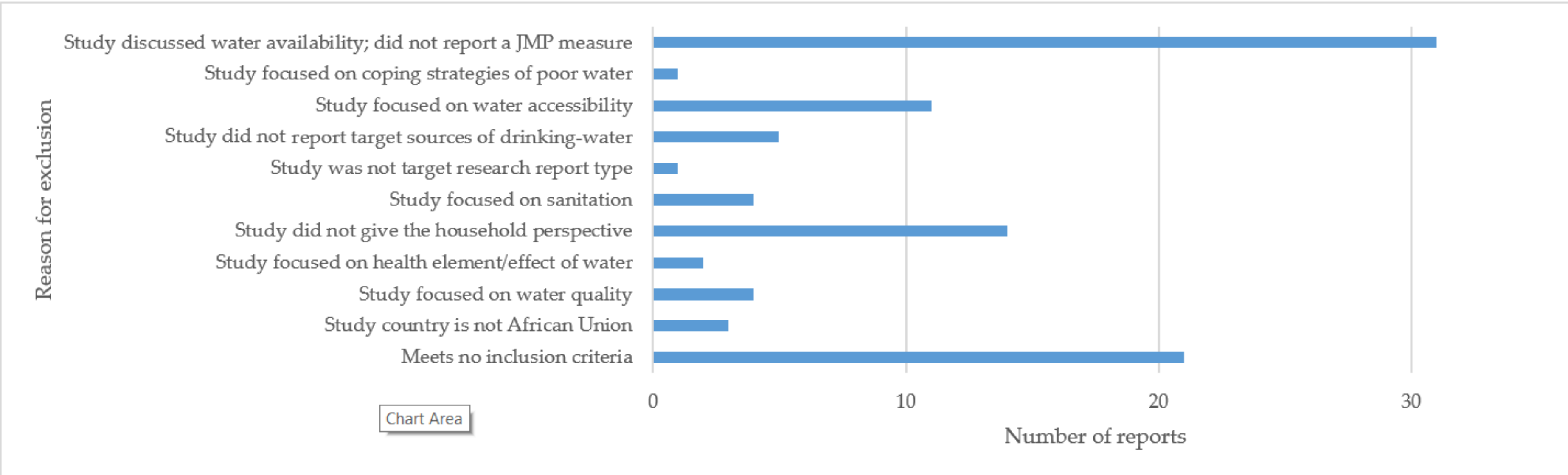
Criteria for quantitative studies *only*	(7)	Statistical methods	Have all statistical methods been described, to a sufficient level of detail whereby replication is possible?	
	(8)	Justification for variables	Has the use of all chosen quantitative variables been explained?	
	(9)	Missing data	How missing data was addressed has been clearly explained.	
	(10)	Precision	Are confidence intervals reported for continuity/water availability estimates?	Y (if you have a field for the confidence intervals/standard error of proportion)

A.5 Reasons for Excluding Studies at Screening Stage



(NB: excluded from figure are reports which did not meet any inclusion criteria (*n* = 1490).

A.6 Reasons for Excluding Studies at Characterisation Stage



A.7 Sample Sizes and Representativeness of Included Studies

Sampling Details		Households				Individuals			
Classification of Representativeness	Sampling Strategy Used by Studies	No. of Studies	Total Sample Size	Mean Sample Size	Range of Sample Sizes	No. of Studies	Total Sample Size	Mean Sample Size	Range of Sample Sizes
Representative	Simple random	7	1685	241	40–761	6	3284	547	27–1080
	Stratified-random	2	2534	1267	674–1860	0	-	-	-
	Systematic-random	3	1183	394	50–1015	0	-	-	-
	Systematic	1	20,000	-	-	0	-	-	-
Non-representative	Convenience	2	200	100	60–140	2	693	347	40–653
	Multi-stage	10	4416	442	114–1203	2	1072	536	194–878
	Purposive	6	696	116	20–246	4	1201	306	22–683
	Quota	1	15	-	-	0	-	-	-
	Self-selection	1	103	-	-	0	-	-	-
Unreported sampling strategy		3	727	242	130–447	1	230	-	-

A.8 Initial Multiple Linear Regression Models

Model includes identified outlier (Smith 2010) and excludes the outlier, of reported LPCD across Africa, based on a subset of studies published between 2000 and 2019

Variables	**Initial Model with All Studies**	**Initial Model Excluding Outlier**
GDP (per capita) (USD)/1000	2.399 (3.02) **	1.485 (2.26) *
Water Scarcity	0.914 (0.43)	2.394 (1.43)
Urban study	17.328 (2.36) *	14.750 (2.55) *
Intervention study	−6.672 (−0.81)	−2.336 (−0.36)
Piped water connection (in yard/house)	20.482 (2.31) *	9.491 (1.29)
Constant	5.037 (0.61)	7.511 (1.16)
Observations (n)	34	33
R-squared	0.489	0.424

*Note: estimated standard errors in brackets. * significant at 5% ** significant at 1%*

A.9 Exploratory Bivariate Regression Model

Model includes reported LPCD and each explanatory variable, based on a subset of studies (*n* = 33) published between 2000 and 2019.

Variable	**Coefficient**	**R-Squared**
GDP (per capita) (USD)/1000	1.079 (1.41)	0.061
Water scarcity	3.905 (2.16) *	0.131
Urban study	16.812 (2.92) **	0.216
Intervention study	−6.319 (−0.84)	0.022
Piped water connection (in yard/house)	14.82 (1.86)	0.100

*Note: estimated standard errors in brackets. * significant at 5% ** significant at 1%*

Appendix B Chapter 5 Supplementary Information

B.1 Included DHS Household, Men's and Individual Survey Questions

DHS Question ID	Question	Response options
Hv201	*What is the main source of drinking water for members of your household?*	*Piped into dwelling; Piped to yard/plot; Piped to neighbour; Public tap/standpipe; Tube well or borehole; Dug well (open/protected); Dug well (protected); Protected spring; Unprotected spring; Rainwater; Tanker truck; Tart with small tank; Bottled water; Surface water (river/dam/lake/ponds/stream/canal/irrigation channel); Other; Missing.*
Hv201a	*In the last two weeks was the water from your main source not available for at least one full day?*	*No, not interrupted for a full day; Yes, interrupted for a full day or more; Don't know; Missing.*
Hv270a	Wealth index for urban/rural	This variable provides a rural- and urban-specific wealth index.
Hv006	Month of interview	
Hv045c	Native language of respondent	
Hv045b	Language used in the household interview	
Hv009	Number of household members	
Hv213	Main material of the floor	
Hv214	Main material of the walls	
Hv215	Main material of the roof	
Mv104/V104	*How long have you been living continuously in your current city/town/village of residence?*	Respondents lists number of years OR selects: *always; visitor; inconsistent; don't know; missing.*
Mv745a/V745a	*Do you own this or any other house either alone or jointly with someone else?*	*Does not own; Alone only; Jointly only; Both alone and jointly.*

B.2 Water Stress Variable Sensitivity Analysis

This was undertaken to assess which water stress variable to use. Each table shows the odds of reporting an interruption for households living under water stress, taken from five multi-level logistic regression models which included each version of the water stress variable (no lag, 1-month lag, 2-month lag, 3-month lag and 6-month lag) with all other explanatory variables.

