‘SMART METERS’ FOR RURAL WATER SUPPLY IN SUB-SAHARAN AFRICA

Submitted by William Ingram to the University of Exeter as a thesis for the degree of Doctor of Philosophy in Engineering, March 2021.

I certify that all material in this thesis that is not my own work has been identified and that any material that has previously been submitted and approved for the award of a degree by this or any other University has been acknowledged.

(Signature) ………………………………………………………………………………

Believe that a further shore
Is reachable from here.
Believe in miracle
And cures and healing wells.

Seamus Heaney, *The Cure at Troy* (1991)

By 2030, achieve universal and equitable access to safe and affordable drinking water for all.

Target 6.1, Sustainable Development Goals (2015)

ABSTRACT

Novel technologies can help make progress towards the goal of universal and equitable access to safe and affordable drinking water for all. Rural communities in sub-Saharan Africa suffer from very low levels of water supply and drastic unsustainability of existing systems. The reasons for this include complex interactions between many factors; it is a ‘wicked problem’.

In recent years, a range of ICT and Internet-of-Things (IoT) innovations have been developed to address limitations to rural water supply. Specifically, pre-payment ‘smart meter’ innovations for communal water points allow for improved revenue collection, real-time monitoring, and improved access. This technology is in the early phases of deployment across sub-Saharan Africa. Current evaluations, particularly in grey literature, have had limited: focus on technical aspects, independent academic rigour, or systems thinking. Significantly, data collected from smart meters has not been used for longer-term insights into rural water supply.

The aim of this research is to investigate how ‘smart meters’ can improve rural water supply service in sub-Saharan Africa. An evaluation of a selected smart meter model was carried out on technical robustness, specifically accuracy of flow measurement and flow rate reduction from debris, and on effectiveness in the socio-economic context in rural Tanzania. This revealed good technical and socio-economic performance. Next, smart meter data from Tanzania and The Gambia was combined with collected survey and interview data to reveal new insights into water collection patterns from rural water points. Then, smart meter data was combined with rainfall data, and the influence of rainy seasons and days of rainfall are quantified. Based on this, ‘weather dependent pricing’ (WDP) has been developed as a novel pricing mechanism based on smart meter pre-payment and remote management, with the objective to incentivise users to maintain using clean groundwater. Potential costs per disability adjusted life year (DALY) averted, economic cost-benefit, sensitivity, and uncertainty of the pricing mechanism have been quantified, and an associated decision support tool has been developed. WDP has the potential to be an ‘off the shelf' intervention with good value for money that can strengthen rural water supply systems and contribute towards climate change resilience.

Key findings from this PhD research include: showing flow measurement is accurate, and flow rate reduction from debris build up can provide a basis for predictive maintenance; empirically showing how smart meters can improve service levels in rural communities; that smart meter data can provide new insights into time and location of water collection, and seasonality; and that weather dependent pricing could significantly and cheaply improve community health.

The research has strong impact potential for current and future smart meter development and deployment (an area growing in relevance), and starts to fill four important research gaps. Suitable settings, broader considerations, policy implications, and potential barriers for smart meters in rural sub-Saharan Africa are expounded, along with how smart meters can strengthen rural water supply systems.

LIST OF PUBLICATIONS

The key outputs from the work are three journal publications as included in Appendix D.

- Ingram, W. & Memon, F. A. (2019). Internet of things innovation in rural water supply in sub-Saharan Africa: a critical assessment of emerging ICT. *Waterlines*, *38*(2), 71-93.
- Ingram, W., & Memon, F. A. (2020). Robustness of IoT-connected e-Taps for sustainable service delivery of rural water supply. *Water Supply*, *20*(6), 2251-2260.
- Ingram, W., & Memon, F. A. (2020). Rural Water Collection Patterns: Combining Smart Meter Data with User Experiences in Tanzania. *Water*, *12*(4), 1164.

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TERMINOLOGY

The term ‘smart meter’ is selected here to best represent the family of newly developed pre-payment Internet-of-Things technologies under investigation. ‘Metering’ best represents the monitoring and revenue collection characteristics and ‘smart’ represents the ‘IoT’ and tag payment characteristics. Other literature also variably refers to ‘smart meters’, ‘prepayment water systems’, ‘water ATMs’, ‘smart taps’, and others. These ‘smart meter’ technologies investigated here are newly designed for the distribution points of de-centralised, small piped water distribution systems (PWSs) in rural sub-Saharan African contexts, and are therefore distinct to other ‘smart meters’ commonly seen in developed world contexts. A PWS can exist with or without smart meters.

AIRS = Atmospheric Infrared Sounder
CHIRPS = Climate Hazards Group InfraRed Precipitation with Station data
COWSO = Community Owned Water Supply Organisation
DALY = Disability Adjusted Life Year
DP = Distribution point (i.e. communal standpipe)
E_P = Price elasticity
GBP = Great British Pounds
GMD = Gambian Dalasi
GPM = Global Precipitation Measurement
GSA = ‘Global’ sensitivity analysis
JMP = Joint Monitoring Programme (UNICEF-WHO)
H_{RA} = Household roof area (m^2)
OAT = ‘One-at-a-time’ sensitivity analysis
P = Price
Protocol A = Interviews with managerial stakeholders
Protocol C = ‘Key informant’ user surveys
Protocol E = Remaining user surveys
Protocol D = Members of Community A1 surveys
PWS = Piped water system

Q (Chapter 4) = Flow rate

Q (Chapter 8) = Demand

R = Rainfall (mm per day)

R_C = Runoff coefficient

RR = Relative risk

SDG = Sustainable Development Goal

TAMSAT = Tropical Applications of Meteorology using SATellite data

TSH = Tanzania Shillings

UNEP = United Nations Environment Programme (UN Environment)

UNICEF = United Nations International Children’s Emergency Fund

USD = United States Dollars

V = Volume (litres)

V_R = Volume of rainwater per household (m^3 per day)

WASH = Water, Sanitation and Hygiene

WDP = Weather dependent pricing

WHO = World Health Organisation

$\%\Delta V$ = Percentage change in volume

$\%\Delta Q$ (Chapter 4) = Percentage change in flow rate

$\%\Delta Q$ (Chapter 8) = Percentage change in demand; desired increase in volume dispensed during rainfall months

Chapter 1. INTRODUCTION

1.1 Background and rationale

Approximately 55% of people in rural sub-Saharan Africa still do not have at least ‘basic’ drinking water services (JMP, 2019). This is unacceptable. Addressing such low service levels is a moral requirement, but is also particularly challenging. Countless actors, including those from national governments, international development institutions, charities, universities, NGOs, and rural communities themselves, have worked hard on this challenge for decades, yet the rate of improvement has not been sufficient. At current rates of improvement, the target of achieving universal and equitable access to safe and affordable drinking water for all by 2030, as enshrined in the Sustainable Development Goals, is unlikely to be met (United Nations, 2019).

The reasons for this lag in progress are multiple and complex, and are introduced in Chapter 2, with one common factor being the unsustainability of services. However, overall, it is clear that innovative new approaches are needed. It is time to move beyond some of the existing paradigms, such as the accepted wisdom of ‘community based management’ or ingrained predilection for handpump technology. The fact that water service rates languish, while other services such as mobile phone connectivity are now almost ubiquitous, further highlights that such low water service levels have no place in the modern world.

Entrepreneurs and engineers have recently stepped up with new proposals and technologies that make use of modern mobile connectivity to improve rural water supply. One example is the growing family of pre-payment based, smart meter enabled water taps or kiosks (referred to here as ‘smart meters’). These have been increasingly developed and deployed in recent years (e.g. GSMA 2020a; Komakech et al., 2019; 2020; Check et al., 2017). These smart meters have the joint capabilities of real-time, remote monitoring of water flow at water points via Internet-of-Things (IoT) connectivity, pre-payment, and automated dispensing of water. Smart meters are designed to improve monitoring and revenue collection to facilitate sustainable management, and therefore improve service levels. These technologies are novel, compared to e.g. coin-operated water kiosks, in that they: benefit from remote pre-payment and instant credit removal from users' tags; they combine pre-payment with data monitoring; remote IoT capacity allows for instant data collection on usage and payment; and they have automated valves for water dispensing. It is this collective ensemble of capacities that allows them to operate in this context in the first place, whereas alternative technologies with only one of these will not be practical, sustainable, or useful. Some early evaluations of different smart meter projects have reported successes in different countries.

In the face of such poor existing service levels, this kind of technology can be presented as a silver bullet solution, and is susceptible to overhype, particularly by technologically minded actors. But at the same time, this must not become a reason to discount the value of smart meters off-hand. New technologies can be game changers by forming key parts of new approaches, and catalysing water supply system strengthening. This uncertainty means that there is now a pressing need for thorough examination of how smart meters can improve rural water supply.

In order to do this successfully, research on smart meters must be in line with the complexity of the rural water supply system. Therefore, research must employ a systems thinking approach that moves beyond linear project evaluations that cannot account for systemic or longer-term challenges. Technical, socio-economic, and environmental factors need to be researched, and potential limitations and challenges identified. At this stage of research, a broad scope is required that encompasses a range of themes and disciplines. Such an approach is undertaken here.

Additionally, in the spirit of 'imaginative new approaches', research now needs to progress beyond evaluations and begin to make use of the very high-quality data available from smart meters themselves. This represents a powerful new opportunity to use smart meters as novel 'research instruments' in the field. Doing so can reveal new understandings of rural water supply and demand. Furthermore, this new data source can be combined with other data sources or studies, for instance using social science methods or meteorological data, to reveal new insights into water collection and provide new methods of management. Pre-payment capabilities in particular can provide new opportunities for management. Consequently, new approaches, insights, and management techniques are presented here.

A better understanding of the role smart meters have to play can help practitioners and policy makers make intelligent decisions about smart meter deployment in upcoming years. Consequently, the research presented here has a pressing need now and as smart meters grow in relevance, and can contribute towards the effort to improve rural water supply for the world's most vulnerable people.

1.2 Aim and objectives

The overall aim of this research is to investigate how smart meters can improve rural water supply service in sub-Saharan Africa. Contexts in Tanzania and The Gambia will be explored, and the research aim will be achieved through the following objectives:

1. Identify and describe the role of smart meters in the context of rural sub-Saharan Africa
2. Generate information on the longer-term robustness of smart meters (e-Tap)
3. Evaluate smart meter effectiveness within the socio-economic setting of rural Tanzania
4. Generate understandings of how smart meters can provide new insights into water collection in Tanzania and The Gambia
5. Develop ways how smart meters can investigate and mitigate the effects of seasonality of water collection
6. Propose broader contextual considerations for effective smart meter deployment

1.3 Research questions

1. What potential do smart meters have for improving rural water supply in sub-Saharan Africa?
2. How robust are smart meters (e-Tap) in the longer-term?
3. How effective are smart meters at improving rural water supply when operating within their socio-economic setting?
4. What new insights into water collection patterns can smart meters provide?
5. What new insights into seasonality can smart meters provide?
6. How can smart meters help mitigate the adverse effects of seasonality of water collection?
7. How and where can smart meters be deployed most effectively?
8. How can smart meters strengthen rural water supply systems?

1.4 Novelty of the research

The work carried can be regarded as novel in the following ways:

- The longer-term robustness (accuracy and debris blockages) is investigated, as opposed to the short-term remedial product development cycle.
- The effectiveness within the socio-economic context is systematically evaluated, as opposed to as a stand-alone monitoring tool.
- It is demonstrated how smart meters can be used as a novel research tool to reveal new, higher-resolution insights into: a) water collection patterns, showing novel findings regarding for instance time of collection and location of water points, and b) seasonality of water collection. This is based on a novel combination of remote smart meter data with social science methods, and with longer and additional meteorological data sets than those employed elsewhere.
- A new use of smart meters is proposed for facilitating the sustained use of clean water throughout rainy seasons, namely with the novel development of ‘weather dependent pricing’. This is based on the findings regarding seasonality. This kind of pricing mechanism is previously unreported, and is now only possible with the added capabilities of smart meters.

- Contextual considerations for smart meter deployment are proposed that go beyond current shorter-term thinking. These provide a critical and measured viewpoint on smart meter appropriateness.

Overall, a novel technology has been investigated, which is representative of a nascent research field of rapidly growing interest (partly driven by the recent expansion of mobile connectivity across Africa). A systems thinking framework has been used which moves beyond a purely technocratic approach. This is not simply a more thorough evaluation; rather, a future direction for rural water supply in sub-Saharan Africa is illuminated, and it is shown how new technology can be used in new ways to leverage systems change.

1.5 Contribution to knowledge

The outputs of the study contribute to knowledge and practice in the following ways:

- This work contributes to understanding of the operation and use of smart meters in rural sub-Saharan Africa, showing that flow measurement is accurate, and flow rate reduction from debris build up is insignificant and can provide a basis for predictive maintenance. It is empirically shown how smart meters improve access to users, monitoring, and revenue collection in rural communities, thus improving service levels and access and reducing marginalisation; and how they are underpinned by effective piped water system (PWS) operation and management.
- This work demonstrates the usefulness of smart meters as a novel ‘research instrument’ to provide detailed information on rural water supply, such as water collection patterns over time and location, and new evidence for seasonality of water collection, which is significant for practitioners and researchers.
- The weather dependent pricing mechanism contributes a new tool that can be used by practitioners to improve rural water supply.
- The work has developed the conceptual understanding of smart meters as new components within the rural water supply system, how and where

practitioners could deploy them, and how they can strengthen the system when deployed appropriately.

Specific potential real-world applications of the research are listed in Section 9.2.

1.6 Overview of thesis

The work presented in the following chapters can be grouped into six main components of work:

i. Identification of smart meter potential and research gaps (Chapter 2)
ii. Technical evaluation of robustness of smart meter (Chapter 4)
iii. Evaluation of effectiveness of smart meter in socio-economic context (Chapter 5)
iv. Investigation of water collection patterns using smart meters (Chapter 6)
v. Investigation of seasonality using smart meters and development of weather dependent pricing (Chapters 7 and 8)
vi. Examination of the implications of findings and broader smart meter considerations (Chapter 9).

Consequently, specific objectives, methods, results, analyses, discussions, implications, conclusions, and further work are all presented within each relevant chapter. A more generalised discussion, implications, conclusions and further work are presented in Chapters 9 and 10. The framework for research is developed and rationalised in Chapter 3, along with a more detailed outline of research conducted (Section 3.4).

The focus of this research is on rural settings rather than urban for two main reasons. Firstly, the ‘smart meter’ technologies under investigation have generally been designed for more rural settings and it is therefore more appropriate to study them in-situ. Secondly, research into technology projects in rural communities is considered to be far behind urban settings (Chambers, 2017), and this research attempts to address this gap. Rural communities also tend to have significantly worse service levels than urban communities. Urban and rural settings present very different contextual factors that will interact with smart meters in different ways, and therefore an exclusive rural focus is justified. Suitability across the urban-rural spectrum is discussed in depth in Section 9.4.

Chapter 2. LITERATURE REVIEW

2.1 Introduction

The objective of this chapter is to identify and describe the role of smart meters in the context of rural sub-Saharan Africa. In order to do this, the scope of literature reviewed in carefully considered. Modern thinking regarding different management models of rural water supply needs to be included so as not to miss crucial systemic lessons. An in-depth review of how failures in service provision and research manifest in a specific country, Tanzania, provides a more detailed illustrative case. Nascent and under-researched novel information communication technologies (ICT), including smart meters, are reviewed. Current research, application, and research gaps are outlined.

Rural water supply in sub-Saharan Africa is shown in this chapter to be a very complex system, therefore a wide range of different literatures is required. Interdisciplinary research is increasingly considered crucial to address complex challenges, particularly regarding water security (Falkenmark, 2001). Practice-focused 'grey' literature is included (e.g. policy briefs and project reports), as in other reviews for such an applied research challenge (e.g. Whaley and Cleaver, 2017). Further specific literature is also reviewed in the following chapters.

A condensed version of this review has been published as the journal article:
Ingram, W. & Memon, F. A. (2019). Internet of things innovation in rural water supply in sub-Saharan Africa: a critical assessment of emerging ICT. *Waterlines*, 38(2), 71-93.

2.2 Review of the general context of rural water supply in Sub-Saharan Africa

2.2.1 The Global Goals and progress in rural water supply

The Sustainable Development Goals (SDGs) set out 17 aspirational Goals and 169 targets in the 2030 Agenda for Sustainable Development (United Nations, 2015a). They call for an integrated approach to social, economic and environmental challenges. The drinking water component of Goal 6 is captured in Target 6.1:

SDG Target 6.1: By 2030, achieve universal and equitable access to safe and affordable drinking water for all.
SDG Indicator 6.1.1: Proportion of population using safely managed drinking water services.

The aim of universal access is more aspirational than the previous Millennium Development Goal (2000-2015) target 7.C, which was only to halve the population without access. Equity and ‘leaving no one behind' underpins the SDGs (Stuart et al., 2016).

The WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation (JMP) produces estimates of progress achieved on drinking water (JMP, 2019). Target 6.1 and its normative interpretation by the JMP are included in Table 2.1, where they are compared against global indicators of progress.

Table 2.1. Comparison of Target SDG 6.1 wording against progress indicators

Target 6.1 language	**Normative interpretation by JMP** (JMP, 2017a)	**Indicator of progress achieved in 2015** (JMP, 2017b)	**Indicator of progress lacking** (JMP, 2017b, WWAP, 2016, United Nations, 2015b)
By 2030, achieve		*Estimates based on 96 countries*	
universal	Implies all exposures and settings, including households, schools, health facilities, workplaces and public spaces	Eight out of ten people (5.8 billion) used improved sources* with water available when needed. 71% of the global population used a safely managed drinking water service	844 million people still lacked even a basic drinking water service and 663 million people worldwide still use unimproved drinking water sources.
and equitable	Implies progressive reduction and elimination of inequalities between population subgroups	One out of three people using safely managed drinking water services (1.9 billion) lived in rural areas	Of the 159 million people who still collect drinking water directly from surface water sources, 150 million live in rural areas and 58% live in sub-Saharan Africa.
access	Implies sufficient water to meet domestic needs is reliable and available close home	Three out of four people used improved sources located on premises. 89% of the global population accessed at least a basic service	263 million people spent over 30 minutes per round trip to collect water from an improved source.
to safe	Safe drinking water free from pathogens and elevated levels of toxic substances at all times	Three out of four people used improved sources free from contamination	2.1 billion people lacked access to safe, readily available water at home.
and affordable	Payment for services does not present a barrier to access or prevent people from meeting other basic human needs	*No internationally agreed benchmark on affordability of drinking water exists* (Hutton, 2012a)	In three out of six global regions, over 10% of the population spends more than 2% of annual household expenditure on water, sanitation and health.
drinking water	Water is used for drinking, cooking, food preparation and personal hygiene	n/a	n/a
for all	Suitable for use by men, women, girls and boys of all ages, including people with disabilities	People living in rural areas and those from poor and marginalized groups are less likely to have access to improved water sources	Three quarters of households in sub-Saharan Africa fetch water away from their home. 50% to 85% of the time, women are responsible for this task.

**see Table 2.2*

The terminology for different drinking water service levels is outlined in Table 2.2. These definitions will be used henceforth, as opposed to others (e.g. IRC, 2014), and provide a benchmark for evaluation of smart meters in Section 5.5.1.

Table 2.2. JMP water service level definitions

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

** Improved sources are: piped water, boreholes or tube-wells, protected dug wells, protected springs, rainwater and packaged or delivered water (JMP, 2017a).*

The overall picture is that the world is not on track to reach SDG 6 (Sadoff et al., 2020), and sub-Saharan Africa is the least likely to reach SDG 6.1 (Hope and Ballon, 2019). However, progress has been made on drinking water. The MDG Target 7.C was met five years ahead of schedule (United Nations, 2015b), and 2.6 billion people gained access to an improved source between 1990 and 2015 (JMP, 2017b). Almost every national government has policies in place to work towards universal drinking water (GLAAS, 2019), and current financing is able to cover capital costs of universal basic service (Hutton and Varughese, 2016). Yet many shortfalls remain, especially in rural sub-Saharan Africa where costs are three times more than in Asia, and it is believed by some that prior progress was at the cost of sustainability. Sustainability of rural water supply incorporates many aspects, with institutional, social, technical, environmental and financial dimensions (WELL, 1998). It should underpin lasting beneficial change in rural water supply. Specifically, this often revolves around the ability to recover from technical breakdown in a water system, however also includes other parts of the system including water resource sustainability, finance, and management as discussed in the following sections.

2.2.2 Interaction of water with general developmental trends

Underlying developmental trends and contextual drivers interact with rural water supply in sub-Saharan Africa. Table 2.3 highlights specific interactions. These trends and impacts are very interconnected.

Table 2.3. Development trend interactions with rural water supply

Trend	Interaction with rural water supply
Demographic change The combined population of the 47 Least Developed Countries (LDCs) is projected to increase from roughly 1 billion in 2017 to 1.9 billion in 2050 (UN DESA, 2017).	Population growth is putting pressure on water resources and pushing more people into vulnerable situations. People also move away from water scarce regions (Gleick, 2014).
Economic growth Growth in sub-Saharan Africa was around 2.7% in 2017, and is expected to rise (World Bank, 2017a).	Increases in GDP per capita in sub-Saharan Africa positively correlates with access to an improved water source with an R^2 value of 0.62 (World Bank, 2017a), yet water resources also underpin economic growth. Water projects bring economic benefits in the long term (Mason et al., 2017; Foster and Briceño-Garmendia, 2010). In developing regions the return on investment on water infrastructure has been estimated at 5 to 28 USD per every 1 USD spent (WWAP, 2015).
Economic inequality Sub-Saharan Africa has higher mean Gini* coefficients (0.43) than the rest of the developing world (0.39) (Bhorat, 2015).	Economic inequality translates to inequality of access to clean water supply. Marginalised poor communities are also excluded from decision-making activities (WWAP, 2015). Economic growth alongside growth in inequality reduces ‘growth-poverty elasticity’, which leads to reduced overall poverty reduction and therefore reduced increase in access to clean water.
Urbanisation In 2014, 54% of the global population lived in urban areas, but by 2050 two-thirds will. Developing countries will see most of this growth (WWAP, 2015).	The number of people in urban areas without access to an improved drinking water source increased from 111 million to 149 million between 1990 and 2012. The virtual water demand of cities from food, goods and energy exceeds direct water use (Hoekstra and Chapagain, 2006). Globally 8 out of 10 people without improved drinking water remain living in rural areas (JMP, 2017b).
Poverty 1.6 billion people still live in	Water security lies at the heart of sustainable development and poverty reduction (Grey and

multidimensional poverty. 31% of these are in sub-Saharan Africa, where the number of people living in extreme poverty has grown substantially since 1990, largely due to population growth (Alkire et al., 2015).	Sadoff, 2007). Lack of access to clean water is a direct cause of poverty. For instance, halving water collection times is shown to increase girls' school attendance by about 7% in Ghana (Nauges and Strand, 2015). Poverty is also a cause of lack of access to clean water, e.g. with limitations on community investments for infrastructure (WWAP, 2015).

** Gini: statistical measure of economic inequality within a population. Higher values indicate greater inequality.*

Economic growth in sub-Saharan Africa has had less of an impact on reducing poverty than expected. The complexities of this hide clear explanations but suggested reasons are depth of poverty, high inequality, mismatch between growth and employment, and rapid population growth (UNECA, 2017). Sub-Saharan Africa is likely to suffer the greatest impacts of inadequate water supply and sanitation measured as a proportion of GDP. Recent projections up to 2050 suggest that economic growth on its own will not be sufficient to eliminate mortality or economic losses that come from poor access to water and sanitation (Fuente et al., 2020). Poverty reduction has been significantly slower in rural areas. In 1990 only 31% of Africa's population was urban, and by 2035 this is projected to reach 49%. As mean consumption in urban areas is two to three times as large as in rural areas in most countries, there is a growing pressure on water resources (UNECA, 2017). In this context, sustainable and equitable rural water supply in sub-Saharan Africa is critical.

Gender inequality is a key and trans-sectorial development challenge. Women's paid or unpaid work is often the single most important factor for reducing poverty in countries globally (Heintz, 2006). Improving women's access to water is a key driver in moving towards equality. Women and girls are responsible for collecting water in the large majority of households with water sources away from the home. This takes time from education or other productive work, and impacts long-term health. It is estimated that women in many developing countries walk for an average of about 6 km each day to collect water, and spend up to 40% of their daily calorific intake carrying water (UNEP, 2010; UNFPA, 2002). Women are often disproportionately affected by droughts, floods and other climate change related impacts (WWAP, 2015), and poor access to water makes women and girls vulnerable to abuse. Therefore, reducing the population with limited rural water supply will have a strong impact on gender equality. Consequently, marginalisation and gender equality is specifically examined regarding smart meter effectiveness in Chapter 5.

2.2.3 Climate change and rural water supply

Water is the primary medium where the impacts of climate change will be felt (UN-Water, 2010), through increased water flow (e.g. floods) and decreased availability (e.g. droughts). The distribution of climate change impacts on water resources varies between global climate models (GCMs) (Cisneros et al., 2014). Increased temperatures and more extreme, less predictable, weather patterns will alter rainfall, river flows, groundwater, and water quality, and increase the complexity of ensuring water security. The Intergovernmental Panel on Climate Change (IPCC) predicts that for each degree of warming up to 2.7°C above preindustrial levels, renewable water resources will decrease by at least 20% for an additional 7% of the world population (Cisneros et al., 2014).

Sub-Saharan Africa is likely to be the worst affected region from climate change regarding availability and accessibility of water supply. In the long-term, a decline in annual rainfall in West Africa has been observed since the end of the 1960s, with the period 1968–1990 seeing 20-40% less rainfall than 1931–1960 (Bates et al., 2008). However, it is understood that impacts of climate change are not uniform across the region and levels of climate variability are several times greater than predicted climate change (Niang et al., 2014; Grey and Sadoff, 2007). Modelling shows that moderate yet variable change in precipitation would directly impact surface water supply in the region (de Wit and Stankiewicz, 2006), with a non-linear response of basin drainage to rainfall. Floods can put water infrastructure at risk and increase contamination (WHO and DFID, 2009). Women have lower adaptive capacity to climate change because of underlying inequalities, lower participation and more reliance on climate vulnerable sectors. Inadequate observational data, interaction of other factors, and uncertainties from GCMs limit understanding (Niang et al. 2014).

It is argued that adapting to climate change requires rationalization of the choice of technologies to be used to deliver sustainable water supply (WHO and DFID, 2009). Understanding the impacts of climate change on rural water supply is important for directing research and development on smart meters. Because of this, specific impacts, and the potential for smart meters to provide resilience, are further investigated in Chapters 7 and 8.

2.2.4 Projected available water resources in sub-Saharan Africa

Africa is the second driest continent (after Australia) and has only 9% of global renewable water resources compared to 18% of the world's population (UNEP, 2010). Approximately 66% of the continent is classified as arid or semi-arid, and around 40% of Africa's population lives in these regions.

However, an estimated 95% of Africa's potential water resources remain undeveloped (WWAP, 2015), and some countries designated as 'water scarce' have substantial groundwater reserves. Africa has 23% of global groundwater resources, yet it is responsible for only 4% of global groundwater abstraction (van der Gun, 2012). Rural communities typically extract drinking water from groundwater resources as they are available nearby, involve lower costs, and are usually free from contamination when extracted from confined aquifers (Schmoll et al., 2006). The role of groundwater as a sustainable source of rural water supply is hard to quantify (MacDonald et al., 2012, Calow et al., 2010), and this uncertainty hinders understanding of the feasibility and sustainability of governance and technology options (WHO and DFID, 2009).

There is now growing understanding that sustainable management of groundwater is important for resilience and adaptation to climate change (FAO, 2016, van der Gun, 2012). About 20% of the world's aquifers are being over-exploited, usually in areas of high populations (Gleeson et al., 2012). Some symptoms of excessive abstraction are:

- Falling groundwater levels with increased pumping costs and lower yields
- Vegetation stress from falling groundwater levels
- Saline water intrusion, often coastal, or other poor quality water inflow

- Loss of aquifer capacity with pressure loss and contraction of porous rock
- Land subsidence with aquifer compression (Smith et al., 2016).

Contrary to climate stresses, recent research (further discussed in Chapter 8) has shown that groundwater in Africa has a relatively high resistance to some impacts of climate change. An estimated storage of 0.36–1.75 million km^3 is more than 100 times estimates of annual renewable freshwater resources, and can therefore be a potential buffer against climate change (MacDonald et al, 2012). No long-term decrease in groundwater storage has been measured between 2002 and 2016 (Bonsor et al., 2018; Pavelic et al., 2012), and groundwater residence times have been shown to have greater resilience across inter-annual precipitation variance (Lapworth et al., 2013). This evidence indicates that there is no significant stress from current abstraction rates, in general. Therefore, it is assumed throughout this research that PWS groundwater resources will remain sufficient, even with increased use of groundwater from improved access with smart meters (see Section 5.5.1), and is not a critical question of study regarding smart meter use at this stage. Practitioners have given different reasons for why groundwater resources are underdeveloped, including the risk of depletion and inequality seen in other parts of the world, poor hydrogeological information, low access to energy for pumping, national policy and expertise, and alternative options (Villhoth and Merry, 2020). The emergence of small-scale solar pumping is expected to drive rural groundwater development.

Furthermore, groundwater in rural sub-Saharan Africa is general considered to be of satisfactory quality, particularly when compared to alternative water sources that are vulnerable to contamination at surface level or in the unsaturated zone (Katuva et al., 2019; Lawrence, 2001). Borehole PWSs like those studied here tend to rely on deep, confined aquifers, which tend to be even higher quality than handpumps, and microbiological water quality has been measured as highest in boreholes (Parker et al., 2010). Consequently, it is assumed throughout this research that water quality from the PWSs with smart meters will not be a determinant that requires investigation (no viewpoints on water quality are provided by users or managerial stakeholders in Chapter 5, which supports this assumption).

Access to water resources is as important as availability, and depletion of groundwater is rarely as concerning as a ‘spiral of water insecurity’ caused by additional demands, infrastructure and socio-economic failures, and failing shallow water sources (Calow et al., 2010).

2.2.5 Water supply and access in rural sub-Saharan Africa

The human requirement for water is so accepted that in 2010 Resolution 64/292 passed through the United Nations General Assembly recognizing the human right to water and sanitation, and that water is a prerequisite for the realisation of other human rights. Scholars have emphasised the need for elevating water to a human right since the 1990s (Gleick, 1996; Jolly, 1998). Gleick (1996) has recommended a basic water requirement for human activities to be set at 50 litres per person per day (lpd), categorised into needs for drinking water (5 lpd), sanitation (20 lpd), bathing (15 lpd) and food preparation (10 lpd).

Affordability of water implies that payment for services should not present a barrier to access. ‘The Dublin Principles’ from the International Conference on Water and Environment (1992) outline that water has an economic value and should be recognised as an economic good. Policy makers have tended to set arbitrary affordability thresholds of between 2 and 6 % of total expenditure (Hutton, 2012b).

Water supply and access remains challenging regardless of water resources, and an estimated 55% of rural sub-Saharan Africa’s population live without basic drinking water service (JMP, 2019). These limitations vary according to wealth inequality, as shown in Figure 2.1, driven by pressures from general development trends outlined above.

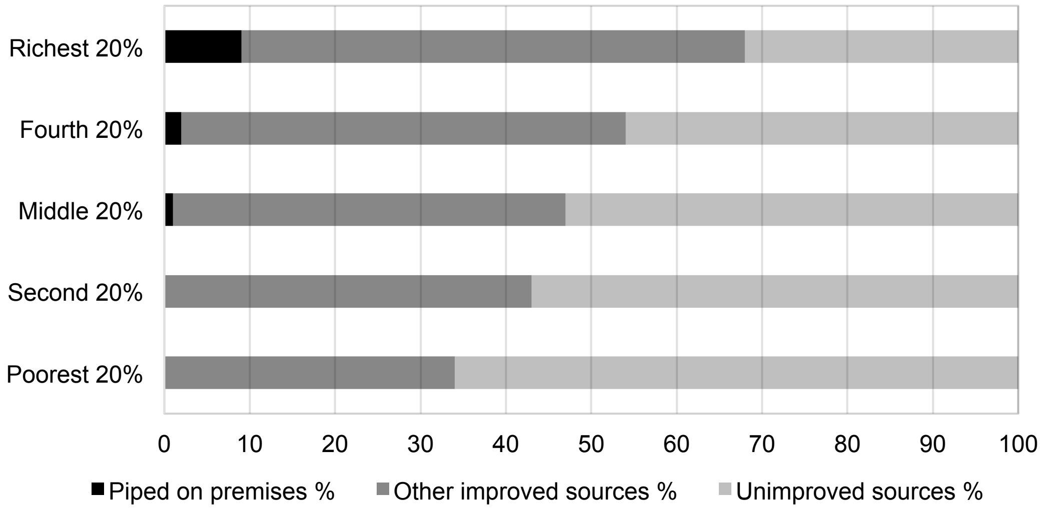

Figure 2.1. Drinking water coverage by wealth quintiles in rural sub-Saharan Africa (United Nations, 2012)

It is well known that limited access to water supply has significant health, economic, educational and social costs. High incidents of waterborne diseases such as diarrhoeal disease from reliance on contaminated unimproved sources translate into economic impacts from healthcare and opportunity costs. Certain water related illnesses reduce the calorific intake from food (FAO, 2017) thus undermining food security. Poor health also reduces educational attainment and entrenches poverty. An effect that has more recently been researched is the psycho-emotional burden of water insecurity, i.e. poor access, availability, usage amount, and perceived cleanliness are causes of stress (Workman and Ureksoy, 2017).

An average round-trip time for collection in sub-Saharan Africa has been approximated as 32 minutes (Tincani et al., 2015), mostly done by women and children. Long and energy-expensive collection has significant impacts. Data from 26 countries shows that a 15-minute decrease in one-way time to collect water is associated with a 41% relative reduction in diarrhoeal prevalence, improved anthropometric indicators of child nutritional status, and an 11% relative reduction in under-five child mortality (Pickering and Davis, 2012). Further travel distances tend to reduce water volumes collected, reducing sanitation and hygiene, and expend extra energy and bodily strain. A review of 21 studies showing that water quantity on its own is an important determinant of health (Stelmach and Clasen, 2015). Time costs form a majority of costs of coping for poor water supply, with household members in a study in rural Kenya spending an average of 2-3 hours per day collecting water, with median total coping costs approximated at 20 USD per month, which is greater than 10% of the income for more than half of the study sample size (Cook et al., 2016). As shown below (Section 2.5.7), a potential benefit of smart meters is a reduction of collection time from water points, and this is examined in detail in Chapters 5.

2.2.6 Understanding rural water supply in sub-Saharan Africa as a wicked problem

Rural water supply in sub-Saharan Africa is evidently a complex challenge. This complexity is further elaborated below. Such complexity is unique to its own local environment. Framing this complexity in both technical and social realms has allowed researchers to examine the possibilities of large-scale systemic change (Casella et al., 2015). Technically, there are limits to information, and existing knowledge systems have uncertainties. An example of this is limitations to data on infrastructure. Socially, coordination between actions, stakeholders, and information across disciplines, scales and sectors is difficult. Therefore, simple solutions such as 'build more water points' are not sufficient, and have been shown as such, as discussed below.

'Systems thinking' has recently come to the fore (Huston and Moriarty, 2018; Lockwood, 2016). Working at a systemic level can address the holistic web of factors that lie behind inadequate rural water supply (Liddle and Fenner, 2017), and is more in line with new paradigms of thinking about water resources as part of a human-technology-environment complex adaptive system (Pahl-Wostl et al., 2011). A focus on the interactions between factors within this complex system is argued to provide more effective strategies to improve service sustainability (Valcourt et al., 2020). 'Systems strengthening' with smart meters is investigated in Section 9.6.

The concept of 'wicked problems' (Rittel and Webber, 1973) applying to rural water supply has been hinted at in policy-focused literature (Casella et al., 2015; Suleiman and Khakee, 2017) however has not been explored further. The concept has been used across disciplines where problems are intractable and more holistic approaches are required. Global climate change is accepted to be an exemplary contemporary wicked problem (FitzGibbon and Mensah, 2012). Here, rural water supply in sub-Saharan Africa is critically tested against the key properties of ‘wicked problems’, presented in Table 2.4.

Table 2.4. Rural water supply as a ‘wicked problem’

Properties of a wicked problem	**Explanation**	**Does this apply to rural water supply in sub-Saharan Africa?**
There is no definitive formulation of a wicked problem	Problem understanding and problem resolution are concomitant	Yes. Diversity and uncertainty of stakeholder understandings over different scales and timeframes. It is a complex adaptive system (Butterworth et al. 2010).
Wicked problems have no stopping rule	There can always be better solutions	Yes. Underpinning development/environment trends will keep changing rural water supply requirements and pressures.
Solutions to wicked problems are not true or false but good or bad	Judgements will vary between stakeholders	Yes. Positives for some may be negatives for others, or may influence factors beyond the system.
There is no immediate and no ultimate test of a solution to a wicked problem	Any solution will generate waves of consequences beyond the present	Yes. System complexity, pace of progress and length of time scales means a solution would alter future systems.
Every solution to a wicked problem is a ‘one-shot operation’ because there is no opportunity to learn by trial and error; every attempt counts significantly	Every implemented solution is consequential and irreversible	Yes. Solutions would directly influence water users’ lives, the environment and future planning, as shown with previous attempted solutions.
Wicked problems do not have an enumerable (or exhaustively describable) set of potential solutions, and there is no well-described set of permissible operations that may be incorporated into the plan	No solution may be found, or more potential solutions arise following one	Yes. Varying situations and influence of rural water supply stakeholders keeps potential solutions re-emerging.
Every wicked problem is essentially unique	Always an additional distinguishing property	Yes. Changing developmental trends, unprecedented environmental change and unique settings.
Every wicked problem can be considered to be a symptom of another problem	Can be linked to a ‘higher level’	Yes. Demographics, poverty, environmental change or previous rural water supply management could be examples.
The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem’s resolution	The choice of explanation is arbitrary	Yes. There is no single correct explanation out of the multiple interconnected factors influencing rural water supply.
The planner has no right to be wrong (planners are liable for the consequences of the actions they generate)	Unlike science, the aim is directly to improve the world where people live	Yes. Solutions would have fundamental impact on rural water users in sub-Saharan Africa across different time-scales.

Rural water supply in sub-Saharan Africa is shown in Table 2.4 to be demonstrably a wicked problem. This provides a fundamental explanation of why actors have failed to achieve universal rural water supply service. This is important to establish at this stage to demonstrate that research in this field must be directed by systems thinking, including novel technologies. Wicked problems have many layers of social and technological complexity and no simple solutions (e.g. smart meters), and thus require dynamic, interlinked, and interdisciplinary solutions. Importantly, because there is no ‘stopping rule’, no solution or technology can reach an ‘end goal’ in rural water supply. Importantly, this also demonstrates that any attempt to address the problem of poor rural water supply is very ‘high stakes’ because it is consequential, irreversible, and must not fail. This includes smart meters. It is therefore crucial (as argued in Section 2.5.7) to generate systemic understanding of smart meter operation, as attempted in this research.

Taken together, this evidence shows that rural water supply in sub-Saharan Africa is inadequate, and is a complex challenge contextualised within conflating developmental trends. Research on novel technologies must employ systems thinking.

2.3 Review of ineffectiveness of rural water supply delivery in sub-Saharan Africa: different models of management

Within the general context outlined, different technologies and management models have been applied to rural water supply. Failures have been underpinned by technical, social, political and economic challenges defined by the management model. Innovative approaches are now required.

2.3.1 Rural water supply systems technology

Rural water supply in sub-Saharan Africa has mostly been provided by simple and inexpensive technologies that can theoretically be installed, operated and maintained by poor communities who have limited access to external finance or maintenance. Technology choice is influenced by environmental, political, cultural, and socio-economic factors, and availability of technical skills, tools and spare parts (Harvey and Reed, 2004). Accordingly, suggestions that simplification increases sustainability and scalability (Lockwood, 2004) are generally true so long as these systemic factors are also considered. For instance, WaterAid has reported that operation and maintenance (O&M) significantly improved in case studies in Mozambique when communities selected the technology themselves (Breslin, 2003). Proposed requirements of rural water supply technology (Skinner, 2003) are:

1) Acceptability to the community regarding e.g. culture, environment, health,
2) Feasibility regarding e.g. local institutional, financial, social factors, and
3) Sustainability.

In Table 2.5, the variety of technologies mentioned throughout the reviewed literature are categorised using the JMP 'improved' and 'unimproved' definitions (JMP, 2017a).

Table 2.5. Different types of rural water supply technology

Improved facilities	Piped supplies: • Tap water on the premises • Gravity-fed systems • Small-scale pumped systems Non-piped supplies: • Protected springs • Handpump equipped boreholes and wells • Wind powered borehole pumps • Solar powered borehole pumps • Motorized borehole pumps • Rainwater harvesting • Protected hand-dug well
Unimproved facilities	• Unprotected springs • Unprotected wells • Distribution of surface water

Researchers have tended to focus on handpump and borehole technology because of their prevalence (Harvey and Reed, 2004; MacDonald et al., 2005). The total number is unknown, but has been estimated at around one million, with 60,000 handpump installations per year across sub-Saharan Africa (Fisher et al., 2015). Some reliance on handpumps into the future is likely because of lack of piped rural water supply and increasing population (Hope, 2015). However, a tapestry of technologies underpin rural water supply in sub-Saharan Africa. These are outlined in Table 2.6.

Table 2.6. Different specific technologies used for rural water supply (from Baumann, 2003)

Technology	**Description**	**Cost of construction (USD) in 2003**	**Estimated yield**
Hand dug well	Constructed with simple tools and lined with concrete rings	900 – 1,500	0.5 m^3 $hour^{-1}$
Hand drilled borehole	Constructed with simple drilling equipment, lined with PVC casing and concrete apron	600 – 1,200	0.5 m^3 $hour^{-1}$
Machine drilled borehole	Depths between 25–200 m. Requires geophysical surveys and hydraulic rotary rigs. PVC casing and concrete apron.	6,000 – 12,000	1–20 m^3 $hour^{-1}$
Upgraded family wells	Lined with fired bricks, and concrete apron and windlass	< 100 for upgrade	Variable
Direct action handpump	Based on a buoyant pump rod directly articulated by the user, water at the up and down stroke.	900 – 1,000	20–60 l min^{-1}
Lever action handpump	(e.g. AfriDev) with open-top cylinder.	900 – 1,000	1–5 m^3 day^{-1}
Diesel mechanised pump	Small diesel engine and generator driving submersible pump. Water storage required, with piped distribution network.	30,000 – 40,000	10–100 m^3 day^{-1}
Solar powered mechanised pump	DC-AC converter or DC-compatible motor. Water storage required to buffer against solar power variation.	30,000 – 40,000	10–50 m^3 day^{-1}
Wind powered mechanised pump	Rotor drives pump via gearbox. Typically applied to high heads.	40,000 – 50,000	3–50 m^3 day^{-1}
Rainwater harvesting	Collection using gutter from impermeable surfaces e.g. roofs.	150 – 5000	Variable
Gravity Systems	Piped and filtered from a spring source to domestic water point, public kiosk or tap.	100,000 – 300,000	Variable

Research in Burkina Faso has suggested that small piped water systems (PWSs) provide services cheaper per user than handpumps over their life cycle, and higher levels of service across rural communities (Pezon, 2015). Smart meters (e.g. eWater taps, Susteq) are based on distribution points of PWSs. PWSs also have the benefit of not relying on arduous, energy draining, and unhealthy pumping by users for each collection. Solar pumping is increasingly seen as the best option for PWSs. On the other hand, PWSs are unsustainable without professionalised management and post-construction support (Marks et al., 2018). All technology requires management.

The reality is that households often access water from a number of different sources for different reasons (Elliott et al., 2019). Therefore, the effectiveness of the technologies mentioned above cannot always be generalised. This is explored more in Chapters 6 and 7.

2.3.2 Dominance of community-based water supply management

New concepts of rural water supply came from the United Nation’s International Decade for Drinking Water and Sanitation (1980-90). The ‘community management’ model (incorporating analogues known as Village Level Operation and Maintenance (VLOM)) emerged as the dominant model throughout the developing world. Community management is based on infrastructure such as handpumps being donated by external agencies or government (the enabler) to communities. These communities then take on the responsibility of operation and maintenance (O&M), which is theoretically purchased from a service provider using revenue that is collected from water users. This is outlined in Figure 2.2. The accuracy of this diagram has been criticised (Mandara et al., 2013) for lacking feedbacks between actors and simplifying the village structures, context specific factors, and mechanisms for accountability.

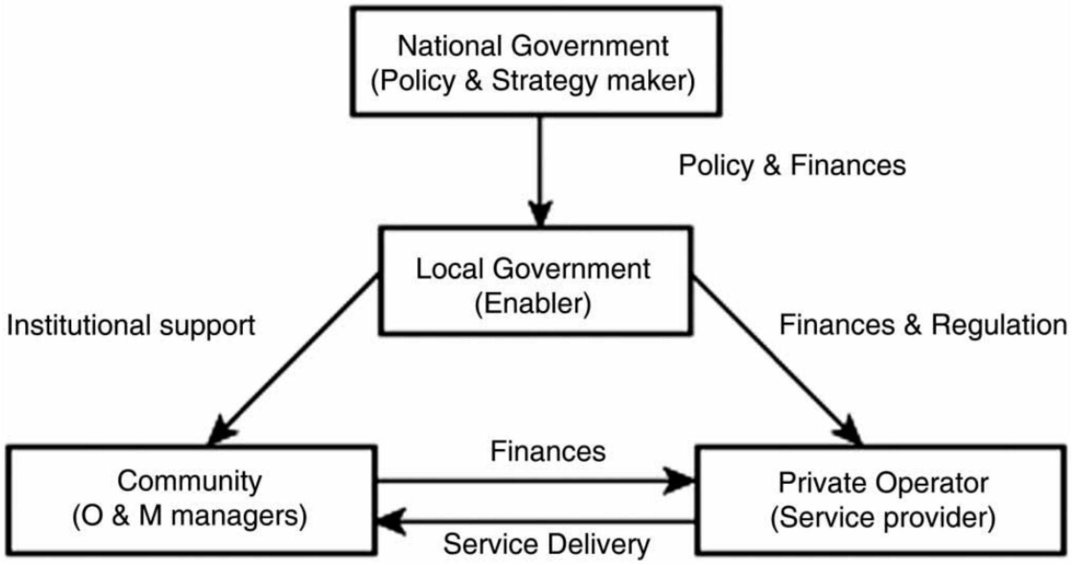

Figure 2.2. Community management model (from Harvey and Reed, 2004).

Community participation, community ownership, and willingness and ability of the communities to undertake O&M are underlying principles. The model was expected to lead to effective technical performance and financial sustainability (Chowns, 2015). Governments, donors, NGOs and institutions such as the World Bank supported the model for the respective reasons of reducing overstretched resources, bypassing government inefficiency and corruption, and reducing the size of the state (Schouten and Moriarty, 2003). It has been argued that it gained prominence as a reaction to central governments' failure, because of the neat quantification of donations with the NGO 'project cycle' approach, and because of prevalent hegemonic and homogenous-minded development theory (Harvey and Reed, 2006). Others agree, and point out that the later supplementation to community management by the 'demand responsive approach' (DRA) was underpinned by pervading neoliberal economic theory (Moriarty et al., 2013). The DRA includes community contribution to initial investment costs as an expression of demand and an indicator of community commitment to sustainability. Rather than a form of 'polycentric governance' (Ostrom, 2010), this was an abdication of responsibility by the state to the communities themselves. The persistent dominance of community management is shown by the lack of government spending on O&M. Globally, in 2011, only 31% of government funding and 7% of aid funding to the water sector went to O&M (Moriarty et al., 2013).

2.3.3 Limitations of community management

It is now argued by most researchers that the community management model leads to unsustainable rural water supply (Whaley et al., 2019; Tincani et al., 2015; Jones, 2011; Jiménez and Pérez-Foguet, 2010a; Hutchings, 2018). Management is a combination of technical, social and financial components, of which community themselves have inevitable limitations (Schouten and Moriarty, 2003). There is general agreement throughout the literature that the fundamental reason why community management is unsustainable is because of communities' lack of capacity (organisation and training) and finance, which is required for O&M. The main cost drivers of O&M are: 1) the technology chosen, 2) remoteness of the projects, and 3) the number of water projects under management (Gibson, 2010).

Without O&M, infrastructure breaks and stays broken. The proportion of non-functioning handpumps across sub-Saharan Africa at any time ranges from 10% to 67%, with a commonly cited average of around one third (RWSN, 2009; Baumann, 2006; Harvey and Reed, 2006; Andrés et al., 2018a), the most up-to-date estimate being one in four (Foster et al., 2020). Including handpumps that do not provide 'sufficient, reliable and good quality yield' can further reduce functionality rates by 50% (Fallas et al., 2018). One study on community managed handpumps in Mali found 90% were inoperable one year after installation (Harvey and Reed, 2004). Another evaluation of 23 projects across sub-Saharan Africa reported that despite standard installation and infrastructure, fewer than half of the projects meet the needs of beneficiaries (WWAP, 2015). A study across 200 villages in Ghana showed that 58% of non-functional handpumps had broken down in the previous six months, tending to take between 18-20 days to repair (Bakalian and Wakeman, 2009). In piped distribution systems, the issue tends to be service falling below an expected level of performance, rather than complete failure.

Lack of finance from poor community revenue collection is a significant determinant in rural water supply sustainability. In Malawi, reported average savings of community management committees were 2% of expected amounts, resulting in slow and sub-standard O&M (Chowns, 2015). Only approximately

30% of rural households were thought to pay for water in sub-Saharan African countries in 2009 (REACH, 2014). Findings from 92,594 water points show that three in five are not accompanied by revenue collection of any kind, with only one in five communities regularly saving funds for O&M (Foster and Hope, 2016). Payment compliance and good financial management are consistently demonstrated to be a key factor of service sustainability (Foster, 2013; Marks et al., 2018; Olaerts et al., 2019; Fisher et al., 2015; Walters and Javernick-Will, 2015). Additionally, revenue collection halts while water points are non-functional, often resulting in a downward spiral. Furthermore, this lack of payment can be predicted by the factors of water quality, rainfall season, and productive water use, further emphasising the need for systems thinking. A critical mass for stable levels of revenue collection is reported to be reached in one case in Kenya when more than 60% of water users are paying (Foster, 2017).

There are additional explanations for community management failure. Some researchers propose that perception of ownership of the technology or management system plays a role (Harvey and Reed, 2006), and others believe that reliance on voluntarism and its inherent informality is more to blame (Hutchings et al., 2015). Poorly considered scales of projects compared to the sizes of communities have also been blamed (Kleemeier, 2000). The homogeneity of the model is flawed (Hope et al., 2012b), and this suggestion aligns with the criticism of Western ‘cultural idealisation’ of communities (Harvey and Reed, 2006). Seasonality of water resources can also have a significant effect on community committee activity and O&M (Kelly et al., 2018) (seasonality is further investigated in Chapter 7).

Community management has been shown as the least preferred option for rural Kenyan communities (Hope, 2015), and community participation is through payment rather than citizenship (Jones, 2011). Research from Mozambique suggests that community managed handpumps can reinforce existing social, economic and political divisions within a population (Van Houweling et al., 2017). Overall, functionality is in dynamic equilibrium between breakdowns and repairs, and management is the key rate-determining step (Fisher et al., 2015).

The failure of community management represents up to 1.5 billion USD in wasted investment over the last 20 years (WWAP, 2015; Breslin, 2003).

2.3.4 Limitations of ‘community management *plus*’

Level of O&M support to communities and involvement of other actors varies along a spectrum, and many adaptations of community management have been tested (Lockwood, 2019; Hutchings et al. 2015; Jansz, 2011). External support is generally associated with improved satisfaction, payment, and functionality (Miller et al., 2019).

‘Community management *plus’* (CM+) is based on a shared O&M responsibility between communities, local authorities and central government (Baumann, 2006). This might involve small repairs being carried out by the community and large-scale maintenance by local authorities. A doubling of handpump lifetime and a 90% increase in the number of functional handpumps is proposed, however these estimations remain not well substantiated. Furthermore, increased investment from more actors on different levels would be required. Considering community management was adopted by governments largely because they could reduce their expenditure and responsibility, this appears to be a fundamental limitation to CM+. Additionally, inefficiencies from multiple management levels are not considered. Furthermore, CM+ is still considered to have the highest levels of community involvement, shown in Figure 2.3.

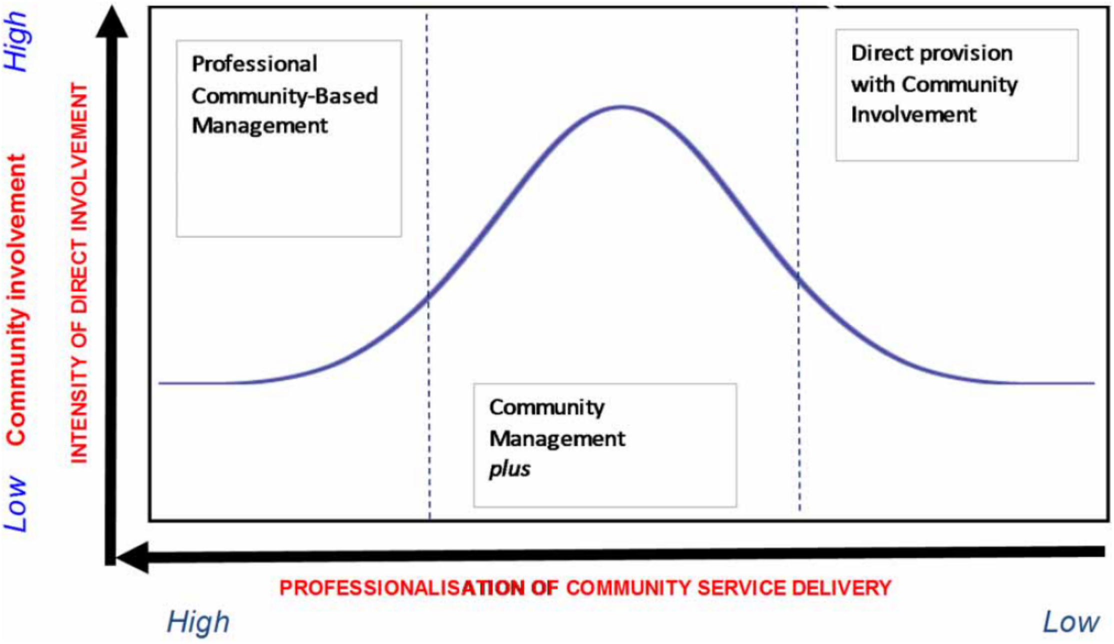

Figure 2.3. Community involvement across a spectrum of management models (from Hutchings et al. 2015)

There appears to be tension between community participation (which remains important for rural water supply) and professionalisation or increased local/central government involvement (which may involve the removal of the community from participation). It is found that out of 174 community management projects worldwide those that were most successful had financial, technical and managerial advice given to the community, and a degree of professionalisation; but also that success is directly related to broader socio-economic factors (Hutchings et al., 2015). Wealthier communities tend to engage more with professional management. This fits with the positive relationship seen between rural water supply sustainability score and national gross national income per capita ($R^2 = 0.51$) (World Bank, 2017a).

Overall, extra dependency of support from outside of the community does not fundamentally overcome the inadequacies of traditional community management.

2.3.5 Review of the service delivery approach

The ‘service delivery approach’ (SDA) (Moriarty et al. 2013; Lockwood and Smits 2011; IRC, 2015) offers a heterogeneous, adaptive, and professionalised management model that can move beyond reliance on communities themselves. Key features are a move away from voluntary arrangements, promotion of alternative service provision, and monitoring of service delivery. This follows from the reasoning that external support is required. The core tenants of the SDA are outlined in Table 2.7.

Table 2.7. ‘Building blocks’ of the service delivery approach (Lockwood and Smits, 2011)

1	Professionalisation of community management, moving away from voluntary arrangements
2	Recognition and promotion of a range of alternative service provider options including self-supply and public-private partnerships (PPPs)
3	Monitoring service delivery, infrastructure functionality, and sustainability using agreed standards
4	Harmonisation and coordination among donors, government and other actors in line with national policy
5	Support to service providers and any community management entities
6	Capacity support to local government or local service authorities in planning, monitoring, regulation etc.
7	Learning and adaptive management from national to local levels to allow for adaptation based on experience
8	Asset management including systemic planning, inventories and financial forecasting of assets
9	Regulation of rural services and service providers through methods appropriate for small scale operators
10	Financial frameworks to cover all life-cycle costs including costly maintenance and support to service providers

A ‘virtuous cycle’ resulting from the service delivery approach has been hypothesised by practitioners, described in Figure 2.4. This may be initiated once progress is made in one or two of the building blocks in Table 2.7 (IRC, 2015). These building blocks have similarities with the ‘WASH system’ building blocks investigated in Section 9.6.

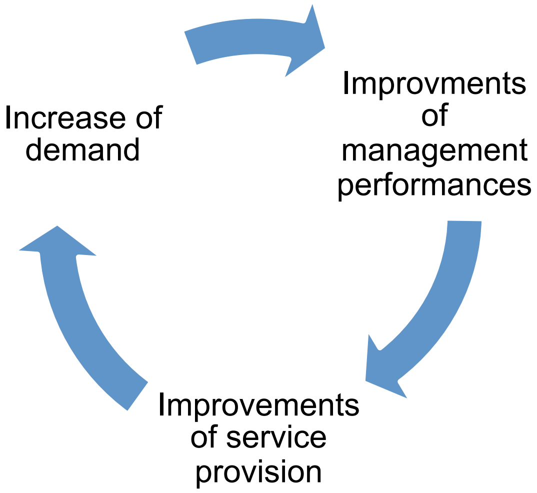

Figure 2.4. Positive feedback loop resulting from the service delivery approach (adapted from WSP, 2010)

Strong interest by governments to promote private involvement or public-private partnerships (PPPs) has been noted (Lockwood and Smits, 2011; WSP, 2010; van der Byl and Carter, 2018; Foster, 2012). This is perhaps because it offers an opportunity to progress beyond community management without governments themselves taking on considerable responsibility and costs. Participation of the private sector and resulting professionalisation can have a positive effect on financial management (WSP, 2010), however there is evidence that private water enterprises cannot be panaceas to rural water supply (Deal and Sabatini, 2020).

Potential limitations include financial feasibility with demand and supply variability, lack of regulation, and service inequalities (Brikké and Bredero, 2003). Wealthier communities should not be “siphoned off by private sector models that make the case for helping the poor even less viable” (Hope, 2015). Aspects of a service delivery approach should have the consent of the communities to avoid disempowerment.

There are a large range of different approaches and models for rural water service delivery and O&M across different settings, and these have been well reviewed (World Bank, 2017b; Aguaconsult and WaterAid, 2018; McNicholl et al., 2019; RWSN, 2019). The Rural Water Supply Network alone catalogues 14 models submitted to them by their implementers (RWSN, 2019). Collective management across many communities is proposed as a way to distribute risks and harness economies of scale (Hope et al., 2012a). For example, the ‘FundiFix’ model for handpump maintenance in Kenya (Hope et al., 2015) is based on professional services, sustainable finance from government, users and investors, ‘smart monitoring’ (discussed below), and institutional coordination.

A quick and simple transition towards SDA is unrealistic. There are three themes to this challenge (Lockwood and Smits, 2011):

1) Tension between the need for broad-based systemic change and the practicalities of localised incremental gains; change will not come through isolated projects and standalone solutions,
2) Some level of harmonisation and coordination between different actors is essential,
3) Change in approaches to rural water supply requires deep and country-specific political engagement.

Governments, donors and NGOs should invest in increasing professionalisation and support to local government, and clarify legal and institutional frameworks.

The move towards SDA can both facilitate and be facilitated by new technological innovations such as smart meters. Technological transitions can form an important part of ‘transition management’ (Kemp, 2007), going beyond just technology and incorporating changes in user practises, regulation, markets, industrial networks, infrastructure, and meaning (Geels, 2002). This is important to establish here as it shows that smart meters can possess catalytic potential for a more general transformation of service delivery.

In summary, inappropriate management has been a key limiting factor in the wicked problem of rural water supply. Successful rural water supply should not just be based on number of people covered, but also as a factor of sustainability. A move from community management to context-specific service delivery approaches can aid progress. Technological innovation will form an important part of this.

2.4 Review of rural water supply in Tanzania: country case study

In order to investigate the understanding from above more fully, specific factors that influence rural water supply in one country are reviewed. Tanzania has been the focus of a relatively high amount of published studies, and is the country focused on in Chapters 5, 6, 7, and 8.