B.2.1 **Ethiopia**

	No lag	**1 month lag**	**2 month lag**	**3 month lag**	**6 month lag**
Water Stress Risk *(Ref: low)*					
Low-Medium	**2.24****	**2.14***	0.72	0.92	1.07
Medium-High	2.21	1.66	1.77	**1.56***	1.25
High	1.18	**2.75****	1.21	1.37	0.81
Extremely High	0.86	1.06	0.94	0.82	1.40
Arid/Low Water Use	1.39	1.46	1.27	1.31	1.34

**p <0.05 **p <0.01, ***p <0.001, - :no data, o: omitted*

B.2.2 **Gambia**

	No lag	**1 month lag**	**2 month lag**	**3 month lag**	**6 month lag**
Water Stress Risk *(Ref: low)*					
Low-Medium	**-**	-	-	1.57	1.49
Medium-High	-	-	-	4.58	-
High	-	-	1.57	-	-
Extremely High	3.00	3.00	1.58	-	-
Arid/Low Water Use	-	-	-	-	-

**p <0.05 **p <0.01, ***p <0.001, - :no data, o: omitted*

B.2.3 **Malawi**

	No lag	**1 month lag**	**2 month lag**	**3 month lag**	**6 month lag**
Water Stress Risk *(Ref: low)*					
Low-Medium	1.63	1.53	**0.60***	1.28	0.35
Medium-High	1.08	1.19	0.91	0.90	0.30
High	0.58	0.40	1.04	0.94	1.47
Extremely High	-	1.18	0.63	**0.30***	-
Arid/Low Water Use	-	-	-	-	-

**p <0.05 **p <0.01, ***p <0.001, - :no data, o: omitted*

B.2.4 **Nigeria**

	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Water Stress Risk *(Ref: low)*					
Low-Medium	4.71	1.73	1.03	-	1.34
Medium-High	0.75	3.07	1.66	0.92	1.63
High	**20.12*** **	**7.95** **	**3.40***	2.23	**2.90*** **
Extremely High	*Omitted*	**16.30** **	**7.87*** **	**3.46***	**1.70***
Arid/Low Water Use	**17.17*** **	**16.40*** **	**16.69*** **	**17.57*** **	**24.34*** **

**p <0.05 **p <0.01, ***p <0.001, - :no data, o: omitted*

B.2.5 **Sierra Leone**

	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Water Stress Risk *(Ref: low)*					
Low-Medium					3.74
Medium-High					-
High	*Omitted*	*Omitted*	*Omitted*	*Omitted*	-
Extremely High					-
Arid/Low Water Use					-

**p <0.05 **p <0.01, ***p <0.001, - :no data, o: omitted*

B.2.6 **South Africa**

	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Water Stress Risk *(Ref: low)*					
Low-Medium	0.97	1.06	1.17	0.860	1.17
Medium-High	**1.69** **	1.27	**1.50***	1.04	**0.58** **
High	**1.61***	**2.78*** **	1.35	0.82	0.67
Extremely High	**1.83*** **	**1.52***	**1.82** **	1.44	**0.34*** **
Arid/Low Water Use	1.32	1.27	1.19	0.87	0.70

**p <0.05 **p <0.01, ***p <0.001, - :no data, o: omitted*

B.2.7 **Tanzania**

	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Water Stress Risk *(Ref: low)*					
Low-Medium	1.25	1.50	1.2	1.16	0.91
Medium-High	1.21	1.01	**2.14****	**1.98***	**0.40***
High	1.85	**2.00****	1.12	1.56	0.90
Extremely High	**2.80***	**4.62****	**3.71*****	1.62	1.46
Arid/Low Water Use	-	-	-	-	-
**p <0.05 **p <0.01, ***p <0.001, - :no data, o: omitted*					

B.2.8 **Uganda**

	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Water Stress Risk *(Ref: low)*					
Low-Medium	*Omitted*	0.63	0.95	1.15	*Omitted*
Medium-High	*Omitted*	-	*Omitted*	*Omitted*	0.87
High	1.04	1.98	**5.19***	1.38	1.45
Extremely High	-	-	-	-	0.69
Arid/Low Water Use	0.99	1.00	0.96	0.99	0.99
**p <0.05 **p <0.01, ***p <0.001, - :no data, o: omitted*					

B.2.9 **Zambia**

	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Water Stress Risk *(Ref: low)*					
Low-Medium	0.92	1.48	1.10	1.27	1.35
Medium-High	0.82	1.51	1.05	**0.45****	0.48
High	1.06	1.64	0.73	**0.28****	0.52
Extremely High	1.35	0.71	0.62	0.72	*Omitted*
Arid/Low Water Use	1.26	1.29	1.14	1.06	1.14
**p <0.05 **p <0.01, ***p <0.001, - :no data, o: omitted*					

B.2.10 **Zimbabwe**

	No lag	1 month lag	2 month lag	3 month lag	6 month lag
Water Stress Risk *(Ref: low)*					
Low-Medium	**0.48***	0.42	0.70	1.08	0.92
Medium-High	0.88	0.76	1.00	0.66	0.63
High	0.71	0.71	1.08	0.93	0.91
Extremely High	**0.40*****	**0.40*****	**0.34*****	**0.38*****	**0.52***
Arid/Low Water Use	1.12	1.01	1.07	1.32	1.90
**p <0.05 **p <0.01, ***p <0.001, - :no data, o: omitted*					

B.3 Weighted Percentages of Households using each Type of Water Service, by Rurality

Country	Rurality	Type of Improved Source			
		Piped onto premises *% (95% CI)*	Piped to neighbour *% (95% CI)*	Public tap or Standpipe *% (95% CI)*	Tubewell or Borehole *% (95% CI)*
Ethiopia	**Urban**	68.6 (66.0, 71.1)	13.6 (11.8, 15.5)	14.3 (12.4, 16.5)	3.5 (2.6, 4.7)
	Rural	5.3 (4.3, 6.3)	3.3 (2.3, 33.9)	53.6 (51.5, 55.8)	38.1 (36.1, 40.2)
Gambia	**Urban**	65.9 (63.9, 67.8)	17.3 (15.8, 18.9)	7.0 (6.1, 8.0)	9.8 (8.6, 11.3)
	Rural	13.2 (11.7, 15.0)	2.1 (1.5, 2.9)	62.6 (60.3, 64.8)	22.1 (20.2, 24.0)
Malawi	**Urban**	43.5 (41.2, 45.7)	12.2 (10.8, 13.6)	34.3 (32.1, 36.5)	10.0 (9.0, 11.3)
	Rural	2.8 (2.6, 3.1)	1.2 (1.1, 1.4)	7.3 (6.9, 7.7)	88.7 (88.2, 89.2)
Nigeria	**Urban**	9.0 (8.3, 9.7)	1.7 (1.4, 2.1)	13.5 (12.6, 14.4)	75.8 (74.7, 76.9)
	Rural	3.6 (3.2, 4.1)	1.4 (1.2, 1.6)	17.9 (16.9, 18.8)	77.5 (76.5, 78.5)
Sierra Leone	**Urban**	9.1 (7.7, 10.7)	14.7 (12.7, 16.9)	50.1 (47.5, 52.8)	26.1 (24.0, 28.3)
	Rural	1.2 (0.8, 1.8)	2.9 (2.3, 3.8)	23.0 (21.3, 24.8)	72.8 (70.9, 74.7)
South Africa	**Urban**	89.0 (88.0, 89.9)	1.6 (1.2, 1.9)	9.1 (8.3, 10.1)	0.3 (0.2, 0.4)
	Rural	49.6 (47.7, 51.5)	6.8 (5.6, 8.0)	33.0 (21.2, 34.7)	10.6 (9.6, 11.8)
Tanzania	**Urban**	38.4 (36.1, 40.7)	38.0 (35.7, 40.0)	16.7 (15.1, 18.5)	7.0 (5.7, 8.5)
	Rural	14.2 (12.9, 15.7)	14.3 (12.9, 15.9)	56.9 (54.9, 59.0)	14.5 (13.0, 16.1)
Uganda	**Urban**	31.1 (29.2, 33.1)	24.3 (22.5, 26.2)	17.1 (15.7, 19.7)	27.6 (25.9, 29.3)
	Rural	5.2 (4.6, 5.8)	4.0 (3.5, 4.5)	9.9 (9.3, 16.7)	80.9 (79.9, 81.9)
Zambia	**Urban**	52.2 (50.0, 54.5)	19.3 (17.3, 21.4)	20.2 (18.6, 21.9)	8.2 (7.2, 9.3)
	Rural	6.8 (6.0, 7.8)	2.5 (2.0, 3.1)	5.8 (5.0, 6.7)	84.9 (83.6, 86.1)
Zimbabwe	**Urban**	69.6 (67.5, 71.5)	1.4 (1.1, 1.9)	7.2 (6.1, 8.6)	21.8 (19.9, 23.6)
	Rural	12.5 (11.1, 13.9)	2.3 (1.8, 3.1)	10.8 (9.6, 12.1)	74.4 (72.6, 76.2)

B.4 Weighted Percentages of Households using each Type of Water Service, by Household Wealth

Country	Rurality	Type of Improved Source Piped onto premises *% (95% CI)*	Piped to neighbour *% (95% CI)*	Public tap or Standpipe *% (95% CI)*	Tubewell or Borehole *% (95% CI)*
Ethiopia	Poorest	5.5 (3.5, 8.5)	11.3 (8.4, 15.0)	50.1 (45.3, 54.8)	33.2 (29.1, 37.5)
	Poorer	21.7 (18.4, 25.5)	13.4 (10.9, 16.8)	40.2 (36.2, 44.3)	24.6 (21.5, 27.9)
	Middle	34.8 (31.5, 38.4)	6.7 (5.2, 8.6)	34.7 (31.2, 38.3)	23.8 (20.9, 26.9)
	Richer	38.3 (34.9, 41.7)	3.3 (2.3, 4.7)	34.1 (30.9, 37.38)	22.3 (19.6, 25.3)
	Richest	40.2 (37.2, 43.4)	4.5 (3.2, 6.3)	34.1 (30.9, 37.4)	21.2 (18.6, 24.1)
Gambia	Poorest	21.6 (18.8, 24.8)	28.0 (24.8, 31.4)	26.1 (23.4, 29.0)	24.2 (21.1, 27.7)
	Poorer	43.6 (40.3, 46.9)	19.5 (16.8, 22.5)	22.9 (20.7, 25.5)	13.9 (11.7, 16.50
	Middle	57.7 (54.0, 61.2)	12.3 (9.8, 15.3)	19.9 (17.6, 22.4)	10.1 (8.0, 12.7)
	Richer	70.9 (67.5, 74.0)	7.8 (2.4, 5.8)	18.1 (15.9, 20.6)	7.3 (5.5, 9.5)
	Richest	83.6 (80.9, 85.9)	0.7 (0.3, 0.2)	19.9 (18.8, 21.0)	12.7 (11.6, 13.9)
Malawi	Poorest	1.3 (0.7, 1.5)	2.5 (2.0, 3.1)	12.8 (11.5, 14.3)	83.6 (82.1, 85.1)
	Poorer	3.3 (2.7, 4.0)	3.3 (2.7, 4.0)	14.7 (13.4, 16.2)	78.7 (77.1, 80.3)
	Middle	7.5 (6.5, 8.7)	3.9 (3.2, 7.8)	13.5 (12.2, 14.9)	75.1 (72.7, 76.1)
	Richer	12.3 (11.0, 13.7)	3.5 (2.9, 4.3)	9.8 (8.7, 11.0)	74.4 (72.7, 76.1)
	Richest	26.0 (24.3, 27.8)	2.6 (2.1, 3.2)	9.0 (8.1, 10.1)	62.4 (60.5, 64.2)
Nigeria	Poorest	2.1 (1.6, 2.7)	1.6 (1.1, 2.2)	16.8 (15.2, 18.5)	79.6 (77.8, 81.3)
	Poorer	3.8 (3.1, 4.6)	1.5 (1.1, 2.2)	17.5 (15.7, 19.4)	77.2 (75.2, 79.2)
	Middle	4.9 (4.2, 5.8)	1.2 (0.8, 1.8)	16.0 (14.2, 17.3)	78.2 (76.5, 79.8)
	Richer	12.1 (11.0, 13.3)	1.3 (1.0, 2.0)	16.4 (15.1, 17.8)	76.3 (74.7, 77.8)
	Richest	12.1 (11.0, 13.3)	1.3 (1.0, 1.8)	13.0 (11.9, 14.1)	73.6 (72.2, 75.1)
Sierra Leone	Poorest	2.1 (1.3, 3.4)	6.5 (5.0, 8.5)	19.1 (25.7, 32.9)	62.3 (58.3, 66.0)
	Poorer	2.7 (1.7, 4.5)	10.3 (8.0, 13.3)	30.6 (26.9, 34.4)	56.4 (52.3, 60.4)
	Middle	3.8 (2.7, 5.3)	7.4 (5.4, 9.9)	40.8 (37.3, 44.4)	48.0 (44.5, 51.7)
	Richer	6.0 (4.3, 8.2)	8.9 (6.6, 12.0)	40.3 (36.7, 44.1)	44.8 (41.2, 48.5)
	Richest	10.0 (7.9, 12.5)	9.9 (7.6, 12.8)	37.6 (33.7, 41.6)	42.6 (38.9, 46.4)
South Africa	Poorest	52.8 (49.8, 55.8)	5.6 (4.4, 7.0)	39.7 (36.8, 42.6)	1.9 (1.4, 2.6)