Tanzania has an estimated population of 50 million people and a human development index (HDI) value of 0.538, ranking 151 out of 188 nations (UNDP, 2020). Population growth of over 3% per year has meant that absolute poverty levels have stagnated despite high economic growth rates of 6–7% per year over the previous decade. 68% currently live in rural areas. Poverty rates fell from 60% in 2007 to 47% in 2016 (JMP, 2017a), and the Gini coefficient is lower than the sub-Saharan average at 0.38 (World Bank, 2017a; UNECA, 2017).

2.4.1 Available water resources in Tanzania

Despite difficulty in measurement and significant regional variation, water security parameters are outlined in Table 2.8.

Table 2.8. Estimates of water security for Tanzania (WRI, 2017; MacDonald et al., 2012)

Baseline water stress Ratio of total annual water withdrawal to total available annual renewable supply	Low (<10%). Some regions of 10–20%, 20–30% and 30–40% exist.
Estimated groundwater storage Variable due to porosity and thickness of each aquifer	~5,250 km^3 (range: 2,040–17,900 km^3). Likely shallow storage <1,000–10,000 mm.
Estimated renewable groundwater availability	30 km^3 per year.
Groundwater stress Ratio of groundwater withdrawal to recharge rates. i.e. >1 could affect future groundwater availability.	Mostly no data.

Drought severity Calculated with drought length and soil moisture percentile from 1901–2008	Low to Medium. Small central region of Medium to High.

Despite low baseline water stress, the average volume of renewable freshwater per capita per year has declined from 7,862 m^3 in 1962 to 1,608 m^3 in 2014; an 80% decrease since the nation's independence (FAO AQUASTAT, 2017). This is attributed to agriculture and other water intensive activities (Komakech and de Bont, 2018).

Climate change is affecting available water resources in Tanzania, with uncertainty of impacts (Cisneros et al., 2014). A combination of 12 different Regional Climate Models (RCMs) predicts temperature increases of 1–2 ^{o}C by 2050 and 3–4 ^{o}C by 2100. Increasing precipitation in the rainy season and decreasing in the dry season is predicted (CLIVET, 2015). Groundwater may provide a buffer against this in the short term (Maurice et al, 2018), and this is investigated with seasonality in Chapters 7 and 8.

One study found rural Tanzanians reported decreased water availability for domestic and agricultural use, resulting in longer distances to walk to collect water (Kangalawe, 2017), likely resulting from a prolonged dry season (UN-Water, 2010). Reduced availability is significant for installation of new rural water supply systems and effectiveness of existing ones.

2.4.2 Ineffectiveness of rural water supply in Tanzania

The Joint Monitoring Programme (JMP) estimates of service levels are shown in Figures 2.5 and 2.6 (JMP, 2019[1]). There was improvement in drinking water service levels and water access recorded between 2000 and 2017, and large disparity between urban and rural populations remains. An estimated 57% of the rural population do not have at least basic drinking water access and 44% still use unimproved or surface water sources. Only 16% of the rural population with improved sources have it accessible on their premises, and 25% of

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[1] Also available from washdata.org

improved source users have piped water (JMP, 2019). Additional surveys have similarly found that 54% of households use unimproved sources for drinking water (Twaweza, 2017; Kwezi, 2017). PWSs are increasing and 80% of schemes implemented in the first phase of the Water Sector Support Project in Tanzania were pumped PWSs rather than handpumps (5%) or gravity schemes (15%) (World Bank, 2016).

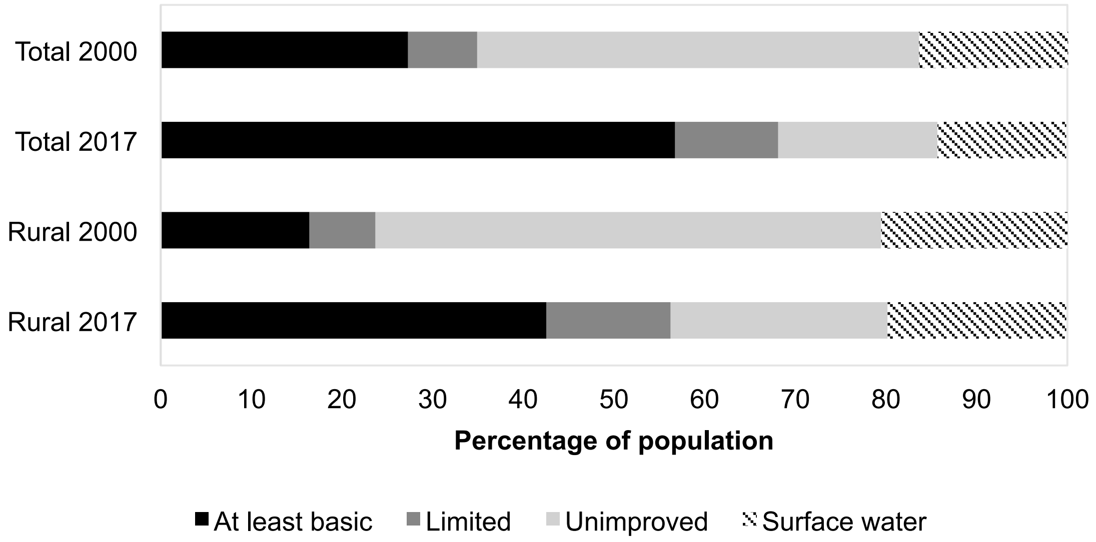

Figure 2.5. Proportion of Tanzanian population using different drinking water service levels

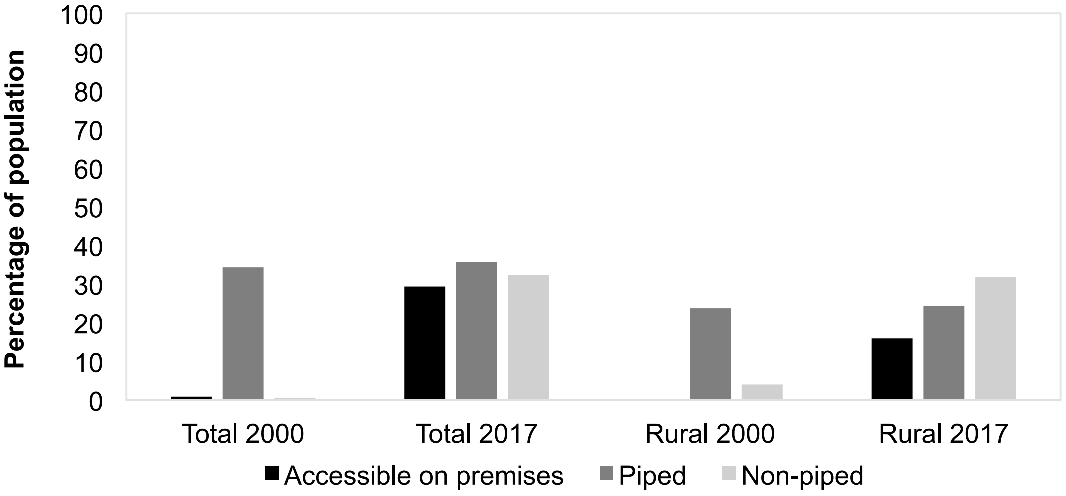

Figure 2.6. Proportion of Tanzanian population with improved water service using piped supply

The Government of Tanzania launched the Rural Water Supply and Sanitation Program (RWSSP) in 2006 with the aim of providing 90% of the population with sustainable and equitable access to safe water by 2025 (Jiménez and Pérez-

Fouget, 2010a; GoT, 2014a; 2016). 2 billion USD have been spent on rural water supply since 2006 (Twaweza, 2017), one of the highest amounts in Africa (Carlitz, 2016). Despite political ambition, rural water supply remains at a very low level. Tanzania has been ranked 10th in the world for people at risk of water insecurity in terms of water and sanitation (Sadoff et al., 2015). Table 2.9 shows how this compares to elsewhere.

Table 2.9. Availability of safely managed drinking water services (in 2017; JMP, 2019)

	Proportion of the population who use:	
	At least basic water services	Unimproved water sources
World	81%	14%
Rural Least Developed Countries group	55%	30%
Rural sub-Saharan Africa	45%	38%
Rural Tanzania	43%	44%

2.4.3 Factors influencing ineffective rural water supply service in Tanzania

In line with Section 2.2.2 above, developmental trends, specifically population growth, hinder efforts. It is estimated that for every new citizen provided with an improved water source there are two new citizens without access (Kwezi and Fonseca, 2017).

There is no definitive factor that the sustainability of rural water supply relies on. It is difficult for research investigating the many potential factors and their interrelation to move beyond generalised assessments and overviews. Aside from underlying trends, the most significant factor is thought by many to be the lack of emphasis on sustainability of existing water systems (Dickinson et al., 2017). Instead, spending is heavily weighted towards new capital investments (World Bank, 2018), with roughly 75% going on construction of new water systems between 2012 and 2015 (Kwezi and Fonseca, 2017).

Poor sustainability is evident in the high non-functionality of water points. It is estimated that 5.3 million people could be provided with improved water sources if the bulk of non-functional water points in Tanzania were made functional (Kwezi and Fonseca, 2017). Approximately 40% of the estimated 77,000 rural water points in Tanzania were non-functional, as assessed by the Ministry of Water and Irrigation in 2015 (Impact Tanzania, 2017a). 45.2% non-functionality out of 65,535 water points has been calculated using Ministry of Water data from 2013 (Klug et al., 2017). The World Bank claims non-functionality is 39.6% (World Bank, 2017b), with another study giving 33% non-functionality (Foster et al., 2020). The accuracy of these estimations is questionable and figures from the Government of Tanzania often do not correlate with other sources. However, the general finding is supported by other more specific studies. One study of 15 rural districts covering about 15% of the total rural population concluded that within the first five years of operation about 30% of water points became non-functional, and after 15 years only between 35% and 47% of the water points remained functioning, depending on the technology (Jiménez and Pérez-Foguet, 2011; 2010b). The most commonly cited detailed reasons for water system breakdown (Klug et al. 2018) are shown in Table 2.10:

Table 2.10. Common causes of water system failures in rural Tanzania

Damaged parts	59%	Pump (49.4%); pipe (22.5%); tap/spout (12.6%); valve (5.1%)
Not enough water	15.5%	Available water resources discussed above
Intentional harm	11.3%	Often cited but not well researched

These low water point non-functionality rates emphasises the importance of smart meter robustness, which is investigated in Chapter 4.

As outlined in Section 2.3.3 above, water point non-functionality is because of lack of O&M, and lack of finance or capacity curtails O&M. Only 42.1% of handpumps in Tanzania are estimated to collect revenue, and only 13.2% collect revenue when they become non-functional (Foster and Hope, 2016). Only approximately 25% of rural households in Tanzania paid for water supply in 2009 (REACH, 2014). Another study estimates that there is no fee collection in 61.6% of water systems (Klug et al., 2017), and that 85.6% of water systems are under community management. When there is a fee collected, 19% of times this is reactive to non-functionality and not from regular revenue collection. Water pricing varies between 1 to 4.6% of rural household income (World Bank, 2017b), and 10% of Tanzania's population spend more than 5% of total annual expenditure on water services, which is far higher than other countries in sub-Saharan Africa (JMP, 2017a). Barriers to O&M are increased by the fact that 80% of new water systems constructed since 2012 have been motorised (World Bank, 2016), which are more costly and complex to maintain. Other factors are inequitable service provision, lack of financial transparency, lack of monitoring, and lack of ownership.

As elsewhere, Tanzania has followed a path towards the decentralised community management model. The National Water Sector Development Strategy (2006-2015) called for decentralisation of water supply management 'to the lowest appropriate level' (GoT, 2006). Management is typically done by Community Owned Water Supply Organisations (COWSOs), recognised in sector policy. The District Water Department (DWD) and the District Water Engineer (DWE) are representatives of the local government and are responsible for the administration and coordination of rural water supply throughout the different villages in the district.

The failing of community management is considered by some researchers the main reason for non-functionality and lack of O&M in Tanzania for the reasons described in Section 2.3.3 (Mandara et al., 2013). O&M therefore becomes impossible. The water points managed by village committees have been demonstrated to have a significantly higher likelihood of failure compared to those managed by private operators or water authorities, regardless of hydrogeology, infrastructure, and other factors (World Bank, 2018; Cronk and Bartram, 2017). There is a lack of trained technicians available, and also a significant lack of resources in the DWD. On average, each DWD has only 10 staff with less than 2% of the local government's budget, and is responsible for 634 water points in 80 villages servicing 265,000 people (Impact Tanzania, 2017b). An administrative disconnect is also reported between local government and the COWSOs, and functionality decreases in more remote districts where DWDs are responsible for more water points. Counter intuitively, a negative correlation was found between available budget and functionality, perhaps highlighting poor spending practises or corruption. Political influence is also evident; a statistically significant trend of water point construction during the lead up to elections can be observed (Impact Tanzania, 2017c).

2.4.4 Specific survey-based studies

A range of small-scale questionnaire-based survey studies have been conducted in rural Tanzania to examine these factors of sustainability at a smaller scales.

Questionnaires across six villages in the Rufiji District (n = 180) showed that the amount of maintenance and the number of spare parts are statistically significant factors for increasing sustainability, with pricing and time taken for collection also influential (Kyamani, 2013).

Surveys of 24 rural water supply projects in the Bahi and Chamwino Districts (n = 136) found that the water point users did not feel sufficiently involved in decision making around technology choice and pricing, and a high correlation ($R^2 = 0.92$) exists between technology choice and project sustainability (Toyna, 2015). 60% of village leaders were unsatisfied with how the technology was operating. Interviews and questionnaires in Lushoto District (n = 100) also found that communities were not involved in decision making around planning, monitoring, or evaluation, because of poverty, poor leadership, and contradictory approaches of different agencies (Mdendemi, 2013). The study also reports that participation only benefits sustainability when other elements of sustainability are considered during the early stages of the project. Research in Mali has reported similar findings (Jones, 2011).

Semi-structured interviews in 38 villages across the Dodoma and Singida regions found that revenue collection was inefficient and improved when a private operator was introduced, and that poor financial management was the primary cause of non-functionality (Haysom, 2006). This study was conducted at the early stages of the now widespread critique of community management (as above), and the need for full cost-recovery via revenue collection is now emphasised.

Surveys across rural Tanzania using mobile phones revealed additional factors (Twaweza, 2017). 43% of households take under 30 minutes round trip (‘basic’ service; Table 2.2), 19% between 30-60 minutes, and 38% longer than 60 minutes. In 80% of households women or children undertake collection. Respondents emphasised distance and number of water points more than sustainability and functionality, likely as they are of more immediate concern.

Conclusions from different specific survey-based studies vary. This further demonstrates the complexity and heterogeneity of the rural water supply challenge.

2.4.5 Limitations to understanding rural water supply in Tanzania

1) Survey studies can examine a specific study area in depth at a specific time, and collect information from communities themselves, revealing more hidden factors around gender, communal power structures and cultural influences. This includes experiences of community members (Young et al., 2019). However, such an approach is limited to the understandings of communities and water users only, whose insight only comes from their own interface with rural water supply. Important systemic aspects will likely stay unmentioned. Additionally, such surveys can only occur periodically, typically as part of small-scale, short-term research. Reporting biases, overestimation, and subjectivity are widespread in surveys around water and sanitation (Thomas et al., 2013). Further, surveys are often primary indicators for measuring progress, especially with sanitation and hygiene programmes, despite being poor proxies (Turman-Bryant et al., 2018). The reliance on survey-based studies is a limitation in the literature. Methodologies that collect more overarching insight are required for a fuller understanding.
2) It has been challenging to accurately measure existing water point numbers, locations, functionality, and associated management, at scale. This is because of the scale, the changing system, and lack of emphasis on collecting and reporting data. Such data would allow for effective and timely monitoring and evaluation of rural water supply (Dickinson et al., 2017; Kwezi, 2017). This would benefit the shift towards a service delivery

approach outlined in Table 2.7, particularly requirements 3 (monitoring) and 6 (capacity support).

3) While some researchers attempt to assess the impact of factors, less work has been explicitly focused on the interconnectedness of factors. This lack of systems thinking is inherent in why progress on rural water supply in Tanzania has been limited despite the amount of spending and political will. In order to understand interconnect between factors, reliable and accurate data is required.
4) Efforts to improve rural water supply from the wide range of actors have often had limited focus on reporting and monitoring, and have been very heterogeneous.

Additional forms of knowledge are required to better understand rural water supply in sub-Saharan Africa including Tanzania.

2.4.6 Expert stakeholder interviews conducted for this review

Expert stakeholder interviews were conducted as part of the literature review stage of this PhD research in order to supplement the available understanding from the published survey studies above, and their synthesis published in Ingram and Memon (2019). Added benefits of expert interviews are that they generate knowledge that is not limited to users or particular case studies, and they increase diversity of the knowledge (Noxolo, 2017; Esson et al., 2017). Perspectives of local stakeholders from Tanzania are important for understanding complex systems that are hard to explain with quantitative data alone (Valcourt et al., 2020). Expert interviews have shown value as practical starting points of research and in reviews of current understanding. As part of this literature review, they provide useful further insight into the complexity of rural water supply in Tanzania.

Methodology: Expert knowledge can be used in an ad-hoc way, which renders its contribution un-acknowledged, non-transparent, and potentially unreliable (Drescher et al., 2013), or used as to rigorously collect empirical data for inputs into modelling activities (Voinov et al., 2016). For the expert stakeholder interviews conducted for this review, expert knowledge is used instead to raise information not uncovered in the literature, and to identify content and opinions (FAO, 1990). Rigour and practicality were balanced.

Eight expert interviewees were selected with officials having experience of working with rural water supply in Tanzania. An attempt was made to include experts with ‘well-contextualised’ knowledge (Drescher et al., 2013) and to represent a diverse range of backgrounds (Voinov and Bousquet, 2010). Profiles of the experts were anonymised and are reported in Table 2.11. Average experience was 10.1 years. A semi-structured interview questionnaire was designed to generate quantitative and qualitative information on expert opinion (FitzGibbon and Mensah, 2012; FAO, 1990). Questions were generated after the above understanding from literature, and categorised into ‘access to rural water sources’, ‘infrastructure’, and the ‘management of rural water supply’. These are outlined in Table 2.12. 16 different factors that influence effective rural water supply in Tanzania were inferred from findings from the literature and expanded to explore other concepts. To generate empirical data, experts were asked to rate how ‘true’ they considered objective statements on a scale of 1 to 5 (5 = strongly agree). Experts were also asked to rate how ‘aware’ of each factor they are in their work. Open-ended interview questions were then used for each factor to allow participants to ‘say what they think’ (Oppenheim, 2000), thus revealing new information.

Ethical principles were adhered to: permission for each interview was obtained beforehand, and each respondent was made aware that responses are personal and not organizational viewpoints, and each gave permission. Each was informed that personal details will be kept confidential and destroyed following research completion, that responses would be aggregated and averaged, and names deleted for analysis onwards. University of Exeter ethical guidelines were consulted and no further ethical implications were found. Opinions are considered equally weighted in this analysis.

Table 2.11. Profiles of experts interviewed, in order of interview

Respondent	Nationality	Job description
Expert 1	British	Regional manager of rural water supply technology company in Tanzania
Expert 2	Tanzanian	Technical engineer and designer of rural water systems, regional civil servant
Expert 3	British	Consultant for a major donor embedded in Tanzanian Ministry of Water providing technical support
Expert 4	Italian	NGO regional director and rural water project manager
Expert 5	Tanzanian	Manager of regional government agricultural agency and partner in local rural water project
Expert 6	Tanzanian	Country director of water development company
Expert 7	Tanzanian	Engineer in District Water Engineer (DWE) office
Expert 8	Tanzanian	Regional programme manager for major international water charity

Results and Analysis: The significance of different factors is indicated by answers to the ‘truth’ of statement across the eight experts, and the amount of consideration of each factor is given by ‘awareness’, both reported in Table 2.12. Further statistical analysis is inappropriate. Additional information brought up is included below.

Table 2.12. Ratings of experts of different factors (1 = strongly disagree, 5 = strongly agree)

Potential factor	*How true is this statement? (1-5)*					*How aware are you of this factor? (1-5)*				
	Number of respondents who selected each rating is represented by the area of each circle									
Access to rural water sources:	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
B1.1. The average distance of travel for users from households to water sources is too long			●	•	⬤		•			⬤
B1.2. The overall number of water sources in rural Tanzania is too low		•	●	•	⬤	•		•	●	⬤
B1.3. Water points are too densely concentrated within communities	⬤	●	●					•	⬤	●
B1.4. There is significant variation across Tanzania of the effectiveness of rural water supply			●	•	⬤	•			⬤	•
Infrastructure:	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
B1.5. The focus on building new infrastructure outweighs focus on maintenance of existing infrastructure	•			•	⬤				●	⬤
B1.6. More new water infrastructure should be constructed in rural communities	•			●	⬤			●		⬤
B1.7. Not enough capital investment is available for rural water supply	●	•		●	●			●	●	●
B1.8. There are not enough trained technicians with sufficient capacity to sustain the rural water supply system		●	●	•	●			●	●	●
Management of rural water supply:	*1*	*2*	*3*	*4*	*5*	*1*	*2*	*3*	*4*	*5*
B1.9. 'Community management' remains the predominant model			•	⬤	●			•	⬤	●
B1.10. 'Community management' does not always work	●	•	•		⬤			•	●	⬤
B1.11. Inefficiencies in political and bureaucratic processes make progress more difficult				●	⬤			●	●	⬤
B1.12. Sustainability of rural water supply is suitably considered in new or existing projects	•	●	•	•	●			●	⬤	●

B1.13. Climate change and environmental change is reducing available water resources in rural Tanzania			●	•	⬤		●		•	⬤
B1.14. More willingness of rural communities to pay for rural water supply would result in more sustainable rural water supply		•			⬤			●		⬤
B1.15. The effectiveness of rural water supply is defined by a combination of multiple factors more than it is by specific individual factors				●	⬤			•	⬤	●
B1.16. Technical innovation within the rural water supply system will add nothing; progress lies in addressing the above factors more effectively	●	●	•		•	•			⬤	●

- Constraints to access to water points for rural Tanzanian communities is evidenced by significance of the long distance of travel and low overall number of water points (factors B1.1 and B1.2). While there is variation across Tanzania (B1.4), generally there are not enough water points to serve the needs of communities. This is supported by the common viewpoint that more water infrastructure should be constructed (B1.6). New infrastructure is still required in an estimated 5,000 communities according to Expert 3. The emphasis of construction over O&M (B1.5) suggests a disregard for sustainability, which is common across sub-Saharan Africa as discussed in Section 2.3. This is reasoned by some respondents to be because it is easier to build new, and that COWSOs tend to want new infrastructure
- Some respondents suggest that there is an overall lack of capital investment (B1.7) in rural water supply in Tanzania. However, most of the respondents suggest that funds with donors and other partners are not the limiting factor, which is instead inefficiency of spending and low value for money.
- There is strong agreement among respondents that community management remains the predominant model in Tanzania (B1.9). Variance of opinion around whether it works (B1.10) is the highest among the factors, and this arises from different opinions on what constitutes community management. For instance, respondents who suggest it can work caveat

this with reasons that correlate with more support or professionalization. No counter-evidence to the limitations of community management outlined above was provided.

- General agreement that global environmental change is reducing available water resources (B1.13) is added to by some respondents' suggestions that human-induced factors such as over-grazing of cattle and local deforestation are equally (if not more) significant for water resource protection. Observed changes to local precipitation were highlighted resulting in some reduced water availability. The lack of available water resources as a cause for some non-functionality is emphasised by some experts.
- The strongest agreement among factors is from inefficiencies in the political and bureaucratic process (B1.11). Sustainability is suggested to have strong emphasis at higher levels of the governance hierarchy (B1.12) but takes time to filter down to the district level. To this end, the potential benefits to sustainability of public–private partnerships were emphasized by some of the respondents, and such partnerships are relevant for ICT technology providers. High agreement and awareness around willingness to pay (B1.14) aligns with the literature findings that revenue collection leads to sustainability (Foster, 2013).
- Agreement across respondents that multiple factors are important (B1.15) further demonstrates the complexity of the challenge. Each respondent emphasized different factors as more important. However, some factors emerged as more significant overall. These include political will, community payment and revenue collection, accountability of payment, the variability of circumstances within which different local authorities operate, and lack of funds.
- These same key factors in Tanzania have the potential to be addressed by ICT innovations. One respondent suggests that technological innovation (B1.16) should precede change in social and management structures, while another suggests that change in management must come before technological innovation otherwise technology will not address the root causes. In reality, iterative and symbiotic development of both is required (discussed in Chapter 9).

A major conclusion from these results from Tanzania and the literature on both Tanzania and sub-Saharan Africa is that there is dramatic complexity among different factors, and uncertainty about extents, explanations, and impacts of these individual factors. This further evidences the ‘wicked problem’ nature of rural water supply outlined in Section 2.2.6. Research has remained focused around individual factors, which risks missing the cross-factor potential that novel ICT innovations bring.

Limitations of expert interviews: More experts with a wider range of profiles would have provided more reliable results and information. Subjectivity of opinions cannot be accounted for in this approach. Overall, the additional insight demonstrated the worth of expert interviews.

2.4.7 Complexity and uncertainty of rural water supply factors in Tanzania

Despite considerable funding and political effort, rural water supply in Tanzania remains ineffective. The reason for this lies in the complex interplay between heterogeneous factors, as examined throughout the literature and expert interviews.

Some prominent, interlinking factors are:

- Underlying developmental trends such as population growth and decreasing water availability
- Lack of emphasis on sustainability of existing rural water systems, and non-functionality of rural water systems because of lack of O&M
- Emphasis on building new infrastructure over maintaining existing infrastructure
- Ineffective and unaccountable revenue collection
- Lack of trained technicians with sufficient capacity and spare parts
- Persistence of community management
- High capital investment requirements and recurrent costs for the community
- Poor community participation
- Lack of support or capacity from local government or other external partners
- Negative political influence
- Poor pricing structures and low willingness to pay

- Number and positioning of rural water points available, and distance from water points that users must travel
- Inappropriate choice of technology
- Inefficiencies in political and bureaucratic processes.

It is shown in the literature included in this review (e.g. Mandara et al., 2013; Cronk and Bartram, 2017; Lockwood and Smits, 2011; Aguaconsult and WaterAid; 2018) and by the expert stakeholders interviewed in Section 2.4.6 that there is a great deal of complexity amongst the factors listed above, and there is uncertainty about magnitudes, explanations and impacts of these factors. Linear attribution of factors is inappropriate. One reason for the limitations to understanding is that research tends to remain focused on existing and preconceived thinking around factors, and there is limited visioning of innovations in the system. How disruptive novel technologies, for example, can provide alternative solutions to existing challenges, as they have done in other sectors, has not been examined in the same depth. The methods and approaches previous research has had to rely on are another reason for these limitations to understanding. Water point mapping and country-level assessments have relied on low quality data sources. Survey-based studies have the limitations listed above.

With this in mind, two key, recurrent factors of rural water supply delivery and sustainability are:

1) ‘Monitoring’
2) ‘Revenue collection/financial management’.

These constitute two of the ‘building blocks for sustainable WASH systems’, discussed in Chapter 9. ICT, in particular smart meters, can address and improve both monitoring and revenue collection, in line with a service delivery approach. These two themes are investigated below. Such technology can help 1) progress beyond the limitations to understanding evident above by providing new methodologies, and 2) improve rural water supply delivery.

2.5 Review of ICT innovations in rural water supply

Innovation in rural water supply in sub-Saharan Africa is required. Technological innovations can help overcome limitations of complexity and uncertainty. Compared with management models, much less substantial debate has yet occurred around the role of novel digital technologies in rural water supply.

The World Bank (2017b) outline one of the key knowledge gaps for improving sustainability of rural water supply to be generating rigorous evidence through primary data collection. ICT has potential to record higher quality and useful data on aspects such as water collection volumes and water point failures, alongside socio-economic and environmental data. Embedded sensors can measure, record and communicate such information in real-time. They can also go beyond this. Here, mobile phone-based and Internet of Things (IoT) enabled technologies are reviewed, with a focus on monitoring and revenue collection, and current smart meter research reviewed.

2.5.1 ICT and the Internet of Things in development

Information and communication technologies (ICTs) such as mobile phones, high-accuracy sensors, and the Internet are increasingly used for development objectives (UNESCO, 2016; Hellström, 2010). Making the benefits of ICTs available to all is included in the SDGs (Goal 9, Target 9c), and ‘ICT4D’ (ICT for Development) has been a growth area of research.

Sub-Saharan Africa now has better telecommunication coverage than access to clean water, wastewater management, and reliable electricity. Rural sub-Saharan Africa is the fastest growing market for mobile phones, with 83% market penetration in 2012. An estimated 10% of Tanzania’s GDP is transacted via mobile commerce (Wesselink et al., 2015). While mobile connectivity for many remains expensive and slow, mobile phones are undoubtedly well-placed to serve needs of marginalised communities. For instance, ‘mobile money’ has expanded financial services to marginalised members of society across sub-

Saharan Africa (Suri and Jack, 2016), thus ‘leapfrogging’ traditional hurdles to development.

The rapidly emerging Internet of Things (IoT) is a globally connected information collection and communication infrastructure. Divergent definitions have been proposed for IoT, which incorporate machine-to-machine communication (M2M) and ambient smart environments (ITU, 2005). Important elements of the IoT are machine-produced data, usually using specific sensors, and its automatically initiated communication (GP Bullhound, 2015). An estimated 20-50 billion devices connected to the Internet are projected to be in operation by 2020 (UNESCO, 2016). IoT can facilitate monitoring that is highly accurate, accountable, timely, cost-effective, and high resolution, that does not rely on active data gathering. A ‘Data Revolution’ is expected to significantly contribute towards sustainable development (UNESCO, 2016; Stuart et al., 2015; UN-IEAG, 2014). IoT is already transforming utility models and improving access to basic energy, water and sanitation services in rural communities (GSMA, 2016; 2019).

Challenges to the effective adoption of ICT in development have been proposed (Pepper and Garrity, 2014). In Table 2.13, these have been expanded and categorised into technical and policy challenges.