Country	Rurality	Type of Improved Source Piped onto premises *% (95% CI)*	Piped to neighbour *% (95% CI)*	Public tap or Standpipe *% (95% CI)*	Tubewell or Borehole *% (95% CI)*
	Poorer	80.2 (78.3, 82.1)	2.1 (1.5, 2.8)	15.3 (13.6, 17.1)	2.4 (1.9, 3.1)
	Middle	80.7 (78.8, 82.6)	3.8 (2.7, 5.1)	12.1 (10.7, 13.6)	3.5 (2.8, 4.3)
	Richer	87.2 (85.7, 88.6)	2.3 (1.7, 3.1)	7.5 (6.5, 8.7)	3.0 (2.3, 3.9)
	Richest	91.4 (90.1, 92.6)	1.2 (0.7, 2.0)	2.8 (2.2, 3.6)	4.6 (3.8, 5.5)
Tanzania	**Poorest**	4.4 (2.9, 6.5)	28.8 (25.0, 32.9)	54.8 (50.3, 59.1)	12.0 (9.2, 15.5)
	Poorer	9.6 (7.6, 12.1)	34.8 (31.1, 38.7)	44.3 (40.6, 48.1)	11.2 (9.0, 13.9)
	Middle	21.1 (18.3, 24.2)	29.4 (26.2, 32.8)	37.4 (34.1, 40.8)	12.2 (9.8, 14.9)
	Richer	30.6 (27.6, 33.8)	26.1 (23.3, 29.2)	32.2 (29.3, 35.3)	10.9 (9.0, 13.3)
	Richest	49.0 (46.0, 51.9)	17.6 (15.4, 20.0)	25.2 (22.9, 27.7)	8.2 (6.7, 10.1)
Uganda	**Poorest**	0.3 (0.2, 0.6)	1.7 (1.2, 2.3)	3.3 (2.7, 4.0)	94.7 (93.8, 95.6)
	Poorer	2.3 (1.6, 3.2)	6.5 (5.4, 7.8)	11.5 (10.1, 12.9)	79.8 (77.8, 81.6)
	Middle	8.8 (7.4, 10.5)	14.9 (13.0, 17.0)	17.3 (15.6, 19.2)	58.9 (56.4, 61.5)
	Richer	15.0 (13.3, 16.9)	16.3 (14.4, 18.4)	17.1 (15.4, 19.0)	51.6 (49.1, 54.1)
	Richest	38.1 (35.7, 40.5)	12.4 (10.8, 14.1)	12.4 (11.0, 14.0)	31.1 (34.8, 39.5)
Zambia	**Poorest**	7.7 (5.3, 11.3)	21.7 (17.4, 26.7)	18.6 (15.9, 21.5)	51.9 (47.7, 56.2)
	Poorer	16.3 (13.4, 19.7)	18.5 (15.1, 22.4)	22.7 (19.9, 25.8)	42.6 (39.0, 46.2)
	Middle	29.4 (25.9, 33.1)	11.1 (9.2, 13.4)	18.7 (16.1, 21.5)	40.8 (37.6, 44.1)
	Richer	41.6 (38.39, 44.8)	8.9 (7.2, 11.1)	10.1 (8.3, 12.3)	39.4 (36.4, 42.4)
	Richest	57.1 (54.4, 59.7)	4.9 (3.8, 6.4)	4.2 (3.3, 5.4)	33.8 (31.3, 36.3)
Zimbabwe	**Poorest**	33.3 (30.3, 36.4)	2.9 (2.1, 4.3)	12.0 (9.6, 14.9)	51.8 (48.4, 55.1)
	Poorer	40.8 (38.0, 43.8)	1.9 (1.2, 2.8)	8.3 (6.7, 10.2)	48.9 (45.9, 52.0)
	Middle	38.7 (35.8, 41.6)	1.7 (1.0, 2.7)	6.5 (5.1, 8.4)	53.1 (50.1, 51.9)
	Richer	36.5 (33.8, 39.4)	1.7 (1.0, 2.8)	9.6 (7.8, 11.7)	52.2 (49.2, 55.2)
	Richest	45.2 (42.3, 48.2)	1.6 (1.0, 2.7)	9.6 (8.0, 11.5)	43.6 (40.6, 46.5)

Appendix B

B.5 Main Effects Models with Odds Ratios and Standard Errors

Multi-level Logistic Regression Analyses of Household Reported Interruptions to Improved Drinking Water Sources for each Study Country, with odds ratios and standard error

	Study Country									
	Ethiopia	**Gambia**	**Malawi**	**Nigeria**	**Sierra Leone**	**South Africa**	**Tanzania**	**Uganda**	**Zambia**	**Zimbabwe**
Households (n):	*8873*	*5937*	*21,690*	*18,454*	*4498*	*9810*	*5889*	*11,442*	*6703*	*6906*
Household clusters (n) :	*535*	*278*	*825*	*1088*	*396*	*732*	*464*	*594*	*452*	*381*
Parameter	*Odds ratio (standard error)*									
Intercept	2.86 (4.46)	0.11* (0.10)	1.07 (0.34)	1.98 (0.12)	0.14* (0.12)	0.20*** (0.08)	1.24 (0.61)	0.94 (0.28)	0.45 (0.39)	0.52 (0.49)
Household-level Factors										
Type of Improved Supply *(Ref: Piped onto premises)*										
Piped to neighbour	1.20 (0.14)	1.17 (0.16)	0.92 (0.09)	1.21 (0.24)	1.08 (0.26)	1.17 (0.19)	1.22 (0.13)	1.20 (0.13)	1.06 (0.13)	0.79 (0.19)
Public tap/standpipe	0.79 (0.11)	1.58** (0.23)	0.98 (0.08)	1.19 (0.14)	1.24 (0.29)	1.31** (0.15)	0.97 (0.11)	1.22 (0.14)	0.92 (0.12)	0.79 (0.12)
Tubewell/borehole	0.47*** (0.08)	0.70 (0.13)	0.13*** (0.01)	0.51*** (0.05)	1.14 (0.29)	0.17*** (0.03)	0.17** (0.03)	0.21*** (0.03)	0.21*** (0.03)	0.16*** (0.02)
Household Wealth *(Ref: Poorest)*										
Poorer	0.96 (0.10)	1.11 (0.12)	0.89 (0.06)	0.90 (0.08)	1.25 (0.21)	0.97 (0.10)	1.23 (0.18)	1.16 (0.10)	0.91 (0.12)	0.92 (0.10)
Middle	0.91 (0.10)	1.12 (0.14)	0.95 (0.06)	0.84 (0.08)	1.16 (0.20)	0.80 (0.09)	1.11 (0.16)	1.09 (0.11)	1.01 (0.14)	0.87 (0.10)
Richer	0.85 (0.10)	1.31** (0.17)	0.95 (0.06)	0.88 (0.09)	1.44* (0.26)	0.76* (0.09)	1.14 (0.17)	1.08 (0.11)	0.93 (0.13)	0.92 (0.11)
Richest	0.90 (0.11)	1.44** (0.21)	1.02 (0.07)	0.69** (0.08)	1.20 (0.23)	0.66** (0.09)	1.20 (0.19)	1.04 (0.11)	0.75 (0.12)	0.86 (0.10)
Type of Place of Residence *(Ref: Urban)*										
Rural	0.19*** (0.04)	1.41 (0.37)	0.49*** (0.07)	1.08 (0.16)	0.22*** (0.07)	4.46*** (0.73)	0.58** (0.11)	0.65** (0.09)	0.25*** (0.05)	0.75 (0.16)
Number of Household Members *(Ref: 1 person)*										
2-3 people	1.11 (0.11)	0.96 (0.15)	1.07 (0.09)	1.08 (0.08)	1.08 (0.21)	1.24** (0.10)	1.27 (0.16)	1.06 (0.09)	1.38* (0.20)	1.14 (0.13)
4-6 people	1.28* (0.12)	1.10 (0.16)	1.15 (0.09)	1.07 (0.07)	0.99 (0.19)	1.38*** (0.11)	1.42** (0.17)	1.06 (0.09)	1.23 (0.17)	1.56*** (0.17)
7-9 people	1.36** (0.16)	1.30 (0.20)	1.18 (0.11)	1.20* (0.10)	1.17 (0.24)	1.72*** (0.20)	1.41** (0.19)	1.24* (0.12)	1.23 (0.19)	1.57** (0.23)
10 or more people	1.50 (0.32)	1.09 (0.16)	1.17 (0.18)	1.07 (0.12)	1.14 (0.28)	1.87** (0.36)	1.59** (0.28)	1.15 (0.16)	1.33 (0.27)	2.34*** (0.56)
Tenure *(Ref: Does not own)*										
At least partly owns	1.01 (0.08)	0.90 (0.11)	1.02 (0.09)	1.10 (0.10)	1.35 (0.21)	1.08* (0.13)	0.75 (0.11)	1.01 (0.12)	1.22* (0.12)	0.95 (0.09)
No information	0.97 (0.07)	0.93 (0.09)	0.97 (0.06)	1.03 (0.07)	1.11 (0.13)	1.17* (0.09)	0.89 (0.09)	1.09 (0.11)	1.03 (0.09)	1.00 (0.08)
Household Cluster-level Factors										
Water Stress with 1-month lag *(Ref: Low)*					*Omitted*					
Low-Medium	12.14** (0.62)	-	1.53 (0.42)	1.73 (1.23)	-	1.06 (0.23)	1.50 (0.33)	0.63 (0.42)	1.48 (0.42)	0.42 (0.22)
Medium-High	1.66 (0.61)	-	1.19 (0.24)	3.07 (2.52)	-	1.27 (0.26)	1.01 (0.29)	-	1.51 (0.52)	0.76 (0.22)
High	2.76* (1.12)	-	0.40 (0.21)	7.95** (6.07)	-	2.78*** (0.58)	2.00** (0.51)	1.98 (1.37)	1.64 (0.43)	0.71 (0.16)
Extremely High	1.06 (0.37)	3.00 (1.94)	1.18 (0.66)	16.30 (24.53)	-	1.52** (0.30)	4.62** (2.37)	-	0.71 (0.20)	0.40*** (0.09)
Arid & Low Water Use	1.46 (0.38)	-	-	16.40*** (8.77)	-	1.27 (0.380	-	1.00 (0.22)	1.29 (2.15)	1.01 (0.65)
Blue Water Scarcity	1.12** (0.05)	1.11 (0.28)	0.99 (0.06)	0.58*** (0.05)	1.15 (0.27)	0.92** (0.03)	1.03 (0.05)	0.82** (0.06)	0.34** (0.11)	1.16*** (0.05)
Change in Urbanisation *(Ref: More urbanised)*										
Less urbanised	0.85 (0.29)	0.91 (0.71)	0.97 (0.22)	0.97 (1.28)	0.41 (0.52)	0.92 (0.39)	0.75 (0.20)	1.23 (0.24)	1.25 (0.48)	-
No change	0.54** (0.13)	1.44 (0.40)	1.21 (0.16)	0.61** (0.10)	0.45** (0.13)	0.92 (0.17)	0.96 (0.21)	0.84 (0.14)	1.24 (0.25)	1.06 (0.24)
Neighbourhood Wealth *(Ref: Poor)*										
Middle	1.04 (0.19)	0.57* (0.13)	1.27 (0.16)	1.51* (0.28)	2.40** (0.82)	0.74 (0.13)	1.16 (0.24)	1.36** (0.19)	1.40 (0.28)	0.82 (0.17)
Rich	1.34 (0.28)	0.81 (0.21)	1.30* (0.15)	2.05** (0.42)	3.90 **(1.53)	0.43*** (0.08)	1.12 (0.25)	2.09*** (0.36)	1.56* (0.33)	0.91 (0.20)
Neighbourhood Age *(Ref: <15yrs)*										
15-30 yrs	1.52 (2.39)	1.19 (0.72)	0.98 (0.29)	0.49 (0.26)	-	0.77 (0.27)	0.54 (0.23)	1.06 (0.24)	1.23 (1.07)	1.49 (1.35)
31-40yrs	0.97 (0.15)	1.54 (0.95)	0.96 (0.28)	0.50 (0.26)	2.67 (2.13)	1.36 (0.47)	0.79 (0.33)	1.00 (0.23)	1.01 (0.87)	1.04 (0.94)
41-50yrs	1.11 (1.71)	1.29 (0.79)	0.92 (0.27)	0.37* (0.19)	1.87 (1.30)	1.34 (0.43)	0.77 (0.32)	1.16 (0.26)	1.19 (1.02)	1.42 (1.27)
>50yrs	0.72 (1.09)	0.83 (0.51)	0.85 (0.270	0.36* (0.18)	1.10 (0.79)	1.17 (0.40)	-	0.92 (0.24)	0.96 (0.83)	1.05 (0.96)
No information	-	-	-	-	-	0.54 (0.42)	0.53 (0.85)	-	-	-
Population Density	1.00 (0.01)	1.00 (0.03)	1.02 (0.01)	1.00 (0.00)	1.07** (0.03)	1.00 (0.02)	1.00 (0.01)	0.99 (0.00)	1.01 (0.01)	0.99 (0.01)
Random-effects Parameters										
Between PSU Variance	1.94 (0.19)	1.73 (0.21)	1.38 (0.10)	4.13 (0.30)	4.88 (0.63)	2.24 (0.19)	2.02 (0.22)	1.12 (0.10)	1.473 (0.18)	1.90 (0.22)

** p<0.05, **p<0.01, ***p<0.001*

B.6 Country Comparison of Water Stress Variables with Different Lags

B.6.1 **Water Stress- no lag**

	Ethiopia	Gambia	Malawi	Nigeria	Sierra Leone	South Africa	Tanzania	Uganda	Zambia	Zimbabwe
Low-Medium	**2.24****	**-**	1.63	4.71		0.97	1.25	omitted	0.92	**0.48***
Medium-High	2.21	-	1.08	0.75	*variable*	**1.69****	1.21	omitted	0.82	0.88
High	1.18	-	0.58	**20.12*****	*omitted due to*	**1.61***	1.85	1.04	1.06	0.71
Extremely High	0.86	3.00	-	omitted	*collinearity*	**1.83*****	**2.80***	-	1.35	**0.40*****
Arid/Low Water Use	1.39	-	-	**17.17*****		1.32	-	0.99	1.26	1.12

**p <0.05 **p <0.01, ***p <0.001, - :no data*

B.6.2 **Water Stress- 1 month lag**

	Ethiopia	Gambia	Malawi	Nigeria	Sierra Leone	South Africa	Tanzania	Uganda	Zambia	Zimbabwe
Low-Medium	**2.14***	-	1.53	1.73		1.06	1.50	0.63	1.48	0.42
Medium-High	1.66	-	1.19	3.07	*variable*	1.27	1.01	-	1.51	0.76
High	**2.75****	-	0.40	**7.95****	*omitted due to*	**2.78*****	**2.00****	1.98	1.64	0.71
Extremely High	1.06	3.00	1.18	**16.30****	*collinearity*	**1.52***	**4.62****	-	0.71	**0.40*****
Arid/Low Water Use	1.46	-	-	**16.40*****		1.27	-	1.00	1.29	1.01

**p <0.05 **p <0.01, ***p <0.001, - :no data*

B.6.3 **Water Stress- 2 month lag**

	Ethiopia	Gambia	Malawi	Nigeria	Sierra Leone	South Africa	Tanzania	Uganda	Zambia	Zimbabwe
Low-Medium	0.72	-	**0.60***	1.03	*variable omitted due to collinearity*	1.17	1.2	0.95	1.10	0.70
Medium-High	1.77	-	0.91	1.66		**1.50***	**2.14****	omitted	1.05	1.00
High	1.21	1.57	1.04	**3.40***		1.35	1.12	**5.19***	0.73	1.08
Extremely High	0.94	1.58	0.63	**7.87*****		**1.82****	**3.71*****	-	0.62	**0.34*****
Arid/Low Water Use	1.27	-	-	**16.69*****		1.19	-	0.96	1.14	1.07