Table 2.13. Challenges to effective adoption of ICT in development

Technical	Reliability	The durability of devices and their correct calibration
	Scaling	Limits to data storage capacity across all the devices
	Power	For usage, recording and communicating accurate/reliable data
	Connectivity	The coverage of the mobile network
	Costs	Could lead to inequality in deployment and use
	Human capacity	Training and understanding of operation or maintenance
	Behaviour	Reluctance or resistance to new technology and management structures in the short or long term
Policy	Sharing of data across borders	Limits to cloud-based storage and analytics
	Access to data/open data	Regulatory issues
	Publishing data	Legislation on confidentiality
	Broader governance issues	Interaction with national policy
	Intellectual property rights	The ownership of the collected data
Overlapping	Inter-operability	Compatibility with other sensor technologies
	Privacy and security	Regarding personal data
	Spectrum and bandwidth	Problem with high population density
	Uniform standards	Will need developing for a new technology

Perceived challenges to the adoption of IoT (and other ICT) technologies has led to nine ‘Principles for Digital Development’ being proposed as guidelines for ICT innovations. These are endorsed by over 300 development organisations (Digital Principles, 2020):

1. Design with the user
2. Understand the existing ecosystem
3. Design for scale (including a ‘systems’ approach to design)
4. Build for sustainability
5. Be data driven

6. Use open standards, open data, open source, and open innovation
7. Reuse and improve
8. Address privacy and security
9. Be collaborative

Privacy and security (8) has received particular emphasis because of the risk of 'datafication' of users and services by private operations in developing countries (Stuart et al., 2015; Oxfam, 2015; Knoblock and Manske, 2017; Taylor and Broaders, 2015; Mann and Lazzolino, 2018).

2.5.2 Application of ICT innovations for rural water supply monitoring and management

Monitoring of rural water supply is a systematic way of generating data, analysing it, and using it to inform action and decision-making, and this is integral to strong rural water supply systems. Up-to-date information is important for daily and long-term action and decisions. Three important economic benefits of quality monitoring data are highlighted (Hope et al., 2020): 1) accountability is enhanced in performance and sustainability of infrastructure investments, 2) planning can become more transparent, avoiding political influence, and 3) information asymmetry is reduced lowering financial risk for investors. Data collection of rural water supply, including water point mapping, is done from international to local levels, in a range of ways. It can underpin budgetary and investment allocation, the planning of construction, rehabilitation, and maintenance, and the assessment of progress and performance (Nyitambe, 2014).

However, data collected on existing water systems is often only used for summary statistics. Data relating to water points across rural sub-Saharan Africa tends to be incomplete, inconsistent and inaccessible. Only 6% of countries report surveillance at the required frequency (WHO, 2019). In Tanzania, the World Bank has called for more resources to go towards information and data collection and analysis to improve decision-making around water management (World Bank, 2017b).

ICT and the Internet of Things can overcome the limitations of previous methods of data collection (outlined above), and improve monitoring for rural water supply (Agenda for Change, 2020; GSMA, 2019; Kumpel et al., 2015; Hope et al., 2012b; Thomas et al., 2018). For instance, remote data collection could provide more accurate, accountable, timely, cost-effective, and higher resolution data, without the need for e.g. surveys (Turman-Bryant et al., 2018).

Monitoring the functionality of water points and systems, water flow, and water availability with increased frequency has the potential to support key parts of the service delivery approach. It is recognised that monitoring must move beyond the project-based monitoring and evaluation (M&E) paradigm and link to surveillance systems (Thomson and Koehler, 2016), and estimates of daily usage and revenue collection via ICT can facilitate a move away from spot-check monitoring. ICT can help overcome the previous limitation of the continual need to update inventories (Mannschatz et al., 2015). Furthermore, open data from ICT collection available to multiple stakeholders (e.g. regulators, service authorities, civil society) can strengthen accountability mechanisms (Welle et al., 2015; Schaub-Jones, 2013) and inclusive decision making, which are limited by lack of access to data (Boateng and Barstow, 2018). For users, this can increase financial accountability and enhance water security (Koehler et al., 2015). For authorities that aim to streamline data management there are also benefits.

ICT can contribute to improvements in revenue collection and managing assets. The three general aspects that require monitoring are: services required by users, performance of service providers, and the performance of the service authority (Lockwood and Le Gouais, 2014), and ICT can help monitor each. More detailed metrics could help improve evaluations of ‘payment-by-results’ schemes (McNicholl et al., 2019; Kwezi, 2018), adding pressure on service providers. Better data collection can help to better understand specific factors of sustainability of water services (Dickinson et al. 2017; Andres et al. 2018a).

ICT can also reduce the cost of monitoring. The average cost of continuous data collection in Ghana is estimated at around 0.05 EUR per person per year, with around 10,000 EUR per district, from labour, training, and external support (Adank, 2017b).

A number of different ICT innovations for rural water supply monitoring objectives using either mobile phones or IoT-enabled sensor-based technologies have been piloted, with varying degrees of success and upscaling (see the review below). There has been significant interest from sector professionals (hype and perception is discussed in Chapter 9), and some reviews and evaluations of these initiatives have been published, mostly as grey literature. Scope of reviews has stayed broad and has mostly focused on mobile phone-based innovations (Murthy et al., 2018).

One review of 40 mobile phone-based WASH (water, sanitation and health) innovations worldwide (Hutchings et al., 2012) shows that SMS reporting (short message service, i.e. text messages) is the most common data collection method, especially when water users reported the data themselves. Data analysis and dissemination has been done through:

- Web-based dashboards
- Web-based mapping that links water points with associated geographic locations
- Broadcasting or bulk SMS reporting out to a large group of users
- Interactive communication with concurrent collection, analysis and dissemination
- Other formats e.g. graphs, plots, spreadsheets and image media.

Another review (Dickinson and Bostoen, 2013; Pearce at al., 2014) shows that ICT innovations fit into five different steps of data/information flow. These are shown in Figure 2.7.

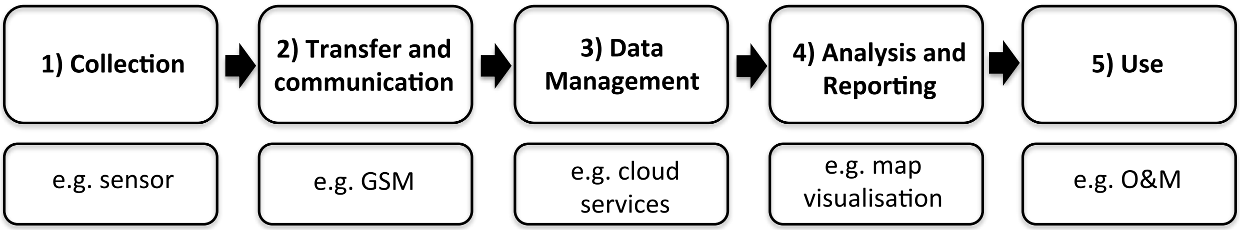

Figure 2.7. Steps of data/information flow of ICT innovations (adapted from Pearce et al., 2014).

Individual ICT projects do not tend to include all of these steps, and therefore ICT innovations are limited to 'islands of success', with many projects failing to collect, process or apply data effectively. There is not sufficient focus on how the collected data gets used, or the reliability of the data over the longer-term (Schaub-Jones 2013).

The joint importance of social design, technical design, and programme design are recognised (Mcgee and Carlitz, 2013; Wesselink et al., 2015). For example, even if technicians can be sent real-time alerts, they still require working mobile phones, network coverage, and capacity to conduct O&M. These components mirror the requirements for rural water supply sustainability outlined above, and inform the design of the research framework in Chapter 3. It is suggested that success is more likely if: 1) the data reporting is led by service providers rather than crowd sourced from the community; and 2) users prefer the data reporting system to previous methods (Welle et al., 2015). This suggests that ICT based solutions to sustainability become more appropriate as rural water supply moves towards a service delivery approach and increased 'professionalisation'; ICT innovations must also be designed to integrate with this shift (Williams et al., 2016). Social, technical, institutional, and programmatic design are all important. While socio-economic context is correctly deemed an important consideration throughout the literature, there is no evidence it is a barrier to success of ICT projects.

ICT has the potential for automated collection of enhanced technical data. Some argue that simple functional/non-functional information is insufficient as an indicator of sustainability (Carter and Ross, 2015; Kelly et al., 2018; Bonsor et al., 2018b; Fallas et al., 2018). Collection of data such as frequency of breakdown, time of non-functionality and time of maintenance, combined with narratives of non-functionality and O&M, would give a more nuanced understanding of sustainability.

ICT can only help in conjunction with strengthening monitoring capacity of stakeholders and frameworks of monitoring (system strengthening is discussed in Chapter 9). Additionally, ICT and IoT monitoring should not displace survey methodologies entirely, which still have a part to play regarding information that cannot be remotely collected, such as qualitative socio-economic factors.

2.5.3 Benefits to finance and payment systems from ICT innovations in rural water supply

Alongside monitoring, revenue collection and financial management is a key factor of rural water supply sustainability. Poor cost recovery is a major obstacle. About 61% of the African population does not pay for formal water services, and for those that do poorly designed tariff structures, low willingness to pay, and poor management of collection hinders revenue collection (Banerjee and Morella, 2011; Nyarko et al., 2007).

Some research has focused on systems of payment and revenue collection using novel ICT innovations. Digital payments are of increasing interest to service providers. A review across a range of service providers and utilities has shown that digital payments can reduce costs of revenue collection by 57-95% from savings of staff and vendors, and that revenues can be increased by 15-37% (Waldron et al., 2019). New technologies and automated data systems are argued to be a driver of sustainable service delivery through financial sustainability of service providers (Thomson and Koehler, 2016).

Many service providers across sub-Saharan Africa have introduced payment options that use mobile money. These have tended to increase timeliness of payment and operational efficiencies. Mobile money can allow direct financial flows to the service provider, coupled with direct and instant information flows. Socio-economic characteristics of users who pay with mobile money do not vary from those who pay by other means (Foster et al., 2012). Mobile payment platforms have been suggested to provide economies of scale with revenue collection and allow flexibility, which is useful considering rural income variability (Hope et al., 2012b).

Pre-payment for water supply is possible with some new ICT innovations, either with cash or loading a pre-payment tag/card (see below). Pre-payment has been considered as a “game changer” for revenue collection, affordability and access (Heymans et al., 2014). Elsewhere, users pay for water at each collection, on a subscription basis, or at unscheduled collection from a community water point operator. Analysis of 27 years of financial records for 100 communities in Kenya shows that ‘pay-as-you-fetch’ fees generate higher revenue and benefit from much better service levels than communities charging flat or monthly fees (Foster and Hope, 2017). Additionally, payment is made fairer as no user is able to relinquish responsibility for payment, which can lead to divisions within communities (Van Houweling et al., 2017).

Financial benefits of ICT are potentially significant. Pre-payment preferences are positively influenced by improvements in O&M and reliability of service (Koelher et al. 2015). Therefore, successful ICT innovation could result in a positive feedback loop where increased revenue collection leads to better service, which in turn increases revenue. This is shown in Figure 2.8. This is complimentary to the theorised service delivery feedback loop shown in Figure 2.4. Better monitoring also improves revenue and financial reporting tracking, and gives confidence to investors and funders.

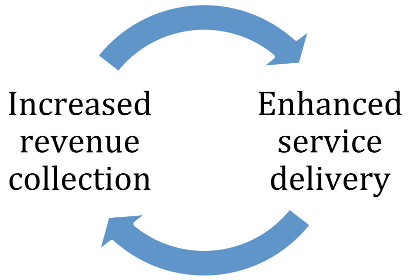

Figure 2.8. Proposed financial feedback loop from successful ICT application

Potential limitations to pre-payment include high capital costs with more expensive O&M, and inequality in access. Pre-payment water systems cannot fix underlying management, pricing, or technical issues. There are other significant determinants to payment; higher payments are associated with higher education and faster repair times, and payment choices are influenced by wealth, sex, seasonality (see Chapter 8), reliability of water point, and access (Hope and Ballon, 2019).

2.5.4 ICT innovations for rural water supply in sub-Saharan Africa

Here, a selection of ICT innovations designed for rural water supply in sub-Saharan Africa that are operational, recently operational, or partly developed are outlined. They are categorised (as per Pearce et al., 2014) into mobile phone based (seven) and IoT enabled (eight). Information was gathered from project promotional material and websites, with some recent peer reviewed journal papers and policy/practice reports. Some, in particular the IoT enabled innovations, have emerged over the last few years. Other examples not included are more focused on urban household connections (e.g. CityTaps, n.d.). Handpump IoT enabled innovations and smart meters are reviewed in Sections 2.5.6 and 2.5.7.

Mobile phone-based innovations:

Akvo Flow: Data collection and mapping software using mobile-based surveys allows users to take GPS coordinates, take pictures and videos, and fill out questionnaires regarding water point indicators. This information is then mapped and can be tracked over time. Community members and partners from 258 different organizations are currently using Akvo Flow (Akvo, n.d.).

Human Sensor Web: Water users and local water authority staff report functionality or water quality information via SMS. On non-functionality, a mass-SMS is delivered to registered community users, and data is disclosed on a dedicated website interface. Limits to upscaling were cost of SMS for community members, capacity of the data processing, and community uptake. Verbal or phone call reporting was preferred over the specific SMS codes required. A limited research endeavour on Zanzibar with 50 water points is no longer operational (Jürrens et al., 2009).

Maji Matone: SMS input from water users about non-functioning water points in Tanzania is sent to district water engineers and local radio and newspapers to publicise reports, inform users, and pressure water service providers. Only 53 SMS messages were received, and only 20 water points were repaired and the project closed. Users likely had low expectations of what O&M would be done and the SMS format was inappropriate for the users (mtega, 2013).

Mobile 4 Water: SMS input from water users about non-functioning water points in Uganda is sent to district water engineers. The message is transmitted to the Mobile 4 Water system, managed by the district water management office. The water service provider is alerted about the non-functionality who then dispatches a technician to conduct O&M. Four hundred previously unknown water points were identified but the project worked slowly and is no longer operational. It was not well tailored for the local context and users tended to phone technicians rather than text. Managers neglected to check for updates and data was not integrated with the national reporting system (Welle, 2015).

mWater: Customizable app-based mobile technology for data collection from field assessments. Provides a cloud-based data and survey management platform allowing real-time assessment. An interactive map using the online water point mapper tool allows users to customize exportable maps. This processing of data can highlight functionality, sustainability, equity, and planning factors. Other sources of data with GPS information can also be uploaded to water point mapper. Used by over 73,000 users in 175 countries to map and monitor water and sanitation sites, with 7 million sites mapped and 400,000 surveys submitted per month (mWater, n.d.; Feighery, 2020).

Pump for Life MSABI: Subscription-based water point O&M service in Tanzania. Payment of 5 USD monthly subscription per water point via mobile money. Focuses on rope-pumps with cheaper O&M costs. Water point data tracked using mobile phone inputs from technicians and used to monitor distribution and functionality of water points, and payments. Currently relies on community reporting of non-functioning water points but plans to integrate sensors for remote detection of non-functionality. 190 water points are included, with 48 schools and 38,000 clients. Over 8,000 O&M visits have been tracked (msabi, n.d.).

Uduma: Digital 'payment as you fetch' from water pumps from a caretaker/vendor, who used a point of sale device to deduct credit from costumers NFC (near field communication) cards. NFC cards are topped up with cash from the vendor or via mobile money (36%). Cashless payments are tracked providing efficiency, accountability, and data (GSMA, 2020a).

IoT enabled innovations:

Charity: Water, remote sensors: Sensors monitor flow from handpumps at regular time intervals. Consists of a stack of capacitance sensors that measures the physical water level in the wellhead to calculate flow, and is tailored to different handpump models. Data is mapped on a dashboard for analysis. Aims to monitor effectiveness of Charity: Water projects and improve response times for O&M, with 6,500 Afridev handpumps in sub-Saharan Africa (Charity: Water, n.d.).

eWater taps: Community standpipes of water distribution systems fitted with an 'eWater tap' by eWATERpay, that is operated with a contactless near-field communication (NFC) tag. Users load their tag with credit using a dedicated app, via mobile money, via a vendor, or at a pre-loaded tap. There is access to the water point throughout 24 hours. Usage data on functionality, flow rates, and revenue collection per individual user and tap are reported remotely to a cloud-based online dashboard and data management system. The service provider assesses non-functionality and usage patterns. Low-power requirements run by battery and small solar array (eWaterpay, n.d.). (This innovation is investigated more in Chapters 4 and 5, and described more in Section 3.2).

Grundfos AQtap: Water pre-payment 'ATM' operated with NFC 'smart cards' loaded with water credits with mobile money or via a vendor. Smart cards are placed on the 'ATM' to provide credit information, and a button on the ATM dispenses water. Can be connected individually or as part of a mini-grid to a

PWS with borehole (Grundfos is a major pump manufacturer) or a water network. Data are remotely reported for analysis (Grundfos, n.d.).

Lorentz smartTAP: Integrated solution of solar pumping (Lorentz is a major pump manufacturer) to a high-elevation tank that is connected to one or more 'smartTAP' water dispensers, which are operated using NFC tags that users pre-charge. Small battery supports solar power. Water credit is sold by a local vendor using a smartphone app, and data are remotely reported for analysis (Lorentz, n.d.).

MoMo (Welldone): 'Mobile monitor' with integrated flow sensor and GSM connection. Sensors collect flow data from rural handpumps in Tanzania. Data is aggregated and sent daily via GSM to a central server using a microSIM, or directly to stakeholders. Low-power requirements and solar power designed for long-term deployment. The modular platform design can be used with a range of sensors and communication media and is open source. Data is collected and managed using an online interface, which allows analysis over time. Strong mobile phone reception is required and one early pilot failed to transmit data because installation was in an area without adequate reception (MoMo, n.d.).

Smart Handpumps: Accelerometers attached to the handles of rural handpumps record pumping velocity and frequency, which is automatically transmitted via GSM to project operators. Non-functionality is recorded when low or no pumping is recorded over a set time, and O&M is triggered. Data is shared with the service provider, local government, and the regulator using a web-interface. In Kenya this has led to a 10-fold reduction in 'downtime' to three days, five times higher revenue collection, and fairer usage and payment. Strong links with local government and service providers have contributed to on-going success. The innovation has also been successfully coupled with 'clustered' handpump management solutions (Hope et al., 2014).

Susteq: Water kiosks (or 'ATMs') fitted with pre-payment meters operated using a contactless (NFC) tag. Water ATMs can support multiple pipe outlets, with a focus on kiosk/ATM hubs rather than individual DPs. Water users load the tag with credit, purchased with mobile money or from a vendor. Usage data are recorded and reported remotely and can be monitored using an online dashboard (Susteq, n.d.).

Sweetsense: Sensors attached to handpump heads continuously collect handpump performance and water flow data and communicate it back to stakeholders. Data can be communicated using Wi-Fi or GSM with a SIM card, with distributed processing between hardware and the cloud. Data are then integrated into an online database and dashboard for analysis. Notifications sent to stakeholders via SMS and email. Two hundred sensors installed on rural Rwandan handpumps in a pilot project demonstrated improved O&M response time by 86% relative to the existing management model (Nagel et al., 2015). Sweetsense sensors have also been deployed on borehole pumps in PWSs.

For the mobile phone based innovations that did not succeed, limitations of volunteer-based crowdsourcing data, along with community preference for phone calls over SMS messaging are demonstrated (Welle et al., 2015; McGee and Carlitz, 2013). Other mobile phone based innovations monitor rural water supply effectively, and have the potential to help facilitate a shift towards a service delivery approach.

In general, the mapping of data collected from mobile phone reporting is shown to have greater suitability for ‘transfer and communication’, ‘data management’, and ‘analysis and reporting’ of data. However, the extent to how they satisfy ‘collection’ and ‘use’ is limited. This is shown in Figure 2.9. For instance, mobile phone reporting is limited by the requirement and inaccuracies of input from either the community or other dedicated stakeholders. Overall, this group of innovations are limited to being facilitators for existing monitoring structures rather than being fundamentally transformative.

There are a range of IoT enabled innovations available for different types of water points or different settings. In general, these have greater suitability for the data ‘collection’ element because they do not rely on voluntary manual input. Embedded sensors remove both the need for manual input and potential reporting inaccuracies. Considering they are designed to address this problem, in general terms there is currently less emphasis at this stage on ‘data management’, ‘analysis and reporting’, and ‘use’, shown in Figure 2.9.

IoT enabled innovations designed for piped systems (eWater tap, Grundfos AQtap, Lorentz smartTAP, Susteq) share the same attributes and essentially provide the same functionalities of: tag-operated pre-payment, flow sensing, and remote reporting to a data management system. Differences lie in technical design (and therefore cost), operation, integration with the PWS, and deployment setting. Herein, this group of pre-payment IoT enabled innovations are referred to as ‘smart meters’.

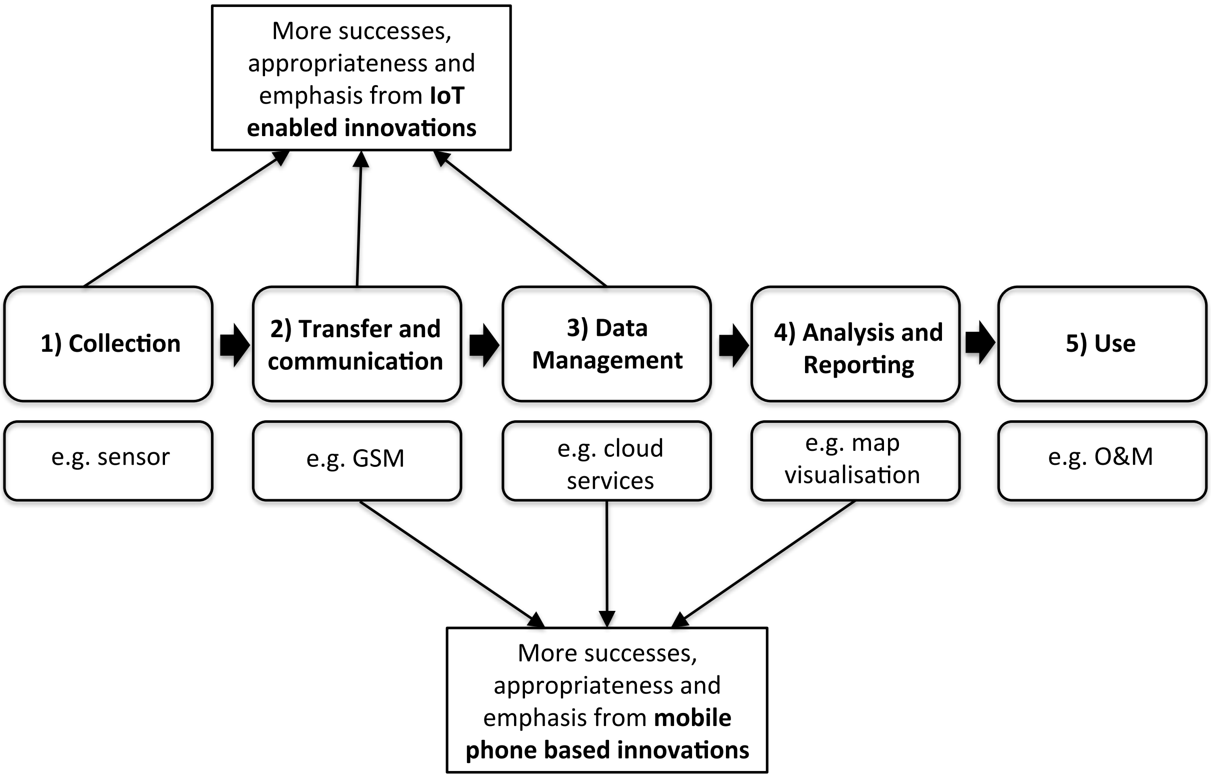

Figure 2.9. Different categorisations of ICT innovation show different areas of appropriateness and emphasis on Pearce et al.’s data/information steps

The ‘use’ step (Figure 2.9) appears to be the limiting step to improved rural water supply. Lack of use of data/information is also shown to be a limiting step for a four-year long ICT data collection project in Ghana (Adank, 2017a). Moving beyond simply assessing the performance of infrastructure to improving service delivery has been challenging (Dickinson et al., 2017). Multiple factors influence this such as uncertainty over which stakeholders have the responsibility for putting the data to use, and how the management system operates. As emphasised above, ICT on its own is not enough to improve service delivery or sustainability of rural water supply, and other factors are important. However, the use of this newly available data is a major research gap as shown below, and is investigated in the following chapters.

Monitoring from smart meters goes beyond mobile phone based innovations, as data collection is automated and continuous. Direct flow measurement is more accurate than flow measured by proxy handle or well-head measurements. One global review on smart meters highlights advantages and disadvantages observed in utilities elsewhere (Arniella, 2017). These have relevance for smart meters in rural sub-Saharan Africa, and this is shown in Table 2.14.

Additionally, daily volume collected data shows volumes withdrawn from PWS tanks, and therefore from boreholes. Despite the proposed sustainability of groundwater resources in sub-Saharan Africa shown in Section 2.2.4, smart meters could be used to monitor and better manage groundwater resources in some marginal instances where this is a concern (Bonsor et al. 2018a; Nigussie et al. 2018; Cobbing and Hiller, 2019). Indications of overall volumetric use from a specific borehole can very accurately show abstraction rates over time. If this is combined with known information on specific aquifers, this new smart meter information could indicate sustainability of supply. This requires adequate spatial and temporal resolution (Mannschatz et al., 2015). One setting where this application could be used to better manage water quality might be where coastal aquifers are used, and precise monitoring of abstraction with smart meters combined with understanding of a threshold of saline groundwater could indicate imminent reduction in water quality. Smart meters would only be a supplementary monitoring tool for these challenges, and solutions lie in further groundwater development and correct borehole siting. Future combination of water quality sensors with smart meters would allow for more accurate and automated management of water quality using smart meters, and this is discussed in the further work section (Section 10.2.1).

Table 2.14. General advantages and disadvantages of smart meters

Advantages of smart meters (Arniella 2017)	**Relevant to smart meters in rural sub-Saharan Africa?**
Lowering the cost of meter reading by eliminating manual meter reading	Yes. Remote data collection means service providers do not need to regularly travel to remote communities
Enhancing employee safety by reducing the number of personnel travelling	Yes. Fewer service providers need to travel
Reducing billing errors and disputes	Yes. Automated metering removes the potential of human error and increases fairness
Monitoring the water system in a timely manner	Yes. Real-time reporting of data
Enabling flexible reading schedules	Yes. Instant availability of information adds flexibility
Providing useful data for balancing customer demand	Yes. Data can be used for understanding demand and supply
Enabling possible dynamic pricing	Yes. Ability to dynamically price credit when needed
Benefitting the environment by reducing pollution from vehicles driven by meter readers	Yes. Reduced visits for meter reading
Assessing Non-Revenue Water in real-time or short intervals	Potentially, if calibrated against water tank level
Facilitating the data to establish night water consumption patterns and offering a more detailed feedback on water use patterns	Yes. High resolution information on water use patterns
Enabling customers to adjust their habits to lower water bills	Potentially. Depending on dynamic pricing
Providing real-time billing information, reducing estimated readings and re-billing costs	No. Pre-payment, not billing
Reducing customer complaint calls and increasing customer satisfaction	Potentially. Enhancing accountability and service provision
Improving the monitoring of potential meter tampering and water theft	Yes. Non-functionality and tampering alerts
Detecting water line leaks sooner	Potentially. If compared in real time to tank level or other DPs

Disadvantages of smart meters	
Front-end capital investment	Yes. Higher capital expenditure
Long-term financial commitment to the new metering technology and related software	Yes. Service providers and partners agree and commit
Ensuring the security of metering data and preventing cyber-attacks	Yes. Cloud based storage potentially vulnerable to hacking and misappropriation of data
Transitioning to new technology and processes with proper training	Yes. Full understanding and commitment required from all stakeholders
Managing public reaction and customer acceptance of the new meters	Yes. Community acceptability is fundamental to sustainability
Managing and storing vast quantities of metering data	Yes. Potential legal problem of data storage location, and practical problem of server infrastructure
Disposing of the old meters	Potentially. Smart taps tend to be the first meters

2.5.5 Evaluations of handpump IoT enabled innovations

The potential of two handpump IoT innovations included above to improve rural water supply has been evaluated in the peer-reviewed literature.

- Smart Handpumps (Hope et al. 2014; Koehler et al. 2015)
- SweetSense (Nagel et al. 2015)

Methods and results from these studies are critically compared in Table 2.15.

Table 2.15. Evaluations of handpump IoT innovations

	Smart Handpumps	**SweetSense**
Sensor and IoT technology	Accelerometer measuring handle movement. Microprocessor, batteries, GSM modem sending SMS messages.	Water pressure measured with differential pressure transducer. Batteries, cellular radio chip, SIM card, accelerometer.
Time resolution of data reported	Hourly reporting (Colchester et al., 2017)	Daily identification of non-functionality based on data collected every 60 seconds
Methods and study	Survey of use of 21 Smart Handpumps in rural Kenya, to	Sensors installed in 181 handpumps in rural Rwanda evaluated.

design	demonstrate failure rate and maintenance time, and payment level. Effectiveness of two maintenance models concurrently assessed over 12 months: 1) 'Crowdsourced' community reporting of non-functionality 2) Non-functionality alerts from Smart Handpumps used to coordinate maintenance. Time between non-functionality alerts and maintenance times (relative to the baseline) used to assess the effectiveness.	Effectiveness of three distinct maintenance models concurrently assessed over 7 months: 1) Community contacts service provider on handpump breakdown 2) Service provider makes periodic visits to handpumps 3) Real-time SweetSense data available to service providers First two models acting as 'controls' for sensor evaluation. Cost of different models also assessed.
Results	Twice as many repairs conducted on model (2) than model (1). Non-functionality alerts reduce mean non-functionality 'downtime' from a baseline of 27 days to under 3 (11.1%). A shift to 98% functionality of handpumps.	Model (3) reduces median non-functionality 'downtime' to 21 days, compared with the first model's 152 days (13.8%), and the second model's 57 days (36.8%). Financial cost approximately similar between three models.

Both studies compared maintenance capabilities of the IoT innovation against alternative maintenance models to evaluate the potential of reducing time of non-functionality of handpumps. The sensor technologies used are different, however the capabilities of reporting non-functionality are both adequate. The larger number of handpumps in the SweetSense suggests greater reliability. Both studies support the findings above by demonstrating high potential for IoT innovations to improve monitoring, data collection, and data reporting, and therefore help move towards a service delivery approach. Reduction of maintenance times are similar for each compared to baseline maintenance models (11.1% and 13.8%). Higher absolute maintenance times for the SweetSense handpumps are because of underlying management structures, showing that this improved monitoring information is only one component of improved service delivery.