**p <0.05 **p <0.01, ***p <0.001, - :no data*

B.6.4 **Water Stress- 3 month lag**

	Ethiopia	Gambia	Malawi	Nigeria	Sierra Leone	South Africa	Tanzania	Uganda	Zambia	Zimbabwe
Low-Medium	0.92	1.57	1.28	-	*variable omitted due to collinearity*	0.860	1.16	1.15	1.27	1.08
Medium-High	**1.56***	4.58	0.90	0.92		1.04	**1.98***	omitted	**0.45****	0.66
High	1.37	-	0.94	2.23		0.82	1.56	1.38	**0.28****	0.93
Extremely High	0.82	-	**0.30***	**3.46***		1.44	1.62	-	0.72	**0.38*****
Arid/Low Water Use	1.31	-	-	**17.57*****		0.87	-	0.99	1.06	1.32

**p <0.05 **p <0.01, ***p <0.001, - :no data*

B.6.5 **Water Stress- 6 month lag**

	Ethiopia	Gambia	Malawi	Nigeria	Sierra Leone	South Africa	Tanzania	Uganda	Zambia	Zimbabwe
Low-Medium	1.07	1.49	0.35	1.34	3.74	1.17	0.91	omitted	1.35	0.92
Medium-High	1.25	-	0.30	1.63	-	**0.58****	**0.40***	0.87	0.48	0.63
High	0.81	-	1.47	**2.90*****	-	0.67	0.90	1.45	0.52	0.91
Extremely High	1.40	-	-	**1.70***	-	**0.34*****	1.46	0.69	omitted	**0.52***
Arid/Low Water Use	1.34	-	-	**24.34*****	-	0.70	-	0.99	1.14	1.90

**p <0.05 **p <0.01, ***p <0.001, - :no data*

Appendix C Chapter 6 Supplementary Information

C.1 Inclusion and Exclusions Reasons for Shortlisted Countries

Shortlisted Country	Data Streams Available	Decision	Reason for Decision
Egypt	User and Provider	Exclude	No regulator data available. User data stream does not include a survey question/metric of drinking water availability.
Ethiopia	User and Provider	Exclude	Provider data that is available for the same years as user data does not have national coverage; since 2012 the number of utility companies in IBNET has reduced from 96 to 17-56 in 2016/2018 when user data is available. No regulator data available.
Kenya	All	Exclude	All three data streams are available, including multiple options for user data. There is overlap in the years that the data is available for each stream however it is not recent (2014).
Malawi	User and Provider	Exclude	No regulator data available. Date of user data (2016) does not match provider data (2010-2014). The latest provider data consists of only 3 utility companies in 2014.
Mozambique	All	Exclude	User data has small sample size (n = 1260 households), it is not geographically aggregated to suitable units and only considers rural areas of Mozambique.
Nigeria	User and Provider	Exclude	No regulator data available.
Senegal	User and Provider	Exclude	No known spatial data available for user strand. No regulator data available.
South Africa	All	Exclude	All three data streams are available and for the same year. Multiple survey/data options are available for the user data stream. Spatial disaggregation of data strands does not match, in particular user and regulator/provider data.
Sudan	User and Provider	Exclude	Provider data is only available pre-South Sudan gaining independence in 2011, whereas user data is based on post-independence (2012-2013). No regulator data available.
Tanzania	All	Exclude	Availability metric for regulator data is not nuanced with the provider and regulator data streams. Regulator data is unavailable for same years as user/provider data.
Uganda	User and Regulator	Exclude	Uganda only has one water provider which is a government run body meaning that data available in IBNET is country wide, therefore it is not conducive to this analysis where data that is disaggregated sub-nationally is needed.
Zambia	All	Include	All three data streams are available, metrics of availability used across all streams are nuanced.
Zimbabwe	User and Provider	Exclude	No regulator data is available, nor are the user and provider data available for the same years.

C.2 Commercial WSC Connections and Population Serviced in 2018

Data source: NWASCO (2018a)

Provider	Number of towns/centres serviced	Total population in service area	Number of connections
Lusaka WSC	6	2,587,512	109,454
Nkana WSC	3	819,546	64,378
Kafubu WSC	3	722,553	64,104
Mulonga WSC	3	528,760	56,755
Lukanga WSC	8	436,515	27,643
Southern WSC	21	489,130	56,536
Chambeshi WSC	12	364,141	23,546
North Western WSC	8	276,720	17,973
Eastern WSC	10	328,038	21,047
Western WSC	10	220,063	16,250
Luapula WSC	7	220,715	7,951
Total	**91**	**6,993,693**	**465,637**

C.3 Variables Included in Multi-level Models and Data Sources

LEVEL OF MODEL	VARIABLE	PROXY/ORIGINAL VARIABLE	DHS QUESTION ID	SOURCE
Outcome Variable	Household Availability of Piped Supplies	-	Hv201a	Zambia Statistics Agency *et al.* (2019)
I - User	Wealth Quintiles	-	Hv270a	
	Month of interview	Interview Date	Hv006	
	Type of Piped Water Supply	-	Hv201	
	Ethnicity*	Native Language	Hv045c	
	Number of Household Members	-	Hv009	
	Tenure	Owns House (alone or jointly)	Mv745a/ V745a	
J – Household Cluster	Rurality	-	-	Pesaresi and Freire (2016)
	Change in Urbanisation	-	-	
	Neighbourhood Wealth*	Wealth index factor score for urban	Hv271a	Zambia Statistics Agency *et al.* (2019)
	Age of Neighbourhood*	Length of Residence	Mv104/ V104	
K – Provider	Provider reported Availability	-	-	International Benchmarking Network (IBNET) (2017)
	Provider reported Consumption (LPCD)	-	-	International Benchmarking Network (IBNET) (2017b)
	Regulator reported Availability	-	-	National Water Supply and Sanitation Council (NWASCO) (2018)
	Regulator reported Consumption (LPCD)	-	-	
	District Level Wealth	-	-	Republic of Zambia Central Statistical Office (2017)
	Provider Non-Revenue Water	-	-	International Benchmarking Network (IBNET) (2017c)

**Variable is derived from other variables/data.*

C.4 Included DHS Household, Men's and Individual Survey Questions

DHS Question ID	Question	Response options
Hv201	*What is the main source of drinking water for members of your household?*	*Piped into dwelling; Piped to yard/plot; Piped to neighbour; Public tap/standpipe; Tube well or borehole; Dug well (open/protected); Dug well (protected); Protected spring; Unprotected spring; Rainwater; Tanker truck; Tart with small tank; Bottled water; Surface water (river/dam/lake/ponds/stream/canal/irrigation channel); Other; Missing.*
Hv201a	*In the last two weeks was the water from your main source not available for at least one full day?*	*No, not interrupted for a full day; Yes, interrupted for a full day or more; Don't know; Missing.*
Hv270a	Wealth index for urban/rural	This variable provides a rural- and urban-specific wealth index.
Hv006	Month of interview	
Hv045c	Native language of respondent	
Hv009	Number of household members	
Mv104/ V104	*How long have you been living continuously in your current city/town/village of residence?*	Respondents lists number of years OR selects: *always; visitor; inconsistent; don't know' missing.*
Mv745a/ V745a	*Do you own this or any other house either alone or jointly with someone else?*	*Does not own; Alone only; Jointly only; Both alone and jointly.*

C.5 Factors Associated with Respondents *'not knowing'* their Service Availability

Explanatory Variables	Binary Logistic Regression	
	Odds Ratio	**(95% CI)**
Native language *(Ref = English)*		
Bemba	3.364**	(2.015-5.616)
Lunda, Kaonde, Luvale	3.518**	(2.015-6.141)
Lozi	2.318**	(1.332-4.035)
Tonga	2.076**	(1.205-3.575)
Other	2.241**	(1.338-3.755)
Type of piped supply *(Ref= Piped into dwelling)*		
Piped into yard/plot or Public tap/standpipe	1.105	(0.885-1.381)
Piped to neighbour	1.224	(0.930-1.613)
Tenure *(Ref= Does not own)*		
At least partly owns	1.210	(1.029-1.424)
No information	0.980	(0.693-1.386)
Household size *(Ref= 1 member)*		
2-3	1.220	(0.914-1.628)
4-6	1.188	(0.899-1.570)
7-9	1.166	(0.851-1.598)
10+	0.999	(0.653-1.528)
Household Wealth *(Ref = Richest)*		
Poorest	0.959	(0.723-1.272)
Poorer	0.942	(0.718-1.236)
Middle	0.984	(0.759-1.277)
Richer	1.003	(0.787-1.279)
Month of Interview *(Ref = Dec'18-Jan'19)*		
Sept'18	1.624**	(1.227-2.150)
Oct-Nov'18	1.661**	(1.269-2.175)
July-Aug'18	1.655**	(1.288-2.127)
Constant	0.153**	(0.083-0.284)
Observations (n)	3047	
Likelihood Ratio Chi-squared (df)	81.16** (20)	

User availability of supplies coded as 1 for don't know, 0 for yes/no interruptions
CI = Confidence Intervals
*p <0.05, **p <0.01

C.6 Provincial Wealth GDP and GDP per Capita Data

GDP and GDP per capita based on 2015 current prices, in Zambian Kwacha (ZKW) and US Dollars (US$) for Utility Company coverage areas.

Provider	Province	Population	GDP (ZKW millions) current prices	GDP per capita (Kwacha)	GDP (US$ million) current prices	GDP per capita (US$)
Chambeshi WSC	Northern + Muchinga - Chama district	2,077,287.13	11,524.74	5,547.98	1,047.70	504.36
Eastern WSC	Eastern + Chama district	1,935,650.87	10,256.06	5,298.51	932.37	481.68
Kafubu WSC	Copperbelt (Ndola, Luanshya & Masaiti districts)	2,362,207.00	52,979.40	22,427.92	4,816.31	2,038.90
Luapula WSC	Luapula	1,127,453.00	5,117.20	4,538.73	465.20	412.61
Lukanga WSC	Central	1,515,086.00	12,624.10	8,332.27	1,147.65	757.48
Lusaka WSC	Lusaka	2,777,439.00	52,186.70	18,789.50	4,744.25	1,708.14
Mulonga WSC	Copperbelt (Chililabomwe, Chingola & Mufulira districts)	548,066.53	12,291.99	22,427.92	1,117.45	2,038.90
Nkana WSC	Copperbelt (Kaluluishi & Kitwe districts)	755,792.42	16,950.86	22,427.92	1,540.99	2,038.90
North Western WSC	North Western	833,818.00	13,760.10	16,502.52	1,250.92	1,500.23
Southern WSC	Southern	1,853,464.00	19,484.00	10,512.21	1,771.27	955.66
Western WSC	Western	991,500.00	5,448.80	5,495.51	495.35	499.59

C.7 Characteristics of Piped Water Users in Zambia

Piped Water User Characteristics	Percentages (%) of Households (n)
Household Size	
1 person	8.7% (264)
2-3 people	26.4% (775)
4-6 people	43.3% (1325)
7-9 people	16.8% (535)
10+ people	4.8% (148)
Native Language	
English	2.9% (87)
Bemba	37.8% (1152)
Lozi	8.9% (271)
Lunda, Kaonde, Luvale	8.7% (256)
Tonga	12.0% (365)
Other	30.1% (365)
Household Wealth (Quintiles)	
Poorest	22.9% (698)
Poorer	17.5% (533)
Middle	17.4% (530)
Richer	19.9% (608)
Richest	22.3% (678)
Tenure	
At least partly owns house	31.9% (971
Does not own	63.1% (1922)
No information	5.1% (154)
Type of piped supply	
Piped into dwelling	23.9% (729)
Piped to yard/plot	35.0% (1065)
Piped to neighbour	19.6% (598)
Public tap/standpipe	21.5% (655)
Availability of supplies	
At least one full day of interruptions in last 2 weeks	45.9% (1398)
No interruptions in last 2 weeks	54.1% (1649)
Month of Interview (Season)	
July-August 2018 (Dry)	46.0% (1401)
September 2018 (Dry)	18.9% (577)
October-November 2018 (Rainy)	23.9% (727)
December 2018- January 2019 (Rainy)	11.2% (342)
	Note: n = 3047

C.8 User-reported Inequalities in Piped Water Interruptions

C.8.1 User-reported Inequalities, by Month of Interview, in Piped-water Interruptions by Provider

Provider	Number of HHs interviewed in the dry season (July-Aug) reporting an interruption	Number of HHs interviewed in the rainy season (Dec-Jan) reporting an interruption	Weighted percentage (%) of HHs interviewed in dry season (July-Aug) reporting an interruption	Weighted percentage (%) of HHs interviewed in rainy season (Dec-Jan) reporting an interruption	Difference dry-rainy (%)	Ratio dry-rainy
Chambeshi WSC	97	24	34.66	18.12	16.54	1.91
Eastern WSC	93	31	28.08	20.46	7.62	1.37
Kafubu WSC	101	22	53.85	8.61	45.24	6.25
Luapula WSC	32	8	42.09	9.46	32.63	4.45
Lukanga WSC	164	106	69.95	16.14	53.81	4.33
Lusaka WSC	402	0	48.81	0	48.81	-
Mulongo WSC	30	16	33.57	3.81	29.76	8.81
Nkana WSC	112	0	55.63	0	55.63	-
North Western WSC	81	22	57.67	5.69	51.98	10.14
Southern WSC	195	73	70.45	7.10	63.35	9.92
Western WSC	94	40	54.11	24.50	29.61	2.21

C.8.2 User-reported Inequalities, by Type of Supply, in Piped-water Interruptions by Provider

Provider	Number of HHs reporting an interruption using a piped to yard/plot or public tap/standpipe	Number of HHs reporting an interruption using supply piped into dwelling	Weighted percentage (%) of HHs reporting an interruption using a supply piped to yard/plot or public tap/standpipe	Weighted percentage (%) of HHs using a supply piped into dwelling	Difference yard/public standpipe - dwelling (%)	Ratio yard/public standpipe-dwelling
Chambeshi WSC	147	12	57.65	6.12	21.42	1.59
Eastern WSC	111	49	55.58	14.20	25.36	1.84
Kafubu WSC	87	90	41.64	35.87	19.16	1.85
Luapula WSC	75	17	70.57	21.49	62.63	8.89
Lukanga WSC	162	83	60.87	27.26	48.99	5.12
Lusaka WSC	552	190	61.63	21.66	44.92	3.69
Mulongo WSC	67	45	65.15	25.56	55.87	7.02
Nkana WSC	141	50	67.49	20.93	55.91	5.83
North Western WSC	113	58	57.67	24.76	40.10	3.28
Southern WSC	170	105	50.78	14.63	16.19	1.47
Western WSC	95	30	50.23	11.53	11.98	1.31