There are some common limitations of the studies. Both operated with free maintenance models, which is not representative of the needs of rural water supply systems, as shown above. The potential that free maintenance contributed to successful results of the studies is not addressed. Both were limited by lack of detail on available water resources and other contextual factors. Additionally, neither study assessed the sustainability of the innovation or discussed how findings could inform future management models. Smart Handpumps did not report an additional unmodified baseline control group as SweetSense did, and the handpump sampling frame was not random. Alternative sources of water were not considered. SweetSense found that a high level of sensor maintenance was required during the study as the sensor casing was not appropriate and battery consumption was much higher than anticipated. These sensors are limited to proxy measurement of flow, which could bring inaccuracy (accuracy of smart meter measurement is investigated in Chapter 4).

Further research has also demonstrated how data from handpump IoT innovations can provide ancillary monitoring information. High-frequency 'noise' waveforms collected from the accelerometers and modelled using machine learning techniques have been shown to be able to estimate the depth of groundwater at a handpump, and classify whether a man, woman, or child is using the pump, with low overall errors, and also reveal information on groundwater use over time (Colchester et al., 2017; Thomson et al., 2018). Borehole measurements using Sweetsense sensors have also revealed information about drought in Ethiopia (Thomas et al., 2019; Short et al., 2018). This demonstrates that IoT innovations can lead to new research and monitoring opportunities beyond their original objectives. This concept is extended for smart meters in the following chapters.

2.5.6 Evaluations of smart meter innovations

Smart meters in households in the developed world have advanced data gathering, residential water demand modelling, user characterisation, and design of management strategies over the last two decades, and have been well reviewed (Cominola et al., 2015). However, new smart meter innovations in sub-Saharan Africa (especially in rural settings) have not yet received the same level of research attention. A new body of evidence has been emerging over recent years of the success of pre-payment smart meters in rural sub-Saharan Africa (most of this has been published during the work that is presented in the following chapters). Evaluations have been conducted in the grey and peer-reviewed literature, largely conducted by practitioners, and their findings are overviewed here.

An examination of how users would perceive potential installation of pre-payment water meters in rural Tanzania showed that existing water services are generally seen as poor, and that new pre-payment innovations would increase transparency, accountability and convenience (Sherry et al., 2019). Some reservations about mobile phone network reliability and marginalisation were expressed but outweighed by the desire for increased sustainability and 'modern' payment systems.

One shorter study investigated the impact of kiosk-based Grundfos AQtaps (n = 20) in Karatu district, Tanzania (Tonya and Mpangala, 2018). It reported that the technology enabled an average 201% increase in revenue collection, with a dramatic reduction in non-revenue water from reduced spillages and exact measurement. Each payment made by users was recorded, and users were confident in correct pricing. Downtime of water points was reported to be reduced from one week (based on testimonies) to less than one day, with an average of 30 minutes for a technician to attend a minor problem. 91-98% user satisfaction with the technology was reported, and the elimination of queue time reduced collection time. New opportunities for vending water credits and selling other products from kiosks were opened. Interestingly, the study reported high revenues in the dry season and low revenues in the rainy season (this phenomenon is investigated in Chapters 7 and 8). These findings demonstrate more positive results compared to an early evaluation in Uganda of a precursor to the Grundfos AQtap (Grundfos LIFELINK), which showed no increase in revenue and a financial deficit (Armstrong et al., 2013).

A recent report on the effectiveness of eWater taps in Babati district, Tanzania, reported similar findings (FLS, 2020): average time taken for collection of water 'plummeted', users collected more water, and water point accessibility went from 3-4 hours per day to anytime access. Revenue collection was reported to have increased by 341%, and local authorities benefited from time and cost savings from tracking operational data. The monitoring allowed for identification of faults in the PWS network, and O&M time reduced. It became apparent that the technology would not be financially sustainable without funding support. Issues were also noted of theft of solar charging panels, confusion from users on system operation and payment, and who had accountability for non-functionality of PWS components. These findings mirror findings from eWater taps in The Gambia (GSMA, 2018), where the importance of full community education around the new technology is also emphasised.

Another report of eWater taps (n = 78) integrated with existing purification and distribution systems in Ghana (GSMA, 2020b) reported saved time for users from quicker water collection, and better overall access to the DPs. The technology allowed target revenues to be reached in a short period of time, and non-revenue water to be drastically reduced. The proportion of payments made by mobile money was increased after initial difficulties in communication to users.

An evaluation of Susteq ATMs (n = 31) in Turkana and Wajir regions in Kenya (Origa, 2018) reported reduced queues leading to better access for women and girls, because of anytime access. A 400% increase in revenue collection was reported, with reduced spillage, and better monitoring of usage to allow for better decision-making around supply and demand.

A more thorough evaluation of both Grundfos AQtaps and eWater taps in Tanzania is reported with similar findings (Check et al., 2017). Both systems were shown to have consistently generated average monthly revenues that exceeded operational expenses. Satisfaction of both users and managers increased, from improved access and preference of new payment methods. Different projects showed increases or decreases of user expenditure for water. Significantly, the report highlighted an almost universal move of users from alternative (unimproved) water sources towards PWS DPs, across all wealth quintiles.

The broadest overview evaluation, which includes AQtaps, eWater taps, and Susteq, in Tanzania, further summarised the key positive effects of these technologies (Komakech et al., 2019). It reported that these smart meters can:

improve revenue collection processes, with the certainty on revenue collection that provides confidence in investment decisions; make tariff collection more efficient, and improve convenience for users and managers, saving time and increasing accountability; provide better value for money to users; open up new commercial opportunities within communities such as credit vending; and provide data generation for monitoring and planning. The evaluators also point out that these technologies help to mitigate distrust between users and COWSOs (Ali et al., 2018). Limitations are also emphasised, specifically that the data, including seasonal data, should find better use for future activities.

An additional evaluation of the sustainability of solar-powered water supply systems in Kenya recommended that pre-paid smart meters (‘water ATMs’) form an important element in system sustainability and would be effective with either community management or a service delivery approach (Oxfam, 2018). It called for NGO or donor funding to extend their deployment, outlining that they “reduce community-committee conflicts by removing the direct interaction of water user committees with collected funds”.

The above evaluations all report benefits of smart meters. These are summarised in Table 2.16. Each of these benefits interacts with the others.

Table 2.16. Benefits of smart meters from current evaluations

Benefit	**Reason**
1. Improved revenue collection	Pre-payment means every payment is efficient, accountable, and recorded. Non-revenue water is eliminated. Exact measurement of flow means spillage is reduced. Better access means more users can collect more water.
2. Improved access to water point	Anytime access because there is no longer a short window of availability, which previously caused long queues. Improved finance and management leads to improved service provision.
3. Improved management and service provision	Accurate, real-time, precise monitoring data allows for improved O&M responses, and better decision-making around supply and demand. Improved revenue collection allows for better financial decisions, and confidence in investments.

This shows that the benefits of smart meters support professionalisation and the service delivery approach. Most of the evaluations noted the importance of full engagement with managers and the local communities.

Smart meters are a novel innovation in that they: benefit from remote pre-payment and instant credit removal from users' tags; they combine pre-payment with data monitoring; remote IoT capacity allows for instant data collection on usage and payment; and they have automated valves for water dispensing. As an ensemble, these capacities make the technology feasible in rural sub-Saharan African contexts. Alternative existing approaches tend to be much less feasible; data loggers would require manual collection of data and bring no immediate benefit to communities or managers; coin-operated water kiosks do not account for security of payment or kiosk, or a non-coin economy (notes and mobile money are often more common), and do not benefit from 100% accountable digital revenue collection direct into service bank accounts; and non-IoT pre-payment using e.g. tokens would still require vendors and does not benefit from remote monitoring. Overall, these smart meters have been specifically and uniquely designed to address the specific set of challenges faced in rural sub-Saharan African communities.

Despite this growing evidence for effectiveness of smart meters, some of the evaluators have independently emphasised overarching limitations (Komakech et al., 2020). Focusing on Grundfos AQtaps, eWater taps, and Susteq, they point out that such technologies are not panaceas, and are instead techno-deterministic innovations that are no more than supplementary to the rest of the rural water supply system. This is correct, and this argument is evident from the above sections in this chapter, and is further extended in Chapter 9. The authors emphasise the high capital costs (see below) are often covered by donors or external funding, and therefore cost-recovery is not inevitable. Strong institutional capacity and know-how is required to get the most from these technologies, and institutional roles regarding O&M and finance have sometimes been mixed up. The study also points out two limitations to technical robustness not covered in the other evaluations: inaccuracy of water flow measurement and dispensing, and the clogging of filters with debris (both of these were also determined independently for this research, and are examined in Chapter 4).

It is not possible to provide accurate costs of the smart meters in question because unit prices have changed dramatically since initial development and are tailored for each project. Costs are not reported in project literature. However, 2019 CapEx unit costs with associated hardware and installation have been reported for some Tanzanian projects (Komakech et al., 2020), as: Susteq ≈ 1,500 USD; AQTap ≈ 3,000 USD; eWater tap ≈ 3,200 USD; with further commission on credit sales varying between 5 and 30%. These are likely to now be inaccurate, however they indicate that these smart meters make up approximately 7-9% of the whole water supply project cost (Komakech et al., 2020), compared to 2-3% estimated for some handpump sensors.

Responsibility for smart meter O&M depends on the management model selected (see Section 9.5.1 for discussion on integration into different management models). Small-scale maintenance is typically undertaken by local mechanics, with more serious repairs undertaken by the smart meter providers if needed. Breakdowns are not uncommon (Komakech et al., 2020), but repairs are typically straightforward, for instance battery replacement. Access to spare parts is critical. O&M costs are therefore not possible to accurately estimate, however the revenue collected theoretically covers this.

2.5.7 Research gaps and opportunities for research on smart meters

There are gaps and opportunities for research on smart meters evident from the above reviews. These are listed below.

1) ***Further independent evaluation:***

The above reviews (mostly conducted during the research presented in the following chapters) have some limitations. Particularly in the grey literature, methodologies are sometimes unreported, results are often unquantified and lacking detail, and some positive claims appear based on extreme versions of findings. Even the more detailed and independent evaluations have, for instance: limited focus on technical operation; restrictions to ‘trials’ or ‘pilots’;

limited ‘systems thinking’; and almost all have limited peer-review (with the exception of Komakech et al., 2020, which is discussed in Chapter 9). Some have had to base findings on conventional metering due to unavailability of smart meter data. These limitations are understandable considering the novelty of the technology, that the evaluations were not designed as academic studies, and that some evaluators understandably want to promote certain smart meters. There remains a need for independent evaluation that fully considers smart meters within the complex context of rural water supply that has been outlined above. Further evaluation may reveal new insights (either positive or negative) on the impacts of the technology, and aid decision-making.

2) ***Technical robustness:***

Technical robustness has not been specifically investigated. In particular, limitations to accuracy of measurement, and blockages with debris are hinted at elsewhere (Komakech et al., 2020), and these specific limitations were also independently identified here. Strainers (e.g. y-strainers) have been included in some smart meters to address blockages with debris, and the impact of strainers and debris build up on flow rates requires research itself. Smart meter developers and manufacturers are responsible for research and development of their products, but some technical questions that may not be worth investing their resources in are important to users. There is a need to examine these challenges to understand their magnitude and to develop solutions. Additionally, the notion has been raised (Wilson et al., 2017; Greeff et al., 2019) of developing software for handpump IoT innovations that can predict non-functionality in advance using real-time water point data, with machine learning techniques, allowing for ‘just-in-time’ maintenance. Investigation of these technical questions could provide the basis for such predictive maintenance for smart meters.

3) ***Use of smart meter data for insights into water collection:***

The evaluations above have focused on investigating the shorter-term benefits to the management and service delivery of rural water supply. The need for ‘use’ of data from ICT innovations was highlighted above, and research has not yet promoted new opportunities and methodologies that ‘use’ long-term data collected from smart meters beyond monitoring (or passing reference), either for research or new management techniques. There is un-tapped potential for the application of this newly available, high-quality data on water supply for understanding patterns of water collection. In other words, smart meters can be seen as ‘field research instruments’ with continual data collection positioned in remote locations. Greater understanding of such patterns could benefit sustainable and equitable access, and address information limitations outlined above, especially if combined with socio-economic surveys and other contextual data. There are now a number of years of historical data. While prudential evaluations are required, new ideas of how smart meter data can be harnessed to help accelerate progress are also needed.

4) ***Insights into, and management of, seasonality:***

Seasonality of water collection and revenue is observed across sub-Saharan Africa. Following on from research gap 3), there is now scope to better understand this phenomenon using newly available smart meter data, and to develop appropriate management strategies based on the novel pre-payment capabilities of smart meters. Smart meters have not yet been employed as tools for seasonal management mechanisms.

It should be noted that new research gaps and opportunities have arisen concomitant with the progressive development of this technology.

A general limitation to previous evaluations is their linear focus, i.e. seeing smart meters as an isolated and purely additive intervention. This is not in line with the complexity outlined above. Research in this domain must be considerate of the unpredictable, complex system with interacting factors and links to other systems. Research must be considerate of socio-economic context and environmental factors.

By completing the research objectives outlined in Section 1.2, following chapters address these research gaps listed above.

2.6 Conclusions and implications for research framework

This chapter has built a picture of the complexity of the rural water supply challenge in sub-Saharan Africa. It has shown why progress has remained limited, with specific reference to Tanzania. A service delivery approach is needed to supplant inappropriate community management models. The landscape of rural water supply is open for application and research of ICT innovations. ICT innovations need to have better ‘use’ of the data they generate. Smart meters present a new opportunity to overcome limitations of revenue collection, financial management, monitoring, and access. Current research has been based on evaluations of the short-term benefits to management brought by smart meters. Four key research gaps and opportunities have been presented.

The complexity of rural water supply has implications for the research framework presented in the next chapter. Rural water supply is a wicked problem, and therefore there is a not a perfect ‘end goal’ that smart meters might help reach. Any benefits are only part of an iterative strengthening of the system, and this is investigated in Section 9.6. The research framework is therefore based on the systemic nature of rural water supply, specifically the evident importance of socio-economic and environmental factors alongside technical factors. Linear and narrow-focused research is not appropriate, and the following research aims to utilise the systems thinking that has been recently called for.

Chapter 3. RESEARCH FRAMEWORK

In the previous chapter the state of the art was reviewed. This showed the need for research on four research gaps that were identified in Section 2.5.7.

This chapter details the overall approach taken to achieve the research aim and objectives presented in Section 1.2, and therefore address the research gaps. The development and choice of the analytical framework, the smart meter used, the evaluation framework, and the outline of the following chapters are detailed. Further specific details on backgrounds and methodologies are provided in each chapter individually.

3.1 Analytical framework

Chapter 2 outlined the complex, systemic nature of rural water supply, and argued that research on smart meters must be considerate of this. A simple, linear, technical focus on the smart meter innovation, or relying on one category of evaluation, would not be sufficient for the research objectives. The importance of avoiding technological determinism regarding smart meter deployment is further emphasised in Chapter 9, and this is also true for research design. On the other hand, researching smart meter interaction with every aspect of the rural water supply system is not possible and would be too broad to deliver a detailed investigation. The analytical framework adopted for this research was designed to incorporate technical, socio-economic, and environmental areas, and is presented in Figure 3.1 along with the components of work from Section 1.6.

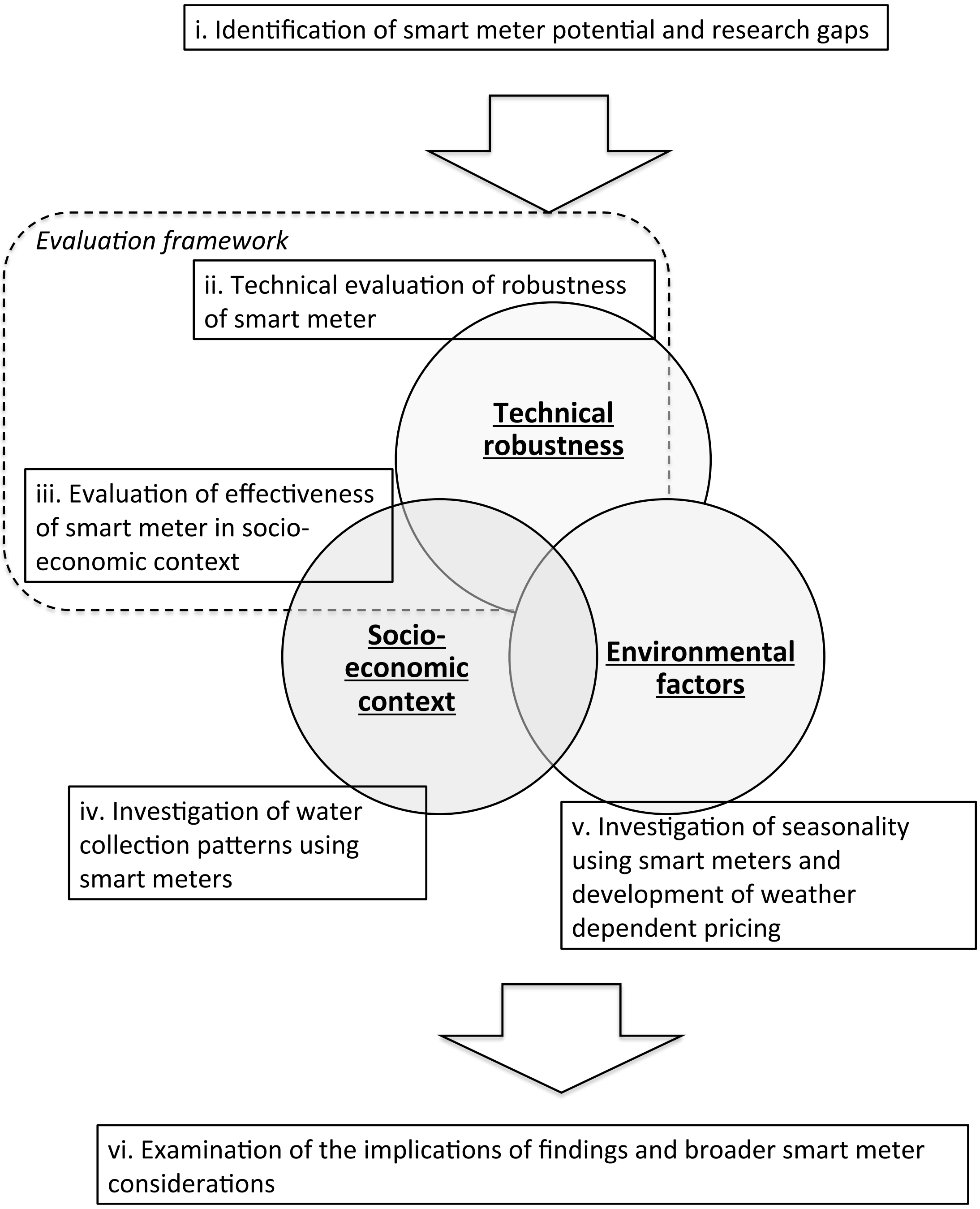

Figure 3.1 Analytical framework for investigation of how smart meters can improve rural water supply

This framework is influenced by the need for systems thinking. It has sufficiently wide inclusion of factors beyond simple technical operation, while still allowing detailed investigation into the key areas needed. Basing the components of work on this framework adds significant value and rigour to the overall research, and allows novel insights to be generated from the interfaces between different areas (for instance the development of weather dependent pricing in Chapter 8). The evaluation framework in Section 3.3 is based on this need for systems thinking.

An interdisciplinary approach is required for this research. Combining technical, socio-economic, and environmental research adds value and goes beyond the smart meter evaluations reviewed in Section 2.5.6. The need for interdisciplinary research in this area has been recognised by researchers. Key limitations to previous research approaches in this area (specifically on the functionality of water points) have been raised as: 1) too little understanding of the ‘socioeconomic milieu’; 2) tendency to consider functionality as only a techno-managerial challenge; and 3) a lack of approaches that study the interface between social (‘software’) and technical (‘hardware’) components of functionality (Whaley and Cleaver, 2017; Setty et al., 2019). Others have also called for more application of research approaches based on interactions between factors (Valcourt et al., 2020).

The recent move towards systems thinking has seen a corresponding broadening of methods. For example, a recent study on groundwater risks in Bangladesh combined social, environmental, financial, and institutional research, with a wider variety of data collection and analysis methods used (Hoque et al., 2019). Studies that focus on technical attributes of handpump functionality have also pointed out the importance of socio-economic characteristics beyond only technical evaluations (Foster et al., 2018). Research on other technologies has benefitted from combining technical and social approaches, for example combining survey and sensor data on cook stove interventions in Ugandan households (Sundararaman et al., 2016), combining water use loggers with qualitative surveys in indigenous communities in Australia (Beal et al., 2018); and toilet use loggers in India (O’Reilly et al., 2015). How combined methodologies generate novel insights is expounded on in more detail in Chapter 6 with regard to water collection patterns. The social science approaches used in Chapters 5 and 6 are based on the principles of ‘grounded theory’, i.e. the inductive construction of understanding through methodical gathering and analysis of data.

Establishing the benefits of a systems thinking approach for research on smart meters is important now considering their expected expansion. The work carried out here aims to provide ‘translational research’ to enhance practical action (Setty et al., 2019), and implications of the research are listed in Chapter 9.

3.2 Approach using one smart meter: eWater taps

A number of smart meters have been developed and deployed and these were listed in Section 2.5.3. As outlined, they share the same basic characteristics and essentially provide the same functionalities of:

- tag-operated pre-payment and valve operation;
- flow measurement; and
- remote reporting to a data management system.

Differences lie in specific technical design and fabrication (and therefore cost), operation of dispensing water, integration with the PWS, and deployment setting.

Because of these inherent similarities, one smart meter model is used to reveal insights that are applicable to smart taps in general: eWater taps. This allows for a more focused research. Findings will also remain relevant for future designs. Inclusion of different smart meters would have introduced practical and comparative challenges. eWater taps are smaller than the other smart meters reviewed, and are built into existing communal distribution points (DPs; standpipes), rather than set-up as kiosks, meaning they can be anywhere on existing PWS distribution networks, and potentially more remote. An example eWater tap is shown in Figure 3.2. Users travel to DPs to collect water in containers. DPs are typically supplied by pipework from an elevated community water tank, which is filled from borehole pumped groundwater (i.e. a PWS).

eWATERpay was established in 2015, with a business model based on unit sales and a proportion of credit sales, and has been operating in Tanzania, The Gambia, and Ghana. At the time of this research, the eWater taps could be categorised as being between pilot testing and fuller scale roll out, with corresponds to between Stage 2 and Stage 3 of Smits' (2014) stages of innovation in the rural water supply sector. Technical and managerial design have had iterative development, with newer versions incorporating solutions to previously observed limitations, for example: valve choice, separation of electronics from plumbing, battery choice and casing, and upgraded firmware and software (these are not investigated in this research).

Figure 3.2 eWater tap in use in Tanzania, with solar panel and antennae at the top of the pole. The tag is held on to the top module with a magnet.

They are operated using a user's NFC tag. This tag is pre-loaded with water credit that corresponds to water volume. To dispense water, the tag is held onto the eWater tap NFC tag reader for the length of time taken for the desired volume of water to be dispensed, and an amount of water credit that corresponds to pricing is automatically removed from the tag. The tag is removed when the user has collected the desired water, which closes the valve. The eWater taps measure flow and time of each use, and send the data on volume dispensed and associated credit removed from the NFC tag to a cloud-based data management system (dashboard) in real-time, via GSM (Global System for Mobile Communications), along with flow rate, time of operation, and user ID. This information is available to service providers/authorities via an online dashboard, who can use it to conduct O&M, visualise volume collected, collection at each DP, and functionality rates. Credits are purchased with cash from a vendor who uses a dedicated app, or using mobile money credit redeemed onto tags on next contact with the eWater tap; credits can also be sent by others to individual tags in this way. Users can collect water throughout the day and night. This model of operation and payment is essentially the same as the other smart meters. Overview of eWater tap hardware and measurement are provided in Chapter 4.

This research focuses on domestic water supply, i.e. used for consumption, cooking, cleaning, and washing in the household. All smart meters are designed for this as the major use, as opposed to for agricultural or economic uses. The focus of this research is on rural communities in Tanzania and The Gambia, which are described in more detail in Chapters 5 and 6.

3.3 Evaluation framework

An evaluation framework for the eWater tap is developed to address the research gap outlined in Section 2.5.7 of independent smart meter evaluation in a rigorous manner. This adds value by ensuring relevance and rigour.

Two relevant evaluation frameworks that exist for technology for development are:

- The Comprehensive Initiative on Technology Evaluation (CITE, 2017)
- The Technology Applicability Framework (TAF; Olschewski, 2013; 2015)

These two existing frameworks were drawn upon for the evaluation framework design here. The TAF has a broader sustainability focus, while CITE focuses more on technical and social concerns. More information on each is included in Appendix A, along with a screening and scoping of eWater taps based on the existing frameworks and the choice of evaluation criteria used here. Evaluation criteria are drawn from both existing frameworks to provide the ten criteria used here, adapted for this evaluation and the specific research gaps. CITE recommends 7 – 12 criteria are appropriate for a full evaluation. Table 3.1 outlines the ten evaluation framework criteria selected, and indicates the broad methods used for each. Table 3.1 also indicates the Chapter that each general method and study is presented in. This framework is based on the need for systems thinking, specifically the inclusion of more than just users or technical testing. A summary table of findings from the evaluation mapped to the criteria is presented at the end of Chapter 5 (Section 5.6). Chapters 4 and 5 also include novel findings and concepts beyond this evaluation.

Table 3.1 Evaluation Framework (EF) criteria and general methods adopted in this study

Evaluation criteria	Technical testing in laboratory	Managerial stakeholder interviews in Tanzania	User interviews and surveys in Tanzania
EF 1. Technical performance			
Accuracy of flow measurement	x		
Restriction of flow	x		
EF 2. Demand from managerial stakeholders			
Impacts		x	
Satisfaction		x	
EF 3. User experience and demand			
Impacts		x	x
Affordability		x	x
User satisfaction		x	x
Likelihood of continued use over time		x	x
EF 4. Accessibility			
Ease-of-use of smart meter and tag			x
Equity of use		x	x
	Chapter 4	**Chapter 5**	

The evaluation framework here aims to evaluate both technical and socio-economic criteria, in accordance with the analytical framework above. Such a multi-method approach has been effective for other evaluations, e.g. The BluePump (Foster and McSorley, 2016), which successfully used technical testing alongside questionnaire-based surveys with users and other stakeholders. It is also designed to collect viewpoints of users along with other stakeholders. This is important because interventions should integrate the 'voice of the community' along with the other stakeholders, which could help close the knowledge-to-action gap (Anthonj et al., 2018).

3.4 Outline of research

Here, the research conducted is outlined per chapter. In each chapter, individual backgrounds, methods, results and analyses, discussions (including relevance to practice and policy), and novelty of work are provided.

In Chapter 4, technical robustness of the eWater tap is investigated as the 'technical performance' part of the evaluation framework (EF 1), using laboratory-based hydraulic engineering methods. This focuses on two aspects that were shown in Chapter 2 as research gaps: 1) accuracy of flow measurement, and 2) flow rate reduction from y-strainers (which have been added to address blockages from debris) and from debris build up within y-strainers. The application of these findings to other smart meters, and how they can provide a basis for predictive maintenance, are shown.

In Chapter 5, the eWater taps are evaluated in the socio-economic context in rural Tanzania, as the 'demand from managerial stakeholders' (EF 2), 'user experience and demand' (EF 3), and 'accessibility' (EF 4) part of the evaluation framework, using survey and interview methods. The impact of smart meters on time taken for collection, the impact on inclusion of community members, the relationship between smart meters and the PWS, and the role of the community organisation (COWSO) are shown.

In Chapter 6, remotely collected data from eWater taps in rural Tanzania and The Gambia are combined with results from the surveys and interviews from Chapter 5 to investigate new insights into water collection patterns from rural DPs. This addresses the research gap to use smart meter data for insights into water collection. Distance users travel to DPs, times of day users collect water in the day, volumes collected by users, and the relationship between volume dispensed and location of DPs are investigated with the new precision available from smart meter data. Relevance of findings for management and planning is outlined.

In Chapter 7, data from eWater taps in rural Tanzania and The Gambia over three years are combined with three satellite-based sets of rainfall (and temperature) data. This extends current understandings of seasonality of water collection. The influence of monthly rainfall, daily rainfall, and days of heavy rainfall on volume dispensed are quantified and corroborated with explanations from users. These relationships are used as a basis for Chapter 8.

In Chapter 8, a novel pricing mechanism for smart meters based on rainfall is developed, with the objective of incentivising users to maintain collection of clean DP groundwater throughout rainy periods rather than from contaminated alternative sources. This addresses the research gap of developing management strategies for seasonality. This novel mechanism is based on smart meter pre-payment and real-time remote management. Cost, health benefits (DALYs averted), economic cost-benefits, sensitivity, and uncertainty of the pricing mechanisms are quantified. A decision support tool is presented. Novel capabilities, behavioural factors, practicalities, limitations, impacts, and contribution to climate change resilience are expounded.

In Chapter 9, the potential applications of the research findings for smart meters are outlined. Suitable settings for future smart meter deployment are discussed, along with broader considerations, policy implications, and potential barriers to smart meter deployment. How smart meters can strengthen rural water supply systems is shown. This has relevance to decision makers.

In Chapter 10, conclusions from the research are presented. Further work is outlined.

Chapter 4. TECHNICAL ROBUSTNESS OF SMART METER

4.1 Introduction

The objective of this chapter is to generate information on the longer-term robustness of smart meters. Following from the research gaps identified in Chapter 2 and the analytical framework outlined in Chapter 3, the robustness of eWater taps is evaluated with laboratory studies. Specific focus is on:

1. Accuracy of flow measurement
2. Flow restriction with y-strainer and debris build up

These have not yet been investigated in other evaluations. This research addresses the technical component (EF 1) of the evaluation framework outlined in Section 3.3. First, the background and need for robustness is outlined, followed by an overview of the eWater tap, experimental procedures, results, discussions, how findings can support predictive maintenance, and conclusions.

This research has been published as a journal paper:
Ingram, W., & Memon, F. A. (2020). Robustness of IoT-connected e-Taps for sustainable service delivery of rural water supply. *Water Supply*, 20(6), 2251-2260.

4.2 Background and need for robustness assessment

The low functionality rates of water points across sub-Saharan Africa shown in Section 2.3 illustrate that technical robustness is a critical part of sustainability. The low functionality rates also illustrate the inherent unavoidability of breakdowns (RWSN, 2009; Tincani et al., 2015). Generally, hardware for rural water supply progresses through stages of ‘use’, ‘breakdown’ and ‘rehabilitation’ even when successful and requires both routine maintenance and occasional major rehabilitation (Klug et al., 2017; Brikké and Bredero, 2003). Technical failure rates are associated with use, environment, and geographic context (Foster et al., 2018). It is suggested that a successful water system is therefore one where management facilitates rapid O&M whenever breakdown occurs (Kelly et al. 2018).

Furthermore, it is increasingly understood that binary 'functionality' is insufficient as an indicator of water point sustainability (Carter and Ross, 2015; Kelly et al., 2018; Bonsor et al., 2018b; Fallas et al., 2020). More nuanced understanding related to accuracy and flow is required. This can better support rapid O&M.

Technical robustness of smart meters has not been specifically investigated by previous evaluations, as shown in Section 2.5.7, yet robustness of smart meters is essential for reliable service. More robust smart meters shall: 1) reduce interruptions to water supply, and 2) reduce the burden (e.g. financial cost) of O&M on the service provider and/or community. Additional benefits include maintaining community satisfaction with the service provider and building trust in the technology. Limitations to robustness is identified as one of the core challenges of conventional pre-paid water meters in urban Africa (Heymans et al., 2014), specifically from moving parts that are subject to physical pressures, but these have not been reported in depth.

The two potential technical limitations to robustness evaluated here were revealed in the literature review and with interviews with eWATERpay technical staff. These go beyond both the shorter-term, reactionary design changes that smart meter developers have undergone, and beyond limitations that should be the responsibility of proper O&M such as replacing worn out components. Longer-term challenges like accuracy or flow restrictions may not be of immediate concern to smart meter providers, but are important to effectiveness of smart meters. Understanding the magnitude of these parameters can help develop solutions. Neither has yet been studied.

First, the study evaluated accuracy of flow measurement in the eWater tap (in this chapter these will be referred to as 'e-Taps' for brevity). Accuracy of new smart meters would perhaps be taken for granted by service providers and authorities. Accuracy of flow measurement underpins the accuracy of monitoring and credit removal from users' tags. This is important for fairness, affordability, investor confidence, trust, and accurate revenue collection, especially over time. 'Use' of data (including for predictive maintenance, see below) requires accurate measurement. Accuracy is underpinned by the precision of the flow meter, but can be influenced by the Flow Count calibration factor. While correct opening and closing of the motorised ball-valve is important for power consumption and precision of use, the flow meter records volume regardless of valve opening. It is therefore the flow meter and not the valve that underpins correct billing. Similarly, flow meters record volume regardless of the impact on flow rate from debris. Inaccuracies in metering are the main cause of 'apparent losses' in the developed world (Criminisi et al., 2009), and poor metering or billing processes are estimated to cause 30 billion litres per year to be lost in developing countries (Andrés et al., 2018b). Here, findings reveal average inaccuracies for e-Taps. A digital calibration tool created by eWATERpay to remotely improve e-Tap accuracy is also detailed.

Second, the study evaluates the impact on flow rate of: 1) addition of y-strainer and interior gauzes, and 2) built-up debris inside the y-strainer that could restrict water flow. Accumulation of debris in drinking water distribution systems is observed globally (Neilands et al., 2012; Carriere et al., 2005) and is especially relevant in rural sub-Saharan Africa where infiltration of grit, sand, organic matter, and plastic waste can be high. Debris can enter PWSs during pipe repairs, tank emptying, from the inside walls of tanks, or any breach in the physical infrastructure. Clogging in traditional water meters is commonly observed. Smaller scale abrasion or blockage also limits impeller rotation and accuracy over time, and can also originate from inorganic scaling and fragmentation, sludge build-up, rust fragments from upstream, and microbial slime layering (Arregui et al., 2005; Ryan et al., 2008). Detailed identification and analysis of precise debris composition in smart meters was beyond the scope of this research (composition is highly variable anyway), and literature and reports from field observation were relied upon: the e-Tap flow meter impeller was occasionally blocked in earlier versions, as pictured in Figure 4.1a, with debris that entered through storage tanks and during pipe repairs, which triggers an automated closure. Because of these blockages, eWATERpay added a y-strainer to the e-Tap design. This y-strainer is pictured in Figure 4.1b, and its position in the e-Tap is shown below in Figure 4.2. Different gauze sizes can be added in the cylindrical casing (pictured). The y-strainer can be opened for cleaning and gauze replacement. This addition of this y-strainer to the e-Tap has now introduced the potential limitation of flow rate reductions. It is uncertain how much this y-strainer might limit flow rate, especially with gradual debris build up within the gauze. This is evaluated here. Results below reveal specific flow rate reductions from y-strainer addition with different gauze sizes, and from build up of different debris loads and sizes. Based on these results, novel flow rate threshold alerts for predictive y-strainer maintenance are proposed. These findings are relevant for other smart meters; at least one other smart meter requires strainer installation (Grundfos, 2018).

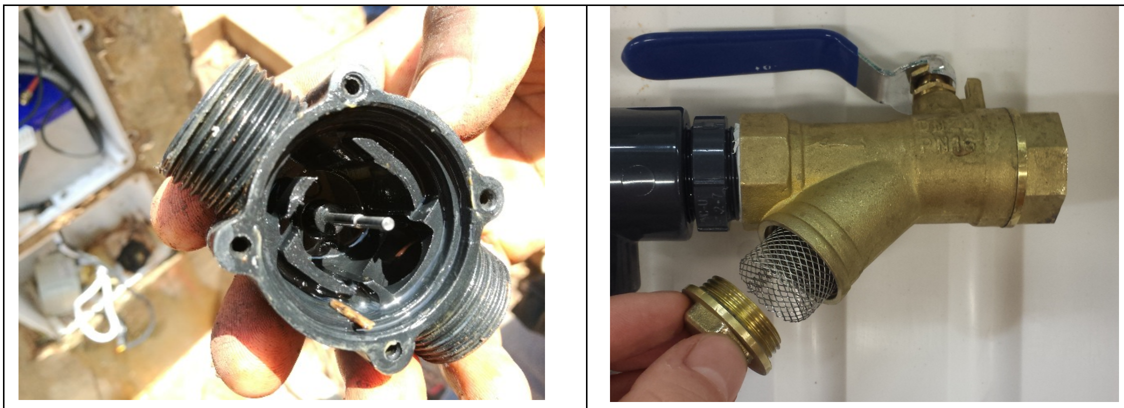

Figure 4.1 a) Twig that blocked e-Tap flow meter; b) y-strainer, with water flow from right to left.

Sensors on handpumps (e.g. handpump IoT innovations reviewed in Section 2.5.5; Hope et al., 2014; Nagel et al., 2015) have the benefit that failures of the sensor on handles or well-heads do not interfere with flow. However, these have lower accuracy (reported at approximately ±15%; Thomson et al., 2018). Non-mechanical flow meters that are not susceptible to blockages (e.g. electromagnetic, Karman vortex, thermal, differential pressure, ultrasonic, or coriolis) remain too expensive and require longer sections of straight piping directly upstream.

Reduced flow rates are important to investigate here as they lead to longer water collection times, queuing, community dissatisfaction, and marginalisation of households far from tanks. Communities in Ethiopia have suggested that low flow is a key factor for water point sustainability (Anthonj et al., 2018). Flow rate depends on pipe diameter and residual pressure (i.e. once head loss from friction is discounted), and depends on water level in the PWS tank, elevation, and other standpipes in the network. There is a wide variability of flow rates measured, and flow rates in The Gambia (~4 – 32 l min^{-1}) tend to be lower then in Tanzania (~20 – 60 l min^{-1}) due to flatter topography, lower tank elevations, and closer DPs. These give time for filling a 20 l container as approximately between 30 s and 4 min 40 s. Recommended flow rate for ¾ inch outlets at DPs in the field are 17 to 25 l min^{-1}, corresponding to 4 to 10 m residual pressure (IRC, 1979). Another hillside PWS in Tanzania reports a range across different DPs of 15 – 108 l min^{-1} (de Haas and Borst, 2012).

Beyond accuracy and flow restriction, it is assumed that the e-Tap is robust regarding user interaction, reporting of measurement data (network reach), power supply, and other basic requirements. This assumption is supported by more than three years of operation, and observation during fieldwork conducted in Chapter 5. Issues that have been separately addressed include separating electronics in a separate module to the plumbing, and increasing battery size and back-up power. Similarly, the firmware and software is assumed to operate well. Other issues such as motorised ball-valve degradation have solutions in regular O&M. Control valve failure and memory card failure have been reported in other smart meters (Komakech et al., 2020), and poorly filled cavities between casing and the concrete DP stand (and inside broken casing) were occasionally observed to harbour bees during the fieldwork of the present study (Chapter 5).

A potential challenge is that measurements on flow rate and use are collected and reported at an unnecessarily high frequently, resulting in the ‘DRIP’ (‘data rich, information poor’) problem. In general, this is an extremely data poor context and any data on flow is useful compared to the baseline of zero. If any frequency of data collection is possible after installation of smart meters (at the same cost and practicality), then the difference between low and high frequency is insignificant compared to the monitoring capacity in the first place. The importance of appropriate integration of data flows with the management model in question is discussed in Section 9.5.1; data and information needs to find use with the correct managers at the correct levels. Regardless, in the study in this Chapter, high frequency data allows more detailed analysis of flow rates, and also on water collection patterns and seasonality in Chapters 6 and 7.

The research here is focused on longer-term limitations to robustness that would otherwise be unlikely to be included in the rapid product development of smart meters. This approach is because of the need for systems thinking outlined in Chapters 2 and 3. It is also important to establish accuracy of data collection for the ‘use’ of data in Chapters 6 and 7.

4.3 Overview of e-Tap hardware and measurement

e-Tap operation was outlined in Section 3.2. The general components are shown in Figure 4.2. e-Taps on DPs are operated using near-field communication (NFC) tags that are pre-loaded with purchased water credits and held onto the NFC tag reader until the desired amount of water has been dispensed. Tag removal closes the tap. Flow and time of each operation are measured, and the volume dispensed and associated credit taken is reported in real-time to the data management system, along with flow rate and other supplementary data.

e-Taps benefit from high accuracy direct measurement of flow. The single-jet flow meter impeller is rotated by the kinetic energy of water flow (Walter et al., 2007) when the motorised ball-valve is opened creating an electrical signal via the Hall effect for each rotation, sent to the control circuit board. The impeller has a density lower than water, designed so floating minimises friction (Arregui et al., 2007). Volume in litres is calculated by dividing Flow Count by the flow meter’s standard calibration value of 330, with flow rate derived from the time measured for each operation. Flow meter inaccuracies are underpinned by the precision of the flow meter but can also therefore be influenced by the Flow Count calibration factor. Single-jet flow meters are cheap, however they are also subject to blockages (as seen above) and varying inaccuracies. A ‘low flow’ error below 4.3 $l\ min^{-1}$ automates closure, which negates the problem of lower accuracies close to 0 $l\ min^{-1}$. The y-strainer blocks debris from flowing into the impeller flow meter and causing blockages.

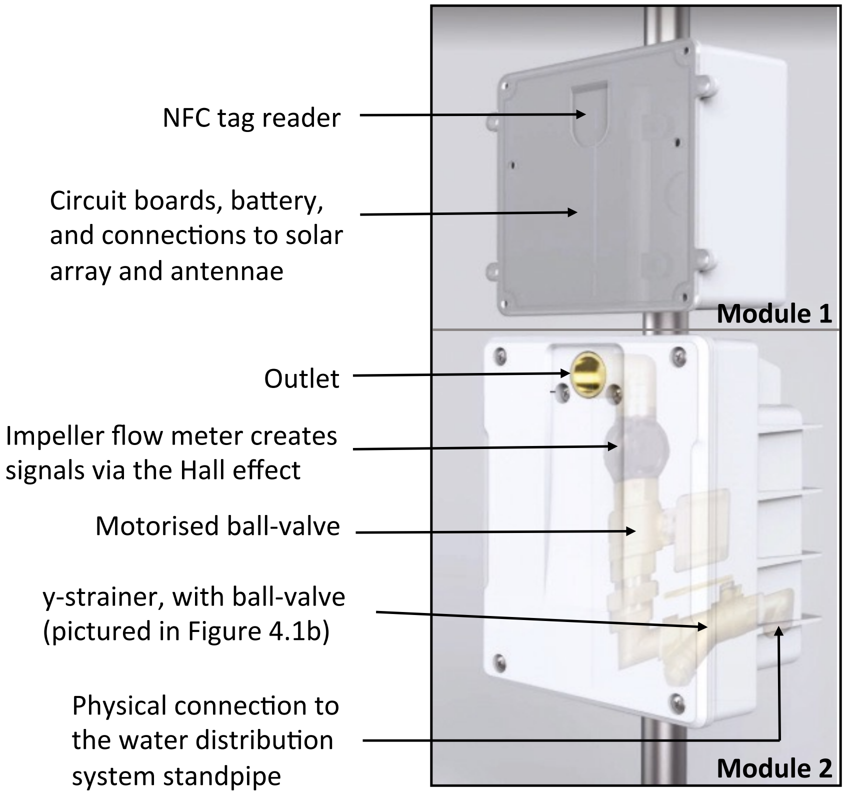

Figure 4.2 General components of e-Tap version 2.5[2] (adapted from eWaterpay, n.d.)

4.4 Experimental and data collection methods

4.4.1 Accuracy of flow measurement

The experimental set-up emulated real-life e-Tap operation, using a hydrobench. This is shown in Figure 4.3. A three-way ball-valve manually directed flow either ‘into’ or ‘away’ from Module 2. A separate flow meter (with custom-built and calibrated digital reader) was positioned on the ‘away’ flow to allow for approximate adjustment of baseline flow rate ($Q_{baseline}$). A pressure dial was added between the three-way ball-valve and Module 2.

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[2] This represents ‘Version 2.5’ from 2017. Technical specifications and tools may alter from those presented. Findings on accuracy and flow reductions remain relevant.

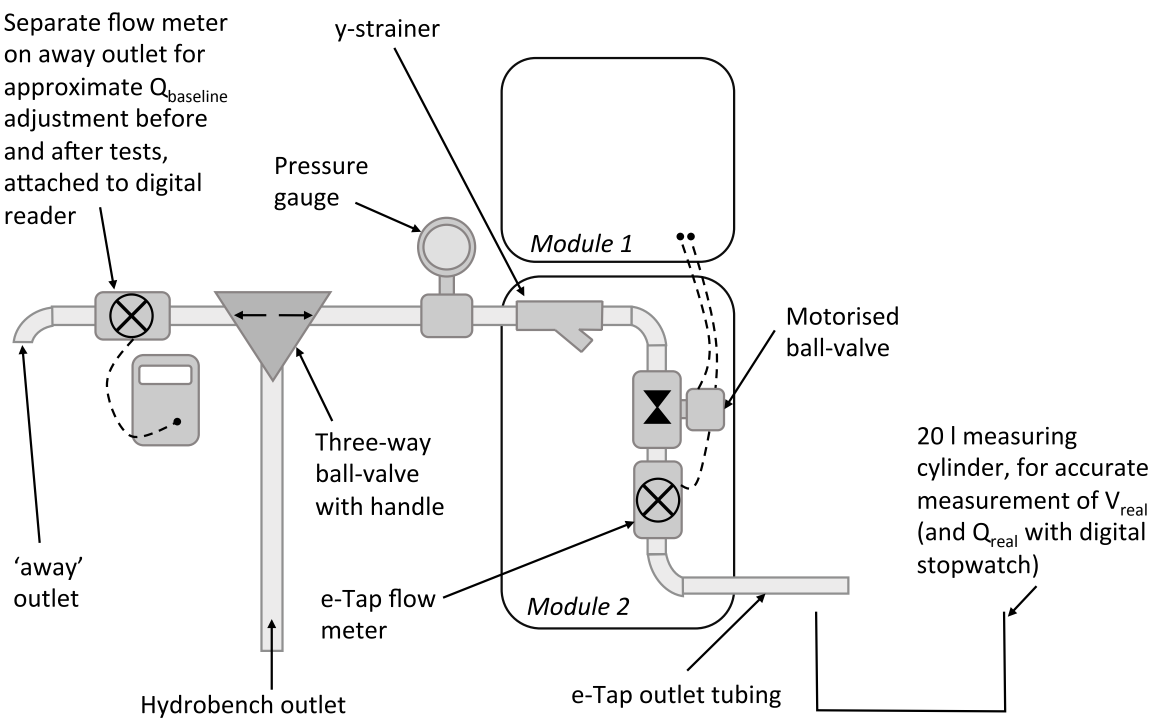


Figure 4.3 Experimental hydrobench set-up

Once water flow was directed 'into' Module 2, an NFC tag was placed on Module 1 as soon as possible to open the e-Tap motorised ball-valve and begin measurement. A digital timer was started as soon as water was observed to flow from the end of the outlet tubing into a calibrated custom 20 l measuring cylinder. Once the water level reached exactly 15 l, measured manually, the timer was stopped, giving an accurate real flow rate measurement (Q_{real}, l min^{-1}), and the tag was removed. The potential of imprecise reading was negated by the choice of a large enough volume and by inducing a swirl in the measuring cylinder. Total volume dispensed once flow had fully stopped was measured, giving V_{real}. This allowed for additional flow caused by the slow shutting of the motorised ball valve.

This procedure was repeated 180 times over a varying Q_{real} of 4.3–38.6 l min^{-1} in order to get a representative data set and provide accurate average and standard deviation values for analysis. Below 4.3 l min^{-1} a 'low flow' error is activated; 38.6 l min^{-1} is the hydrobench pump limit. This range suitably replicates the observed range in The Gambia (4–32 l min^{-1}) and Tanzania (20–60 l min^{-1}). The 'overload flow rate' at which this class (B) of single jet flow meter should be able to operate within the required accuracy is ~83.3 l min^{-1}, which is far beyond the tests here. Three different flow meters of the same model were used to discount potential effects of testing one faulty unit. The volume and the flow rate measured by the e-Tap ($V_{e\text{-}Tap}$ and $Q_{e\text{-}Tap}$) were manually calculated to two decimal places using Flow Count and reported seconds ($t_{e\text{-}Tap}$), therefore avoiding rounding errors (which had a normalised mean of 1.54%). The percentage differences (%Δ) between 'real' experimentally measured volumes and volumes measured by the e-Tap are calculated using Equation 4.1 (Criminisi et al., 2009):

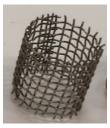
$$\%\Delta V = \frac{V_{e-Tap} - V_{real}}{V_{real}} \times 100 \tag{4.1}$$

The international standard ISO 4064 permissible error range for water meters is ±5% at flow rates lower than the transitional flow rate (this is known a Q2, and is specific for each meter), and ±2% at flow rates above Q2 (ISO, 2014; Walter et al., 2007). Once operating in the field, Q2 has been suggested to increase to ±8%, and above Q2 to ±3.5%, respectively (van Zyl, 2011). Here, an error range of ±5% across flow rates is taken as a permissible range. From a practical standpoint, an acceptable error might be considered as closer to ±10%, which is more in line with smart handpump measurement errors. However, because accuracy underpins fairness of payment here, ±5% is taken as more suitable and more in-line with calls from the practitioner community, and with expectations from commercial in-line flow meters.

4.4.2 Flow rate reduction from y-strainer and debris

Decrease in $Q_{baseline}$ was measured across varying gauze sizes, debris sizes and debris loading of the y-strainer. Individual components of Module 2 were set up as above, with flow meters before the three-way ball-valve, and after the Module 2 components (with digital reader, calibrated). Percentage flow rate reductions from a maintained $Q_{baseline}$ between set-ups without the y-strainer (and associated elbow) and with the y-strainer were measured across a $Q_{baseline}$ range of 3.0–17.6 l min^{-1}. This was then repeated, keeping the y-strainer in place, with seven gauzes of varying pore size (0.15–3.24 (and 63) mm^2; shown in Table 4.1), across a comparable $Q_{baselines}$ range.

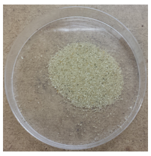
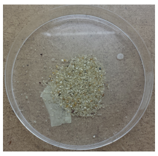
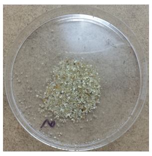
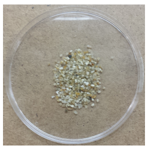
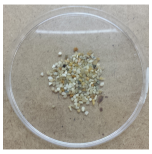
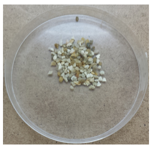
Table 4.1. Custom manufactured y-strainer gauzes. Height = 22.5 mm, diameter = 20.0 mm.

Gauze number	**1** 	**2** 	**3** 	**4**[a] 	**5** 	**6** 	**7** 
Gauze pore area (mm^2)	>63	3.24	1.95	1.38	0.42	0.36	0.15
Pore widest point width (mm)	>3.0	4.2	1.8	1.3	1.2	0.7	0.6

[a] *standard from strainer manufacturer*

Next, debris size (μm) and debris loading (g) were varied across the variable gauze sizes. A constant $Q_{baseline}$ of 6.7 l min^{-1} was used as varying this was shown to be insignificant. A T-inlet between the three-way ball-valve and y-strainer allowed for 'spiking' of debris while maintaining the required flow rate. Silica sand was chosen to simulate the effect of observed heterogeneously sized debris (as in Puig-Bargiés & Lamm, 2013) and provide generalisable flow rate reduction results. Sand has been observed to cause blockages in The Gambia. Six sand size ranges were selected (300–425 to 2,000–2,360 μm; shown in Table 4.2), collected using vibrating sieve stacks, washed and oven-dried.

Table 4.2. Six size ranges of sand used to replicate debris built-up

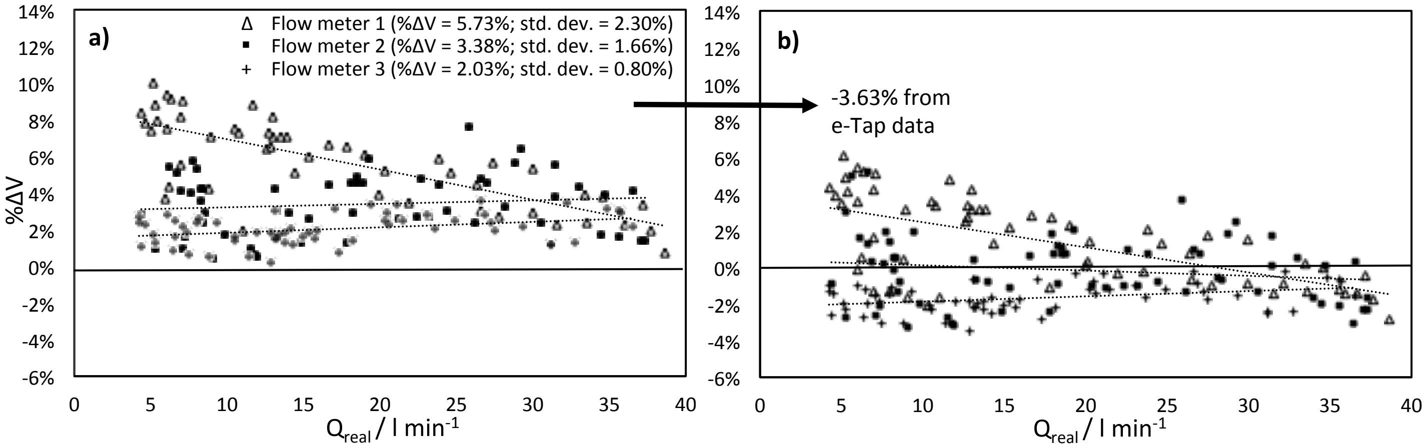
Sand size	**A** 	**B** 	**C** 	**D** 	**E** 	**F** 
Sand size / μm	300 - 425	425 - 600	600 – 1180	1180 – 1600	1600 – 2000	2000 – 2360

The cylindrical interior space of the y-strainer gauze (~7.1 cm^3) fills with 10 – 11 g of sand. Variable loads selected were: 0, 4, 7, 10, 13, 16, 19, and 22 g. Variable combinations were (in order): 6 × gauze sizes, 6 × debris (sand) sizes, and 8 × debris loads (cumulative), giving 288 measurements. Percentage decrease from $Q_{baseline}$ (measured as the flow rate at 0 g of debris loading, for each new gauze size) was measured for each. Gauze 1's pores (63 mm^2) were too large to allow any build-up, and it was excluded from the final analysis.

4.5 Results

4.5.1 Accuracy of flow measurement

$V_{e\text{-}Tap}$ is larger than V_{real} by a mean of 3.63% (%ΔV) across all measurements. The standard deviation across these %ΔV is ±2.26%. There is significant variation between the accuracies of each flow meter tested (shown in Figure 4.4a). This variation was verified by an additional ten repeats across the $Q_{baseline}$ range on flow meters 1 and 2.



-3.63% from e-Tap data

Figure 4.4 a) %ΔV against Q_{real}, disaggregated for flow meters tested; b) reduction of inaccuracies by general calibration of data from Figure 4.4a downwards by –3.63% (this is explained in Section 4.6.1 below).

Flow meter 1 is most inaccurate, with a higher mean %ΔV and standard deviation values, and also an evident negative correlation of %ΔV with increasing Q_{real}. Flow meter 3 is the least inaccurate. In general, volume inaccuracies seem not to be sensitive to variation in flow rate within this range. The inaccuracy revealed here can be addressed by a general recalibration of all e-Tap data by 3.63%, as shown in Figure 4.4b (see Section 4.6.1).

The percentage error between 'real' and measured flow rates (%ΔQ) was also calculated as above for each measurement, and is shown in Figure 4.5a; %ΔQ against Q_{real} shares the characteristics of %ΔV against Q_{real} for the flow meters, however with a significant positive correlation and higher errors (mean = 6.61%, standard deviation = ±2.87%). This apparent misalignment is due to an erroneous time constant that incorrectly increases each $Q_{e\text{-}Tap}$. An addition of 3.95s to each e-Tap recorded time ($t_{e\text{-}Tap}$) brings both the mean %ΔQ and the correlations of each flow meter into alignment with %ΔV, as seen in Figure 4.5b. The motorised ball-valve was measured to take a mean of 4.00 s to fully open. This erroneous time constant is therefore shown to result from the time difference between the addition of the tag to the e-Tap and water flowing from the e-Tap outlet, which is ~50 cm downstream from the motorised ball-valve in this experimental set-up (interior volume = 230 ml). The same result is achieved by subtraction of 1.51 s from the t_{real} values, which confirms this explanation. This means volume provides more accurate measurements that flow rate.

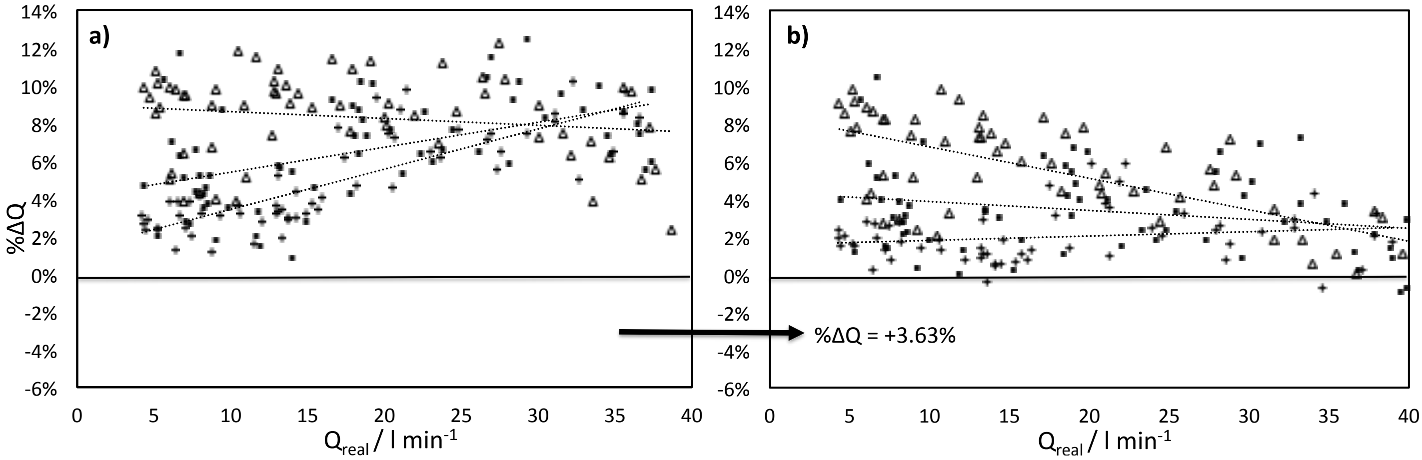


Figure 4.5 a) %ΔQ against Q_{real}, disaggregated for flow meters tested; b) addition of 3.95 s to each measurement in Figure 4.5a.

4.5.2 Flow rate reduction from y-strainer and debris

The addition of the y-strainer in Module 2 causes negligible flow rate reduction across the $Q_{baseline}$ range tested. Decreasing gauze pore sizes without debris causes insignificant reductions, with a maximum 4.8% decrease with the smallest pore size (Gauze 7; 0.15 mm^2). This is shown in Figure 4.6.

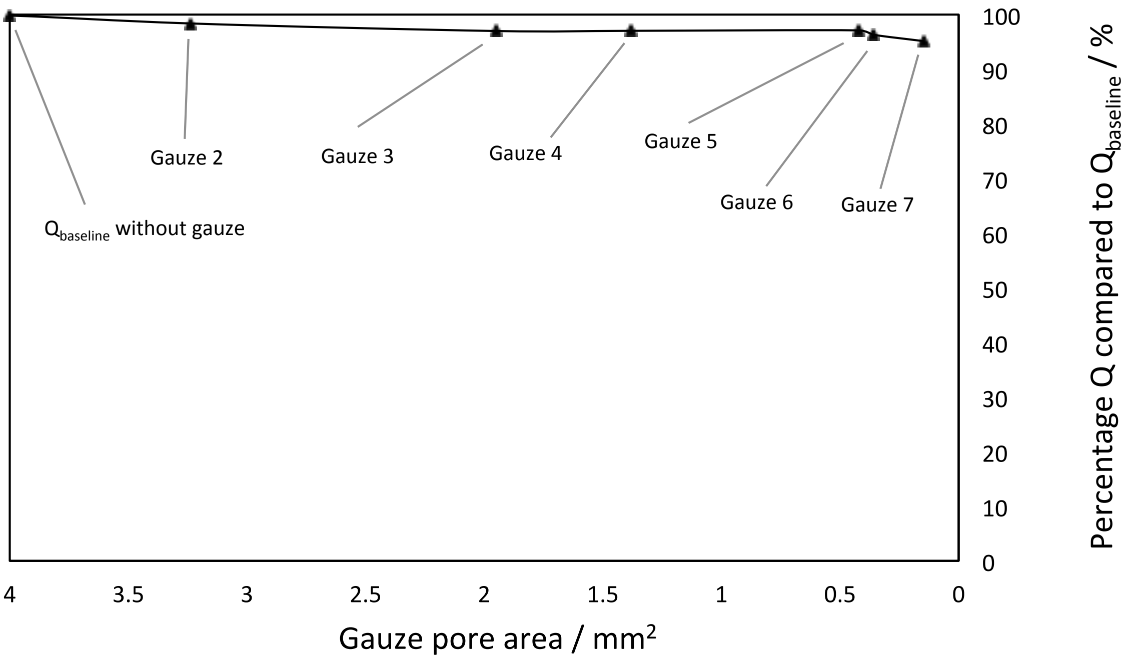


Figure 4.6 Flow rate reductions from $Q_{baseline}$ for different gauze sizes

Figure 4.7a shows that loading of debris in the y-strainer generally leads to decreased $Q_{baseline}$. Flow rate decreases become significant at approximately 13 g of loading (with a mean flow rate reduction of 1.57%). This corresponds to when the cylindrical gauze has filled with sand (10–11 g) and the horizontal y-strainer interior also begins to fill. After this point, $Q_{baseline}$ decrease is more significant for gauzes with smaller pore sizes. Smaller pore sizes in the range of ~0.15–0.36 mm^2 (Gauzes 6 and 7) cause an average ~15% decrease of flow rate with 22 g of debris.