C.8.3 User-reported Inequalities, by Household Size, in Piped-water Interruptions by Provider

Provider	Number of 1-person HHs reporting an interruption	Number of HHs with >10 people reporting an interruption	Weighted percentage (%) of 1-person HHs reporting an interruption	Weighted percentage (%) of >10 people HHs reporting an interruption	Difference 1 person - >10 people HHs (%)	Ratio 1 person - >10 people HHs
Chambeshi WSC	19	15	8.14	7.36	0.78	1.11
Eastern WSC	16	9	11.80	4.83	6.97	2.44
Kafubu WSC	17	6	7.13	3.47	3.66	2.05
Luapula WSC	5	6	1.24	6.65	-5.41	0.19
Lukanga WSC	25	13	15.60	7.92	7.68	1.97
Lusaka WSC	75	45	6.99	3.30	3.69	2.12
Mulongo WSC	10	7	4.14	5.18	-1.04	0.80
Nkana WSC	14	14	7.50	6.48	1.02	1.16
North Western WSC	27	6	8.84	2.39	6.45	3.70
Southern WSC	47	13	13.84	3.11	10.73	4.45
Western WSC	9	14	6.48	5.17	1.31	1.25

C.8.4 User-reported inequalities, by Household Wealth, in Piped-water interruptions by Provider

Provider	Number of HHs in the richest quintile reporting an interruption	Number of HHs in the poorest quintile reporting an interruption	Weighted percentage (%) of HHs in richest quintile reporting an interruption	Weighted percentage (%) of HHs in poorest quintile reporting an interruption	Difference richest-poorest HHs (%)	Ratio richest-poorest
Chambeshi WSC	21	100	12.56	42.05	-29.49	0.30
Eastern WSC	53	41	18.25	20.74	-2.49	0.88
Kafubu WSC	82	20	31.83	11.04	20.79	2.88
Luapula WSC	22	32	25.52	33.01	-7.49	0.77
Lukanga WSC	83	53	31.50	28.09	3.41	1.12
Lusaka WSC	226	53	26.19	5.24	20.95	5.00
Mulongo WSC	40	7	25.55	6.30	19.25	4.05
Nkana WSC	54	12	21.77	6.41	15.36	3.40
North Western WSC	68	45	32.09	14.19	17.90	2.26
Southern WSC	79	77	5.936	25.46	-19.52	0.23
Western WSC	42	67	17.39	48.51	-31.12	0.36

C.8.5 User-reported inequalities, by Tenure, in Piped-water interruptions by Provider

Provider	Number of households reporting an interruption who at least partly own	Number of households reporting an interruption who do not own	Weighted percentage (%) of HHs reporting an interruption who at least partly own	Weighted percentage (%) of HHs reporting an interruption who do not own	Difference partly own- does not own (%)	Ratio partly owns- does not own
Chambeshi WSC	63	87	30.24	35.05	4.81	1.16
Eastern WSC	52	87	24.44	45.00	20.56	1.84
Kafubu WSC	38	116	19.69	51.94	32.25	2.64
Luapula WSC	27	45	25.51	41.16	15.65	1.61
Lukanga WSC	54	138	23.67	43.17	19.50	1.82
Lusaka WSC	128	475	16.39	55.40	39.01	3.38
Mulongo WSC	16	67	16.99	56.22	39.23	3.31
Nkana WSC	31	128	14.67	58.67	44.00	4.00
North Western WSC	66	67	35.57	35.47	-0.10	1.00
Southern WSC	76	165	25.66	43.61	17.95	1.70
Western WSC	35	80	15.16	36.79	21.63	2.43

C.8.6 User-reported inequalities, by Native Language, in Piped-water interruptions by Provider

Provider	Majority language spoken in provider coverage area	Minority language spoken in provider coverage area	Number of HHs who speak the majority language reporting an interruption	Number of HHs speaking minority language reporting an interruption	Weighted percentage (%) speaking majority language reporting an interruption	Weighted percentage (%) speaking minority language reporting an interruption	Difference majority-minority language (%)	Ratio majority versus minority language
Chambeshi WSC	Bemba	Luvale & Kaonde & Lunda	218	2	94.42	1.43	92.99	65.84
Eastern WSC	Other	Lozi	173	2	87.52	3.04	84.48	28.83
Kafubu WSC	Bemba	English	145	4	64.47	1.42	63.05	45.43
Luapula WSC	Bemba	Luvale & Kaonde & Lunda	90	5	88.57	4.21	84.36	21.02
Lukanga WSC	Bemba	Lozi	114	8	45.10	3.21	41.90	14.07
Lusaka WSC	Other	English	430	7	46.91	0.40	46.51	116.11
Mulongo WSC	Bemba	English	94	1	74.78	1.08	73.70	69.37
Nkana WSC	Bemba	Lozi	144	3	62.84	0	62.84	-
North Western WSC	Luvale & Kaonde & Lunda	English	114	2	54.73	1.23	53.50	44.39
Southern WSC	Tonga	English	198	6	47.58	0	47.58	-
Western WSC	Lozi	English	137	1	71.80	0	71.80	-

C.9 Household Cluster Inequalities in Drinking Water Availability by Provider

(The percentage (weighted) of households, by household cluster characteristics, reporting an interruption to their supply in each provider coverage area)

	Difference Poor-Rich HH Clusters (%)	Ratio Poor-Rich HH Clusters	Differences City-Rural Areas (%)	Ratio City-Rural Areas	Differences City-Unpopulated Areas (%)	Ratio City-Unpopulated Areas	Difference No change-Urbanised Areas (%)	Ratio No change - Urbanised Areas	Difference Young - Old Neighbourhoods (%)	Ratio Young - Old Neighbourhoods
Chambeshi WSC	27.43	2.05	38.85	6.66	11.78	1.35	14.48	1.34	26.70	3.81
Eastern WSC	15.69	1.60	35.54*	-*	-19.02	0.65	9.12	1.20	-67.12*	-*
Kafubu WSC	13.13	1.32	37.48	2.34	65.55*	-*	63.72	4.51	30.29	5.43
Luapula WSC	-9.44	0.82	40.87	5.32	10.12	1.25	-19.58	0.67	-12.81*	-*
Lukanga WSC	14.77	1.37	73.71*	-*	47.42	2.80	50.98	3.08	-13.89	0.42
Lusaka WSC	-28.71	0.30	91.93	33.83	93.56	81.17	60.52	4.41	12.48	2.08
Mulongo WSC	-27.65	0.39	70.82	10.28	78.45*	-*	71.38	5.99	-4.69*	-*
Nkana WSC	-23.64	0.31	61.77	4.53	79.27*	-*	70.65	10.33	-36.37*	-*
North Western WSC	-29.44	0.33	53.22	7.75	45.28	3.86	-52.60	0.31	-13.60	0.41
Southern WSC	72.78	8.95	49.83	3.94	56.04	6.22	71.08	5.92	-4.06	0.01
Western WSC	38.96	2.91	-22.00	0.00	-47.78	0.00	45.28*	-*	-26.81	0.24

**Household did not report an interruption in one of the socio-economic categories being compared*

NB: Negative values show an inverse relationship between the groups of the socio-economic characteristic

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