Smaller sand sizes cause greater reductions in flow rate (until the sand is small enough to pass through pores). Figure 4.7b–h demonstrates the significance of this, and the ~13 g threshold. Sand A (300–425 μm) shows $Q_{baseline}$ decreases of ~32% with both Gauzes 7 and 6 with 22 g loading, shown in Figure 4.7c and 4.7d. Figure 4.7e shows that at a large enough gauze size, the smaller sand sizes (Sand A) begin to pass through. Here, sand <425 μm was too small to ever block the impeller. The second flow meter was blocked in 33% of all measurements, emulating blockages in the field.

Disaggregated reductions of $Q_{baseline}$ for different gauzes in Figure 4.7c–h show that smaller gauze sizes allow for build-up of smaller sand sizes, and a combination of both small gauze size and small debris size results in the greatest $Q_{baseline}$ decreases.

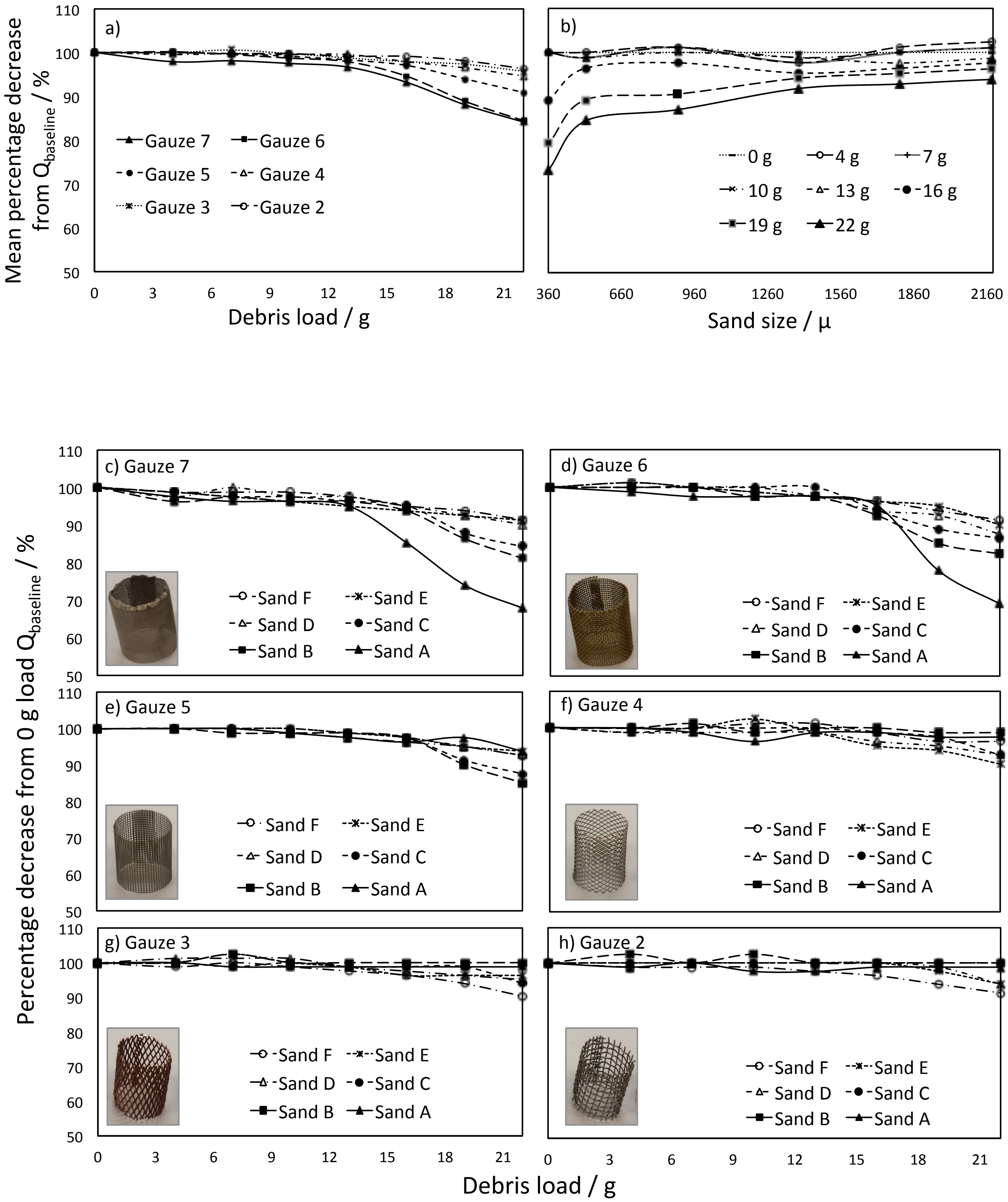


Figure 4.7 a) Mean percentage $Q_{baseline}$ decreases over increasing debris loads for each different gauze size, averaged for all six sand sizes; b) $Q_{baseline}$ decreases for Gauze 7 with increasing debris loads, across varying sand size; c)–h) disaggregated $Q_{baseline}$ decreases per gauze size with varying sand sizes, across increasing debris loads.

4.6 Discussion and impact on e-Tap design

4.6.1 Accuracy of flow measurement

Calculation of more precise values directly from Flow Count avoids rounding errors from integers equivalent of up to ±0.6 l out of a 20 l collection bucket, which may accumulate over time, and %ΔV is a better indicator of flow meter inaccuracy than %ΔQ as it excludes the additional uncertainty from experimental measurement of time. Volume is also a more relevant metric of water collection than flow rate regarding accuracy of credit removal and volumetric monitoring.

An average of 3.63% too much water is being recorded by the e-Taps, shown in both %ΔV and %ΔQ. This marginal inaccuracy may be because of incorrect calibration in the measurement of volume from Flow Count. (Minor imprecision in flow meter components and turbulence of flow result in the spread seen in the measurements). This average is within the ±5% acceptable inaccuracy, however 25.9% of measurements are greater than +5% inaccuracy. Mean standard deviation equals ±2.26%, which extends to +5.89% inaccuracy.

Inaccuracy against Q_{real} or V_{real}, in accordance with flow rate variability in the field, extends the potential inaccuracy range to its maximum of 0.78% – 10.05%. The overload flow rate (Q4), where flow rates are high enough to cause the error curve of a flow meter to exceed the required error range, is likely to be far beyond the expected flow range here (van Zyl, 2011). Axial wear reduces accuracy more when closer to 0 $l\ min^{-1}$, avoided here by the automated closure at low flows.

Therefore, it appears that very slightly excessive credit is currently being charged from users per use, and slightly excessive water collection is being reported, probably resulting from an incorrect flow calibration value. This inaccuracy also has a range of uncertainty.

Higher-precision flow meters (e.g. Class C and D[3]) are expensive, bulkier, and impractical. Instead, a general calibration of all reported data using the mean %ΔV reported of 3.63% will bring the mean %ΔV to 0%, as shown in Figure 4.4b above. Then, 95.45% (two standard deviations) of the above measurements would fall within ±4.54% inaccuracy, within the acceptable ±5%. This can be practically achieved with an adjustment of the flow calibration value from 330 to 318. (If alternative testing were to show different error values, this calibration could be adjusted accordingly to still bring inaccuracy within ±5%, and the findings here are generalisable.)

To this end, a calibration application (for smartphone or web browser) was developed by eWATERpay for use at individual e-Taps in the field (or remotely). The application remotely commands the e-Tap to dispense a given volume of water, which is measured and re-entered to recalibrate the e-Tap. While the precision methodology employed in this paper is not possible in remote locations, repeats of the same principle will provide an acceptable accuracy range (ensuring flow rate is not unusually low or high for each water point). This protocol also allows for community engagement and transparency. In general terms, this demonstrates that software solutions can be used to overcome physical limitations to the precision of the e-Tap components. When compared with expensive manual calibration in laboratories, this finding demonstrates significant novel potential of smart meters and other such IoT-enabled technologies.

4.6.2 Flow rate reduction from y-strainer and debris

Any decreased flow rate from y-strainer addition is negligible, with a maximum of 4.8% with the smallest gauze size. Build-up of the 13 g of debris in the y-strainer required before flow rate starts to reduce is likely to take some time in e-Taps, depending on debris levels in the water distribution system. Risk of ‘non-functionality’ because of the y-strainer is low; even with 22 g of debris and the smallest gauze size, flow rate only reduces by one-third. The benefit to robustness of the e-Tap by limiting flow meter blockages is therefore highly

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[3] Flow meters are classified into A, B, C, and D depending on precision. Class A and B meters are cheaply available.

preferable.

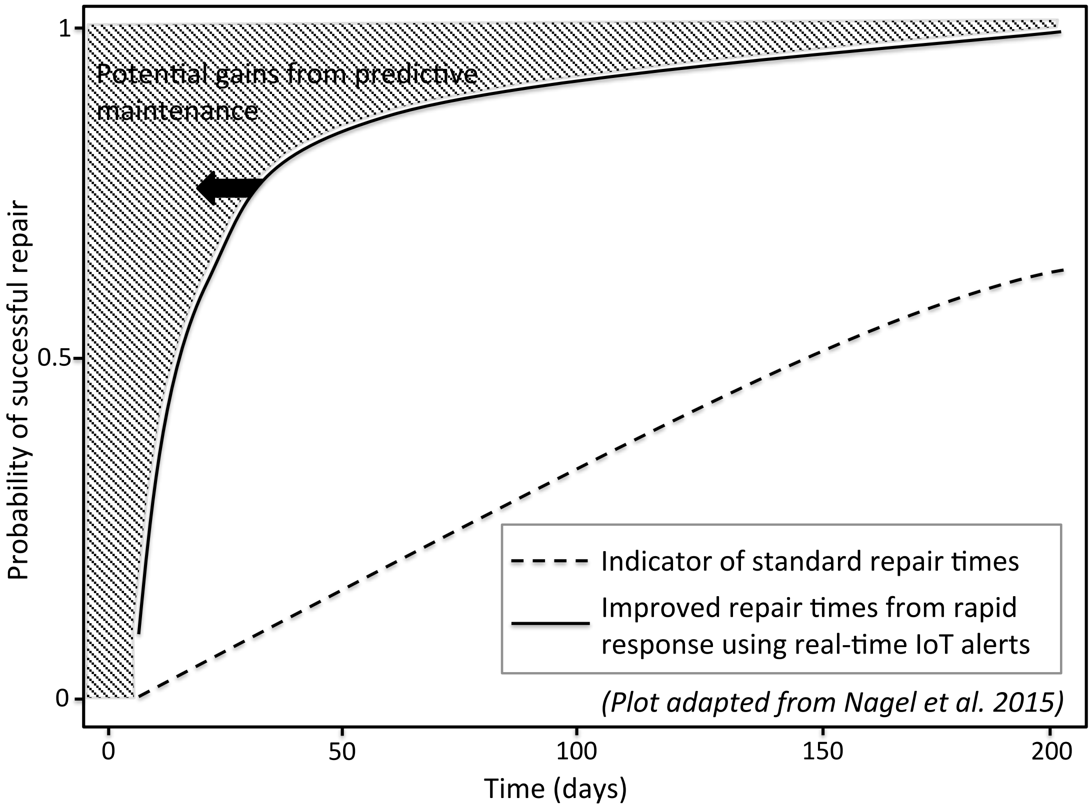
If characteristics of the debris are previously known for specific water distribution systems, these results can inform the choice of gauze size using the findings reported in Figure 4.7c-h. For example, if a PWS is known to have concentrations of debris of roughly 600 μm, the selection of a gauze with pore size 0.42 mm^2 would protect the flow meter and only reduce flow by ~15% with 22 g of debris. These findings also apply to other smart meters. For example, the Grundfos AQtap includes a strainer with small pores (Grundfos, 2018), and this is likely to reduce flow rates more significantly once filled with debris.

The y-strainers require periodic cleaning. For strainers in domestic or standpipe meters, the WHO and IRC advise cleaning at least once a year (Brikké & Bredero, 2003). Water distribution systems in sub-Saharan Africa vary in flow rates and debris loads. Therefore, annual cleaning does not facilitate efficient maintenance, and some e-Taps may be left with high debris loads for long periods, which may cause reduced flow or trigger associated microbial health risks. Now, this empirical understanding of flow rate reductions from different debris and gauze variables can be combined with remote visualisation of flow rate reductions in real-time via the online data management system. For example, gradual reductions in flow rate at an e-Tap, compared with either a longitudinal baseline or other e-Taps in the system, could alert service providers to significant debris build-up. This in turn can generate information about debris infiltration locations in the piped system, or average debris size from flow rate reductions across e-Taps or at one specific e-Tap, informing O&M. Knowledge of specific debris type and size can hone this.

4.6.3 Predictive maintenance using flow rate

Recent work on IoT innovations on handpumps has succeeded in automating alerts of non-functionality and reducing maintenance response times (e.g. Hope et al., 2014; Nagel et al., 2015). These were outlined in Section 2.5.5. Even with these 'fix-on-failure' successes, water points remain non-functional for at least some time.

Automatically predicting non-functionality before it happens using real-time data collection would allow preemptive maintenance per water point or system, with obvious resource efficiency benefits. Accurate predictions would theoretically reduce non-functionality time to zero. This is plotted in Figure 4.8, which shows that amount of time taken for successful repairs would fall to zero, which is far more favourable than even shortened repair times from real-time failure alerts. This would have disproportionate socio-economic and health benefits. Even short remissions to alternative unimproved water sources result in very significant health impacts (Brown & Clasen, 2012). Enhanced service delivery can positively feedback to increased demand, management, and sustainability, as shown in Section 2.3.5. The availability of conventional routine preventative maintenance has been associated with continual service provision in Nicaragua (Cronk and Bartram, 2018) and minimized operational and capital maintenance expenditures (Butterworth and McNicholl, 2018).



(Plot adapted from Nagel et al. 2015)

Figure 4.8 Potential gains of time to successful repair of water points from predictive maintenance compared to real-time failure alerts

Some recent research has advanced 'preventative maintenance' for handpumps using handpump sensors and supervised ensemble machine learning (Wilson et al., 2017). Threshold-based binary outputs informed a decision whether to dispatch a mechanic, and these were ‘trained’ with four categories of failure events based on usage, flow, event duration, and handle motion. This was able to predict handpump breakdowns mostly on the breakdown day, or day before. The analysis was based on accelerometer and pressure gauge measurements as proxies for flow rate, bounded by three minutes after pump handle vibrations had stopped. This is suggested to hypothetically save 7% of overall costs compared to a scheduled maintenance model. Similarly, other research has further combined lightweight, in situ machine learning methods with more powerful cloud-based ones for successful predictive failure of up to 61.6% (Greeff et al., 2019).

Higher accuracy in-line impeller flow meters in smart meters offer greater potential for predictive maintenance than proxy flow or mechanistic measurements from handpumps, particularly regarding debris build-up. There is reduced additional uncertainty between physical reality and statistical machine learning (Si et al., 2011). Real-time and remote use of high temporal resolution data has already been successful with remotely controlled pressure-reducing valves in municipal water distribution networks in the developed world (Creaco & Walski, 2018).

An effective method to achieve this with e-Taps is to create alerts to unacceptable flow reduction thresholds from a baseline that is derived from a longitudinal average of recent flow rates. This would alert when debris build-up had become significant and cleaning is required. Once a flow rate threshold is consistently passed over a long enough period of time to discount underlying flow rate fluctuations, an alert can be sent to the service provider. This can be tailored to specific e-Taps and gauze sizes. To this end, $Q_{baseline}$ reduction alert thresholds are proposed in Table 4.3. These have been calculated based on the debris build-up measurements reported in Figure 4.7c-h after the 13 g y-strainer filling threshold has been crossed. For example: if an e-Tap has gauze pore sizes of 0.36, then as the gauze fills with 13 g, then 16 g, then 22 g of debris (of all debris sizes) the flow rate will be measured to drop to approximately 97.9%, then 94.7%, then 84.5% of the $Q_{baseline}$. Therefore, setting an alert for when a longitudinal average of recent flow rates drops below 93%

would be a good indication that the y-strainer now requires cleaning. This example recommended threshold is shown in Table 4.3 as >7%. A suitable length of longitudinal average would be approximately five days, as this would account for daily fluctuations in flow rate from different PWS tank levels.

These values presented represent approximate thresholds that could be practically applied depending on known gauze size in operating e-Taps. As seen, smaller gauze pore sizes would necessitate higher $Q_{baseline}$ reduction alert thresholds. Thresholds should also decrease as gauze pore sizes get larger, in line with the relationship between pore size and flow rate seen in Figure 4.7c-h. The error range of the flow meter revealed above would mean that thresholds lower than 5% would give higher likelihoods of ‘false alerts’ resulting from imprecision of the flow meter. Therefore, 5% is recommended as the threshold for larger gauze pore sizes rather than lower thresholds.

Table 4.3 Recommended flow rate reduction thresholds for debris build-up alerts

Gauze pore size (mm^2)	Mean measured percentage reduction (%) from $Q_{baseline}$ (100%) for all sand sizes, for loadings at:			Recommended percentage reduction threshold for predictive cleaning alert, based on a longitudinal average *(Recommendations in italics disregard ‘false alerts’)*
	13 g	16 g	22 g	
0.15	96.31	93.04	84.37	> 9% *(> 9%)*
0.36	97.94	94.65	84.50	> 7% *(> 7%)*
0.42	98.35	97.11	90.92	> 5% *(> 4%)*
1.38	99.59	97.96	94.70	> 5% *(> 3%)*
1.95	98.79	97.97	95.76	> 5% *(> 3%)*
3.24	99.18	99.18	96.35	> 5% *(> 2%)*

This technique would utilise the newly available high-quality data for accurate predictions, and would use empirical measurements that reflect real flow rates, rather than relying on probabilistic machine learning. Higher resolution and accuracy flow rate data from e-Taps now allow predictive maintenance to move beyond the limited assessment of either ‘working’ or ‘broken’ water points (Carter and Ross, 2016). Application of real-time flow rate data for predictive maintenance would be a tangible ‘use’ of data, so far overshadowed by ‘collection’, ‘transfer’ and ‘analysis’ with this kind of monitoring data as shown in Section 2.5.4.

It is important to note that benefits from predictive maintenance would be lost without a responsive maintenance team (Brocklehurst, 2018), financial sustainability, a robust water distribution system, and the other systemic requirements of sustainable water systems. On the other hand, accurate and prognostic remote water point monitoring can enhance each of these requirements over time and help move towards the service delivery approach.

Application of flow rate threshold alerts in the field would allow refinement of the thresholds proposed in Table 4.3. A longitudinal study with control would be required (beyond the scope here) to assess the accuracy and gains from predictive cleaning, how this compares with other O&M required, and the feasibility of acting on such alerts. These alerts could apply to any similar technology in the future.

Furthermore, if smart meters develop additional sensing capacity such as pressure sensors (proposed in Chapter 10), additional parameters can refine predictive alerts. This could provide information of the whole PWS, for instance on tank level or burst pipework. Because smart meters have fewer mechanical moving parts that gradually wear compared to technologies such as handpumps, non-functionality is more likely to occur suddenly. Therefore, predictive maintenance ‘upstream’ could be more useful.

Harmonization between ‘hardware’, which constitutes the physical infrastructure, and ‘software’, which connotes management and O&M, is argued to be vital for rural water supply sustainability (Whaley and Cleaver, 2017; Pearce et al. 2014). Overall, this would provide a smart method to bring these together.

4.6.4 Limitations of the study and further work

This study has addressed the research objective well, and has progressed beyond it by providing an empirical basis for predictive maintenance. Evaluating accuracy across more flow meters would be more representative of the many of e-Taps currently operating. Inaccuracies were similar enough to extrapolate general findings. It was also not possible to represent heterogeneous debris, however disaggregating sand sizes provides extrapolatable data. The more precise instrumentation available in the laboratory delivered more precise results than possible in the field. Manual tag removal and stopping timing were subject to minor inaccuracies however these were shown to be negligible in the findings presented. Higher flow rates were not possible on the hydrobench, however the available range (4.3 to 38.6 l min^{-1}) is considered sufficient, especially when considering the recommended range of DP flow rate (~17 to 25 l min^{-1}).

Specific ideas regarding technical development of smart meters beyond the scope of this research are outlined and justified in Chapter 10. Regarding accuracy, further work could focus on air pockets within the PWS pipe network. Air pockets are common in PWSs (Nuages and Whittington, 2010) and form from dissolved air coming out of solution from pressure change, leaks into pipes, bends in pipework, and tank emptying, and can result in occasional but significant flow measurement inaccuracies from rapid impeller rotation. Air-release valves would likely provide practicable solutions. Additionally, creating a uniform jet profile across the flow meter interior with the insertion of channels or gauze would help increase accuracy. Another challenge relating to the y-strainer is the potential of introducing trace contaminants (e.g. Pb, Cu) into the flow leaching from corroded brass. Use of high quality brass components will reduce this risk. Similarly, a new risk of microbial contamination from biofilms on debris build up can be reduced with cleaning, as discussed above.

Furthermore, detection of leakage in the network could be a potential new application of smart meters. One practical method could be to visualise or automate alerts for low-flow non-functionality at individual smart meter DPs while others maintain higher flow rates. This could indicate a leakage upstream from the DP in question. Alternatively, rapid flow-rate drops across a network would indicate upstream leakage. Combination with a tank float-sensor would improve accuracy by allowing direct comparison between tank volume and volume dispensed from DPs. Regardless of this added capacity of smart meters, leaks on small rural PWSs tend to result from dramatic and visible events (e.g. a farmer accidently breaking a pipe, or erosion), and therefore leak detection is unlikely to ever require smart meters. The PWS is often visible to much of the community or management committee, unlike hidden urban networks which require remote leak detection.

4.7 Conclusions and novelty of work

In this Chapter, an evaluation of the robustness of e-Tap operation has been presented, focusing on the accuracy of the flow meter reading and on flow rate reduction caused by y-strainer addition and debris build up. This has suitably addressed the technical robustness research gap found in the literature review, focusing on limitations to robustness across longer timescales of operation, which is a new contribution. This was important to investigate at this stage considering the expected increase in smart meters. This research has moved beyond the previous binary understanding of functionality.

Novel findings suggest that the e-Tap measurement of flow is marginally inaccurate with an average relative error of +3.63%. Varying baseline flow rate does not significantly impact this. This means that users have been collecting a slightly lower volume of water for the credit that they are paying for. This is very insignificant compared with broader benefits to rural water supply sustainability and access that are shown in Chapter 5. A general calibration across e-Taps by 3.63% will fine-tune accuracy. Importantly, this finding shows that the smart meter measurements of volume used in the following chapters are reliable and accurate. The benefits of blocking debris reaching the e-Tap flow meter with the addition of the y-strainer outweigh any minor flow rate reductions observed. These reductions are negligible for all gauze pore sizes measured until roughly 13 g of debris builds up inside the y-strainer gauze. The novel results here can inform decisions of approximate gauze size to install, refined when the nature of the debris is known. The importance of good flow rate is further emphasized by users themselves in Chapter 5.

These novel findings have direct application in planning and management. A calibration software application for staff use in the field has been developed. The flow rate reductions relative to debris build-up for specific gauze sizes provide a novel basis for accurate predictive maintenance using alerts based on thresholds proposed here. This benefits from high-accuracy flow meters on e-Taps (compared with proxy measurements used on different technologies). This contribution demonstrates the new ability to remotely and cheaply refine data collection measurements, and use software solutions for hardware problems. This ability for service providers to improve service delivery remotely has significant and original benefits beyond the smart meter benefits established in Section 2.5.6, with potential to support the service delivery approach and harmonize hardware with management processes. The study has demonstrated the enhanced capacity available from a combination of high-resolution sensing data and remote analytics, and shows that potential benefits of smart meters go beyond those currently established.

Chapter 5. SMART METER EVALUATION IN SOCIO-ECONOMIC CONTEXT IN TANZANIA

5.1 Introduction

The previous chapter has evaluated the technical performance of a smart meter, which addressed EF 1 evaluation criteria from the evaluation framework (Table 3.1).

Now, the objective of this chapter is to evaluate the effectiveness of smart meters in their socio-economic context in Tanzania. This addresses research gap (1) identified in Section 2.5.7 of the need for further evaluation within the socio-economic system. This Chapter will help uncover new understanding of smart meter operation, which is important for good decision-making. The analytical framework in Section 3.1 outlined why investigation of smart meter interaction with socio-economic factors is important and part of a more systemic approach.

The socio-economic evaluation criteria from the evaluation framework (developed in Section 3.3) that are investigated here are as follows:

EF 2. Demand from service providers

- Impacts
- Satisfaction

EF 3. User experience and demand

- Impacts
- Affordability
- User satisfaction
- Likelihood of continued use over time

EF 4. Accessibility

- Ease-of-use of smart meter and tag
- Equity of use

These criteria are evaluated using interview and survey methods with managerial stakeholders and users in Tanzania. This fieldwork approach is used because it generates information directly from those who interact with smart meters themselves.

Main findings from previous evaluations (e.g. Check et al., 2017; GSMA, 2020a) have been improved revenue collection, improved access to DPs, and improved management and service provision. These were shown in Table 2.16. The evaluation here adds value by contributing more solid evidence on these impacts, and revealing novel information on other impacts, including: accountability, technical glitches, satisfaction, quantification of time saved, use of newly available time, improvements to O&M, community health, affordability, likelihood of continued use, ease of use, tag loss, tag sharing, and user comprehension. The findings here also further understanding of: the benefits of saved water collection time; how smart meters can include more marginalised community members; and the fundamental importance of the PWS and community management organisation.

The key findings from this evaluation (and Chapter 6) have been published in the journal article:

Ingram, W., & Memon, F. A. (2020). Rural Water Collection Patterns: Combining Smart Meter Data with User Experiences in Tanzania. *Water*, 12(4), 1164.

5.2 Background and study sites

Tanzania was selected for this evaluation because of the focus in the literature review (Section 2.4) and availability of smart meters. Across rural Tanzania, the population without basic drinking water service stands at 57% (JMP, 2019), higher than the regional average, and even communities with recorded water points are not guaranteed year-round service (Twisa and Buchroithner, 2019). The characteristics of rural communities available for study in Tanzania share many attributes with other rural communities across sub-Saharan Africa. The main community selected for evaluation (herein referred to as Community A) is outlined in Table 5.1. eWater taps have been operating here approximately two years before the study. This community was selected out of approximately five possible communities with eWater taps in Tanzania because enough time has passed for impacts and limitations to become apparent, as opposed to more recently operational communities. This allows for more learning opportunities.

Table 5.1. Characteristics of Community A

Location and topology	Rural community in Northern Tanzania ~15 km from nearest town, widely spread within agricultural valley at 1,370 m elevation.
Water resources	Sufficient shallow groundwater with approximately 80% of unlined wells < 30 m deep (in town ~15 km north; Pantaleo et al. 2018). Seasonal surface water in riverbeds and dams.
Demographics	Rapidly growing young population.
Livelihoods	Overwhelmingly agricultural, subsistence or wage based.
Roads	Some graded, no tarmac. Dirt paths.
Agricultures	Predominantly maize, with some sunflower, banana (when there is a water supply), ground vegetables, cassava, yam, and other root vegetables. Almost entirely rain-fed.
Seasonality	Seasonal rainfall and temperature (see Section 7.3)
Vulnerabilities	Limited healthcare, access to services and opportunities, and education. Vulnerable to shocks from the economy, rainfall variability, and state policies.
Ethnic groups	Predominantly Iraqw and Gorowa.
Languages	Kiswahili, Iraqw and other tribal languages, with limited English.
Size	Large spread; six sub-villages across approximately 10 km^2.
Population	No accurate or recent census available. • *Mtendaji* (village executive office) estimates 3,746, with 1,500 under 5 years old • Manual households count using satellite imagery (n = 270-300) multiplied by mean number of residents per households (5.9; see results below), gives approximately 1,680 people.
Housing	Concrete, earth-brick, or mud-wood, with corrugated metal or grass roofs (see Chapter 7 regarding rainwater harvesting).
Public buildings	Shops and eateries in the centre, churches and a mosque, two primary schools, one secondary school, health clinic, village council office and storeroom, Community Owned Water Supply Organisation (COWSO) office.
Mapping	See Figure 5.2

The degree of scarcity of water resources has not been specifically quantified in Community A, however because of its location and climatic attributes this is not a pressing issue, particularly in comparison to more arid parts of East Africa. Shallow and deep groundwater is relatively available, and surface water is readily available particularly during rainy months (seasonality is outlined in Section 7.3). At the time of fieldwork, Community A had not been included in previous formal research studies at the time of fieldwork, to the authors knowledge, however since PWS installation in 2015-2016 it had been subject to visits from NGO and local government staff. No specific data on waterborne disease in Community A was available, however it is clear from the below findings that diseases have been reduced from previously high levels by the PWS and the impact of smart meters on clean water access. It therefore shared this attribute with many other rural communities. Experiences between different communities will always vary, however the small size, agricultural setting, and use of domestic water mean that user experiences will find relevance with users in other such communities. Overall, this community is generally representative of other rural communities in sub-Saharan Africa, particularly in climactically similar parts of East Africa, where smart meters operate. The findings are therefore translatable to other rural communities in Tanzania and sub-Saharan Africa, particularly to small communities (e.g. < 500 households) with seasonal agriculture and insignificant water scarcity. The common nature of the small-scale gravity-fed PWS also makes findings translatable across many such communities that have similar systems, which are increasingly built in such settings (see Section 2.3.1), and can help guide decision-making regarding smart meter installation.

Community A has a PWS (pictured in Figure 5.1) with a 50 m^3 elevated water tank on a hillside served by a solar-powered motorised borehole pump 1.1 km away in the valley. The borehole is 78 m deep with a pump capacity of 6,000 $l\ hr^{-1}$ (6 $m^3\ hr^{-1}$; 100 $l\ min^{-1}$), and approximately 10 hours of pumping fills the tank, which depends on available solar power from 32 solar panels. The PWS has 13 named distribution points (DPs) gravity-fed from the elevated tank; the shortest and furthest distance between two is 240 m and 1.1 km respectively (mean = 480 m), and the furthest DP from the tank is 2.6 km. These are indicated on the map below (Figure 5.2). The PWS was installed in 2015-2016. Each of the 13

DPs has the eWater tap on the DP, and is available to all households (discussed below). Deep boreholes 15 km north from Community A satisfy WHO and national quality standards (Pantaleo et al., 2018), and the water quality from this PWS is assumed to be similarly high; no information from the evaluation suggested otherwise. A COWSO (Community Owned Water Supply Organisation) exists and is mandated by national policy to conduct O&M and revenue collection, which should have ten members. This is another attribute of Community A that has translatability to many other communities, as (as shown in Section 2.3.2) the ‘community management’ model remains relatively dominant in this context. Water costs 25 TSH per 20-litre container (1.25 TSH per litre, or ~0.0004 GBP).

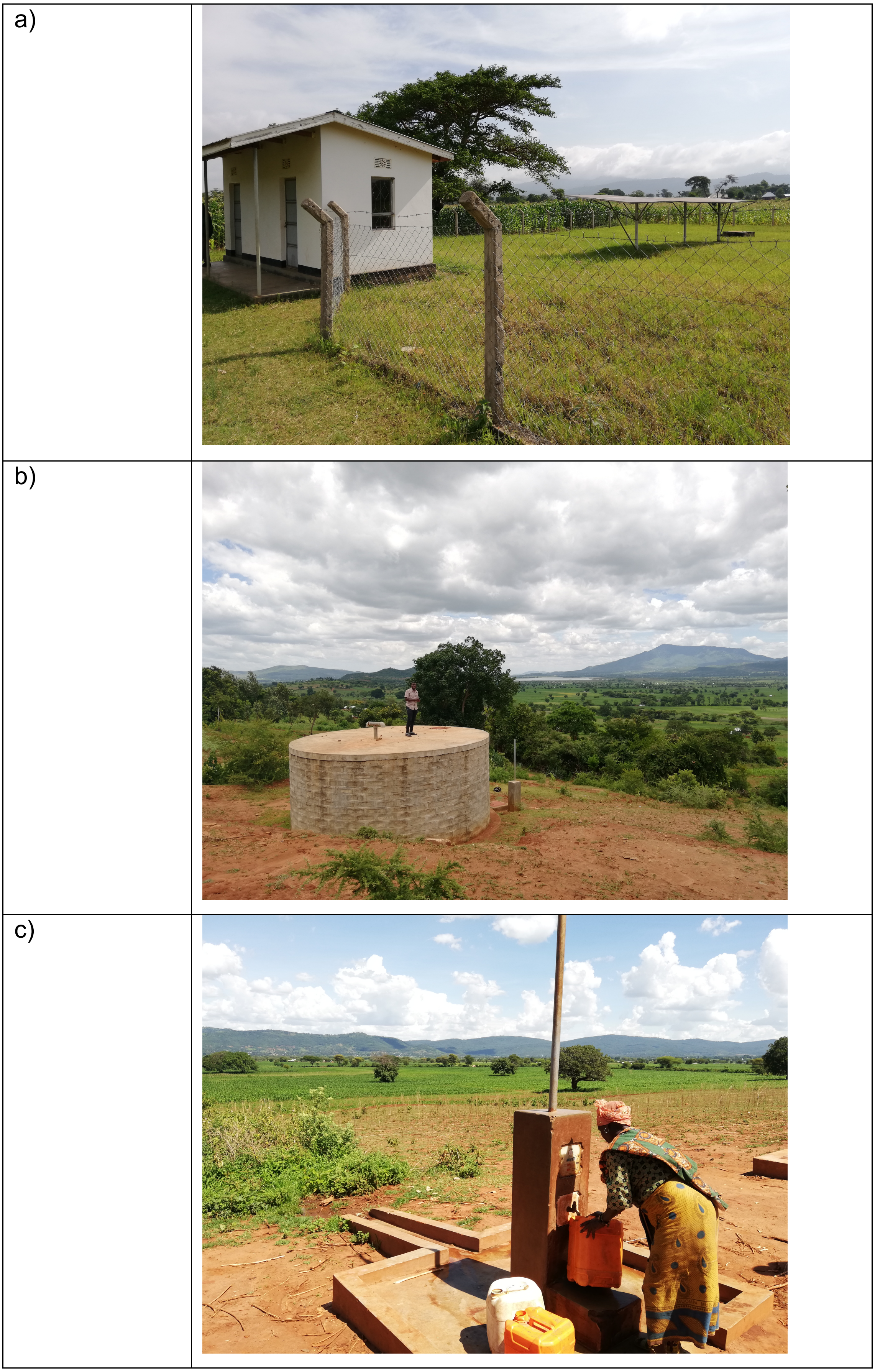


Figure 5.1 a) Borehole and solar powered-pump, with COWSO office; b) Elevated 50m^3 water tank; c) DP with eWater tap in use (source: the author)

In additional to the PWS, alternative water sources are two functioning handpumps with part-time vendors (and more than six broken handpumps), two north-south parallel riverbeds, seasonal rain and surface water, lined wells, and a small dam that fills with rainwater built for livestock watering; these are not the focus of this study.

An additional community was included in this evaluation in order to act as a control. This community (Community A1) is <4 km from Community A, across a river in a different administrative ward. This is also mapped in Figure 5.2. It shares most of the attributes of Community A such as electricity and road access, but is not reached by a PWS. Users rely on shallow wells, riverbeds, and streams, and one functioning handpump.

5.3 Study approach and methods

The approach used for this research aimed to uncover information about user and managerial stakeholder experience. This was considered the best way to evaluate effectiveness of smart meters in this context. Semi-structured interviews, survey questionnaires, and observation were conducted in Community A between February and April 2019. Using a case study community allows for collection of information in an in-depth and ordered way from an appropriate range of voices and sources, and enables deeper insights for broader application across sub-Saharan Africa.

The steps of this study were done in the following order:

1. Development of evaluation framework (and confirmation of technical robustness in Chapter 4)
2. Selection of study site: Community A
3. Rough stakeholder mapping, including key informants, and introductions with community members
4. Interviews with managerial stakeholders [protocol A]; and observation of PWS and smart meters [protocol B]

5. Interviews/questionnaires with 'key informant' users [protocol C], then remaining users [protocol E]
6. Observation and interviews with users in Community A1 [protocol D].
7. Analysis of qualitative, then quantitative findings; with triangulation.

The detailed methods selected are presented below, and are based on established methods as referenced below. Questions in protocols were developed (below) based on the specific evaluation framework criteria. Questions were mostly designed to be objective, and some are designed to uncover subjective experiences of users. Some additional questions were also included based on the objectives of Chapters 6 (water collection patterns) and 7 (seasonality). Some questions were slightly refined after new information from Step 3 above and after pilot interviews.

Attempts were made to limit the extractive nature of the research in accordance with the family of approaches known as 'participatory rural appraisal' (Chambers, 1993; 1994) to limit imbalance of perceived power between the researcher and respondents, and to adhere to the 'Lean' research principles or 'rigour', 'respect', 'relevance', and 'right-sized' (D-Lab, 2015). This was done by, for example:

- Expanding the range of respondents as wide as possible
- Using pen and paper with 'active listening', rather than an expensive tablet, to limit imbalance of perceived power
- Conducting interviews when suited the respondent not the interviewer
- Providing explanations to users when asked
- Ensuring sample sizing was representative and 'right size', i.e. not needlessly big.

The influence of social desirability bias was recognised regarding the smart meters, and care was therefore put into ensuring questions were objective, simple, and non-leading. Objectivity of the researcher was explained to each respondent beforehand. Other stakeholders who had less reason to give biased responses gave similar responses to users, confirming bias was limited.

Questions used are developed as below, and mapped to each evaluation criteria. Quality of information depended partly on respondent rapport.

Interviews were conducted with an interpreter from Kiswahili into English like in other studies in this context to ensure that questions were asked in an understandable and respectful way (e.g. Behnke et al. 2017). This increased interview length and therefore limited available time. Additionally, throughout fieldwork non-structured and ‘do-it-yourself’ observations on eWater tap use were conducted, and this was useful for better understanding user responses and experiences.

Overall, this approach used in this study adds rigour to the data collection, analysis, and results, therefore adding value. This helps address the research gap in the literature review of further independent, academic evaluation.

5.3.1 Managerial stakeholder interviews

Table 5.2 presents the respondents and methods used for the managerial stakeholder interviews. Conducting these more qualitative interviews before user interviews had the benefit of uncovering relevant contextual information about rural water supply in Community A, and of making introductions and relationships in the community, which was important considering the approach outlined above (in particular ‘relevance’ and ‘respect’).

Table 5.2 Managerial stakeholder interviews and methods

Managerial stakeholder	Method selected
Mwenye kiti (chairman) of village council	Unstructured interview on introductory information on rural water supply in Community A
District Water Engineer (DWE) for district	Unstructured interview on introductory information on rural water supply in district
Members of the village council: *Mtendaji* (village executive officer) and 13 members (m:f = 8:5).	Unstructured 'focus group' at monthly village council meeting for introductory purposes and for detailed information on community context.
Members of the COWSO (Community Owned Water Supply Organisation) n = 8 COWSO members labelled in Results (Section 5.4) as: (MS1), (MS2), (MS3), (MS4), (MS5), (MS6), (MS7), and (MS8).	Unstructured 'focus group' at monthly COWSO meeting to uncover detailed information about their experience, rural water supply context, and capacity of COWSO. Did not cover the questions in protocol A (below) so group pressures did not influence responses. Protocol A: Individual semi-structured interviews (protocol A; Appendix B) with COWSO members (mean interview length 57 min; n = 8; male:female = 5:3). 27 open and closed-ended questions mapped to evaluation framework criteria, conducted when convenient for respondents over four days. 1 x Secretary-Accountant, 1 x *Mwenye kiti wa COWSO* (chairman), 1 x signatory, 5 x *Djumbe* (advisors).
Secretary of COWSO (Respondent MS1; identified as most knowledgeable)	Further unstructured interview for detailed information on the RWS infrastructure and in-depth context of RWS system.

As most managerial stakeholders are also users, their experiences and responses are also included in the results relating to user experience.

5.3.2 User interviews and questionnaires

In order to capture a wide range of household types, minimise risk of representation bias in this study, and provide a more representative sample with the available fieldwork, sampling of respondents was split into two groups, as suggested for rural WASH studies of this nature (in Giné-Garriga et al., 2013), which were sampled consecutively with different interview protocols:

Protocols C and E (Appendix B). Different random selection methods were used for each group, and there were no different household characteristics between groups.

The first group were ‘key-informant’ respondents and were given a longer semi-structured interview protocol of 49 questions: protocol C. This featured both: a) quantitative closed-ended or multiple choice questions designed to provide accurate and measurable data (e.g. ‘How many hours per day is the smart water point that you use functional?’; ‘Who collects water in your household most often?’; ‘How is this price for your household?’); and b) qualitative, open-ended questions, designed to provide new, experiential information (e.g. Young et al., 2019) from a variety of user experiences (e.g. ‘How is it using the smart meter?’, ‘Who in the community is not able to use the smart meters’?). Therefore, benefits from both are provided. Mean interview length was 42 min; sample size (n) = 32; male:female = 3:5. Six per day was possible. The protocol’s 49 questions were categorized into background information (including household characteristics and disaggregated source choice), demand from DPs (including experience of using smart meters, affordability, and satisfaction), and accessibility of collection (including travel, time taken of collection, time in the day, and ease of use). Alternative sources (Anthonj and Brockleburst, 2019) were not deemed an appropriate focus and specific questions were not included because the focus here is on smart meters and PWSs, as justified in Chapter 6. It can be hard to differentiate impacts of smart meters from those of PWSs in the first place, as discussed below, but these questions and analysis aimed to distinguish between the two.

The second group (protocol E) was asked only the 36 quantitative, closed-ended questions from the first interview protocol to reduce the length. This was to allow more respondents to be included within the limited timeframe therefore reaching the required sample size (below) and making statistical analysis more accurate. Mean interview length was 20 min; n = 30; male:female = 1:2.

This study therefore benefits from the new information uncovered from the first sample group, and the improved accuracy from the second group. Both protocols also incorporated some questions and additional measurements regarding water collection patterns and seasonality, which are for the objectives in Chapters 6 and 7, which utilised the same fieldwork.

In both groups, one respondent from each household was asked to respond. As in surveys of this nature, ‘households’ are treated as users. The GPS location was taken for each interview, which are presented in Figure 5.2 (and also used in Chapter 6).

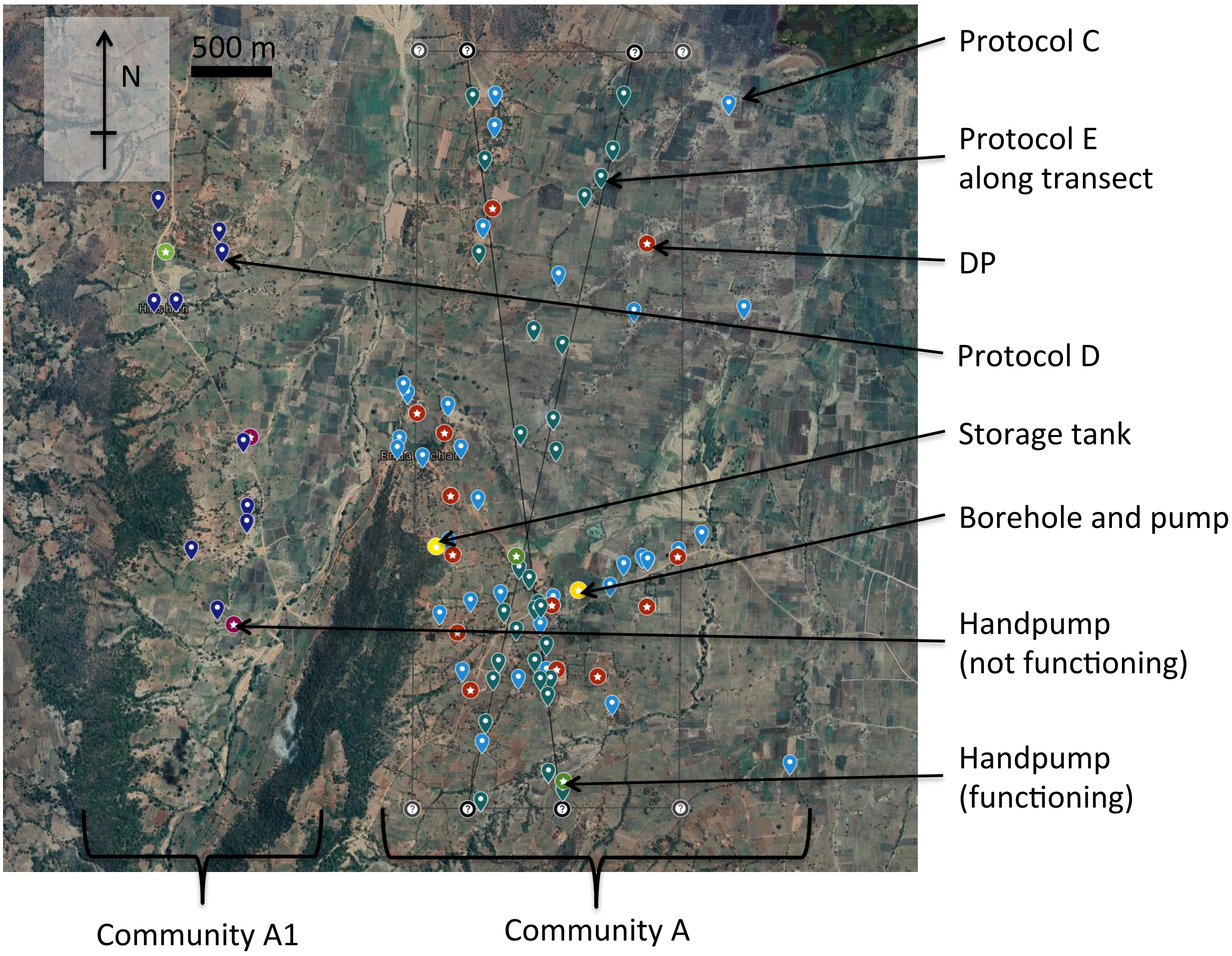


Figure 5.2 Map of Community A showing locations of user interviews, transect walks, DPs, and key PWS components; Community A1 is shown on the West side of the river

Sampling of the first user group (protocol C) was achieved by selecting households from satellite imagery as randomly as possible, while at the same time ensuring that each sub-village was represented. This avoided any visual bias on type of household (e.g., wealth, household size), and allowed qualitative information to be generated from across the relatively diverse sub-villages and geographies in the community. For the user second group (protocol E), randomness of household selection was prioritised for the purposes of purely statistical analysis, and a transect walk was selected to eliminate bias. A transect walk is a systematic walk along a defined path through the sample community, and is a useful method of random sampling when no census list of households is available (Pérez-Foguet and Giné-Garriga, 2018). This was done after the first group interviews, and benefits by incorporating potentially marginalised households away from paths and by ensuring a diversity of respondents across hilltop, village ‘centre’, agricultural plain, and other locations. Two transects of 5.3 and 5.4 km in length were drawn over satellite imagery of Community A, as shown in Figure 5.2, using randomised coordinates (from a random number generator) on the edges of a rectangular boundary (~ 10 km^2). Households within 30 m of the line were sampled, in order. The benefits of these combined sampling methods outweigh perfect randomness.

The sample size of users was selected in order for the analysis to give the best representation of the community, while suitably balancing precision, confidence, ‘right-sized’ research, and the capacity of the fieldwork to provide the required information. Overestimating the number of households in Community A at 300, descriptive analysis to a precision of ±12.5% and a confidence level of 95% requires a sample size of n = 60 (as prescribed for rural water supply surveys in small communities by Pérez-Foguet and Giné-Garriga, 2018). This is deemed a good balance between precision and fieldwork capacity for providing the required information, and is preferable to different sample size calculations used in larger communities elsewhere (e.g. Angoua et al., 2018). Household number is less than 300, giving confidence to this required sample size. In total, n = 62 was achieved. Other studies in similar rural communities have sampled, for example, n = 27 (Foster and McSorley, 2016), average n = 12.5 per community (Behnke et al., 2017)), and n = 40 (Mwamaso, 2015). Overall, the sampling methodology used in Community A is robust and very suitable for uncovering qualitative information and generating quantitative data.

Distances from respondent households to DPs were measured using the GPS locations for analysis here and in Chapter 6. In order to accurately measure distances that best represent the reality of users’ collection journeys satellite imagery was used, as it is less susceptible to subjective inaccuracies from estimation by respondents or researcher. This also benefits by removing unnecessary questions for respondents, in line with ‘right sized’ research. Measurements can be taken as either Euclidian, i.e. straight lines (as in Cook et al., 2016), or along path routes. Circular (i.e., Euclidian) buffer zones within 500 m of a water source in small town settings in Mali overestimated catchment of households by 14%, as they do not describe true travel distance travelled (Martínez-Santos, 2017). Likewise in Community A, distance measured along paths was longer than Euclidian measurements by an average of 22.5%. Both types are included in results below, however distances measured along paths are used in the analysis as they give a truer representation of the non-linear journeys users take.

Analysis of quantitative data included descriptive statistical techniques including measures of central tendency and dispersion, frequency distribution, and regression. Qualitative data followed: 1) manual transcription, 2) familiarisation with answers, 3) categorization and coding of answers, 4) mapping to evaluation framework criteria, 5) identification of similarities across responses (as all done in similar qualitative analyses e.g. Rieger et al. 2016), and 6) drawing out of key findings for cross-reference against quantitative findings, and interpretation. This follows the relevant steps from the ‘framework method’ for qualitative analysis (presented by Gale et al., 2013). Some qualitative answers could be quantified themselves. This analysis draws enough richness from the data to address the research objective. The multivariate nature and size of the dataset make more involved statistical analysis inappropriate. Analysis of these data is also extended in Chapter 6 for investigation of water collection patterns.

5.3.3 Comparison with neighbouring community

It was recognised that, due to the new nature of the technology, and unique setting and PWS, a perfectly representative control study was not possible. However, a control study using slightly amended interview protocols (protocol D, 26 questions, Appendix B) in a neighbouring village to Community A (<4 km in order to minimise extraneous differences) gave good contextual comparisons of water collection and a ‘reality check’ (mean interview length 24 min; n = 10; m:f = 6:4). Sampling was conducted the same as for protocol C. This is a more reliable control then another far away community with smart meters in a different setting as many of the external variables are similar or the same. This was designed to elicit objective comparisons as a ‘baseline’ of rural water supply.

5.3.4 Approach limitations and ethical considerations

There are some unavoidable limitations to the methodology used. First, it was not possible to conduct a longitudinal study because of practicalities of fieldwork. Findings are only representative of the time of the fieldwork; however this is appropriate for the research objective considering the longer-term impacts of rural water supply projects and the time smart meters have been operating in the community. The smart meters themselves will have developed beyond the time of this research and so the technical glitches highlighted, for example, are likely to have been addressed. Additionally, only one community could be evaluated in this way. Using a control study site that has a PWS but no smart meters would not have given as representative results at Community A1; however it is a challenge to differentiate impacts of smart meters from impacts of a PWS in the first instance. The analysis attempts to address this accordingly.

Secondly, there are some potential limitations to the data collection. These may originate from unavoidable ‘barriers’ between researcher and respondents of perceived agency, language, and inability to comprehend users realities. Quality of interpretation did vary somewhat with fatigue, repetition, occasional Iraqwi-Kiswahili-English interpretation, and concepts of time (people tend not to memorise everyday timekeeping). The most significant potential limitation would have been social desirability bias, however this was minimised as outlined above. There was some minor gender and age imbalance in the sampling caused by younger men being unavailable because of farming. Furthermore, some questions were not included in the protocols because they are not relevant to the evaluation framework criteria (or Chapters 6 and 7), and did not fit with the ‘right-sized’ or ‘respect’ parts of the study approach. These included perceptions around accuracy of flow measurement, wealth of household, and education levels, assessments of which are prone to inaccuracies.

Detailed research and ethical considerations received approval from the University of Exeter (ethics code: eEMPS000026v2.1) and specific steps included all respondents being told before each interview the purpose of the questions, and that their answers will remain anonymous, confidential, and destroyed after the work is completed, and that participation is voluntary. Respondents were also asked: Are you happy to be interviewed on this topic?; Are you happy for your anonymous responses to be included in publications?; and Do you have any questions? Names were encrypted during each collection and no respondent was under the age of 18.

5.4 Results

Here, the results from the above methodologies are presented according to the evaluation framework. Individual responses or evidence from individual respondents are indicated in the text as follows:

- managerial stakeholders from protocol A = e.g. (MS5);
- ‘key informant’ users from protocol C = e.g. (C1);
- remaining users from protocol E = e.g. (E10); and
- members of Community A1 from protocol D = e.g. (D4),

and quotations are provided in italics.

An overview summary of the evaluation is presented below in Section 5.6.

5.4.1 Characteristics of managerial stakeholders and users

The details of the managerial stakeholders interviewed are included in Table 5.2. The eight members of the COWSO were best placed to provide contextual information on rural water supply. They are also members of the community, users, and some act as credit resellers. Four of the COWSO members worked collecting revenue from vendors or ensuring that DPs were operational before the smart meters were installed, and can therefore provide comparative insight.

Members gave varied opinions on the most difficult responsibility of the COWSO, ranging from: maintaining PWS infrastructure and doing quick repairs, sometimes paying from their own resources (MS5, MS1, MS7), addressing the low levels of understanding of users (MS2), relationships with users during poor service levels (MS1, MS2), and the inability to expand the PWS to households not yet reached (MS4, MS6). The secretary-accountant, the only member given a smart phone, checks DP functionality and revenue collected throughout the day, and relays information to the COWSO. He does not look at information on flow rates (this supports the need for automated threshold alerts proposed in Section 4.6.3).

Protocol A revealed that most COWSO members had very little agency or knowledge of the PWS. This is limited by education, time available for meetings, motivation, and wealth. The secretary-accountant is left to do the majority of the work. The biggest monthly expenditure of the COWSO is wages for watchman at the solar pump, the village technician, and the secretary-accountant. Major pump failure has been the largest cost (e.g. 1,000–1,500 GBP). Pipework often leaks (farmers and erosion also cause pipe bursts) but this is relatively cheap to repair. The tank outlet has broken once since installation (MS1, MS7, MS8), and the pump has broken twice (MS1, MS4, MS5, MS7). The COWSO does not have adequate finance available for the larger costs, but tends to for smaller maintenance tasks and wages. Detailed financial information was not available. Even with the increase in revenue from the smart meters (see below), members believe the low price of water remains the limiting factor for cost recovery.

The mean number of residents per household was found to be 5.9; std. dev. = 2.3; range = 1–11. The majority (89%) state their occupation as farmer, and mean age is 38; std. dev. = 15.4; range = 19–78. Mobile phone ownership is as expected, with mean per household of 2.0, and mean per person as 0.34 (19% of households have smartphones, and this does not appear to be a good indicator of household wealth). Women and/or children participate in water collection in 100% of households sampled. Only four users answered that they do not use a smart meter DP as their main source of drinking water, instead using lined wells or riverbeds that are closer more often. Of this sample, ~77%

of users (41) include smart meter DPs as their main water source for cooking; ~64% (34) as their main source for clothes washing; ~36% (19) as their main source for bathing; and ~26% (14) as their main source for their domestic animals (but these had very few animals; most animals are watered at the dam). The mean volume collected reported by households from DPs is 133 litres per day (see Section 6.5.2 for comparison with smart meter measurements). Non-users (n ≈ 9) either think the DPs are too far from their households, have stopped using DPs because of irregular water supply, cannot afford to replace a lost tag, are long-term visitors in the community, or have preferable free alternative surface water or well sources. Overall, while alternative sources account for collection of more non-consumptive domestic water as expected, smart meter DPs are the most significant domestic source, and the focus on the PWS here is justified. The price of credit is the same per litre before smart meter installation. Approximately 17% of users answered that this is too high.

Members of Community A1 investigated show similarities with Community A, confirming it as suitable comparison for the purposes here (mean age of respondents = 37, household size = 6.4, mobile phone per person = 0.31). Respondents used either the functional handpump if close enough, or the riverbed, for all domestic uses, with mean litres collected of 128 litres per day.

5.4.2 Demand for smart meters from managerial stakeholders

Impacts

The major beneficial impact expressed by the managerial stakeholders was the increase in revenue collection, which is the COWSO’s main concern. This increase is from pre-payment and automated collection which removed the need to pay water vendors at each DP (who collected a proportion of revenue, sometimes too much), and from the removal of non-revenue water which was from profligate washing out of buckets and vendors allowing free collection. Every litre is now valued economically and users typically use only one or two litres now to wash out buckets and clean hands. Greater water use from any-time collection (see below) also increases revenue. Lack of records limits analysis of revenue and costs, however this does not limit the major result reported from managerial stakeholders. All respondents to protocol A answered that tracking of revenue collection from vendors was ‘hard’, and it is ‘better’ with smart meters. Comparing cash collected against old manual meters, done monthly, was inaccurate because of non-revenue water and dishonesty from vendors, and the COWSO lost a lot of money (MS1, MS2, MS3, MS5). With smart meters, the volume dispensed and revenue collected are automatically reported, and the money can go directly to the COWSO bank account (MS2, MS3, MS7, MS8). This new method has made COWSO meetings *“a lot easier and more accountable”* (MS1). It was emphasised that it was initially difficult to show users that each drop is now paid for but now users understand and are happy with this.

Reporting of breakdowns or problems with the PWS is now better for the COWSO (MS1, MS2, MS3, MS4), who have access to real-time information, unlike before when communication was difficult (MS2). This remains partially limited by only one COWSO member having access to the information via the smartphone, and some information is still through word of mouth.

Some negative impacts were also raised that arise from technical glitches. Occasionally users report collecting volumes of water that do not match the credit removed from the tag (MS1, MS2, MS5, MS7), which undermines revenue collection, and some credit resellers have reported not receiving credit despite payment with mobile money. As users, some COWSO members have experienced occasional drastic inaccuracies of credit removal from their tags (e.g. only receiving two containers rather than forty). It was also reported that some tags have been wiped of credit on their first use. Users are more likely to report overcharging than undercharging, which has likely also been occurring. Tag failures were ranked as the most important improvement needed. These technical challenges appear to relate to the timing of software upgrades[4] (and flow measurement inaccuracy, as shown in Chapter 3), and are therefore not fundamental or long lasting. Respondents emphasise the need for a smoother software update process. Respondents have also emphasised the theft of a smart meter solar panel from one of the DPs which led to a long disagreement

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[4] An alternative explanation of more drastic inaccuracy of credit removal is air pockets in the pipework. Solutions to this have been discussed in Chapter 3.

about whether the responsibility for replacement should be with the households in the sub-village or with the COWSO, during which the DP was non-functional (the solar panel design has since been made more secure). Additionally, higher fees for resellers (currently 5% of revenue) were called for (MS2), as mobile phone tariffs needed for sales sometimes outweigh earnings.

Satisfaction

Managerial stakeholders indicate overall high satisfaction. The benefits to finance, monitoring, and accountability outweigh infrequent negative impacts from any technical glitches, and all managerial stakeholders accept the smart meters as an improvement. Hypothetical suggestions of what might make the COWSO want to stop using smart meters in the future include not making enough revenue (MS1), a better system or technology (MS2, MS6), or if there are significant failures and the COWSO is not fully involved (MS3). There is general recognition that infrastructure does break, and that the smart meters are adequately robust. Some limitations to technical robustness proposed include quick battery drainage (MS2) and theft of solar panels (MS3). While the smart meters themselves are designed to be tamper-proof and secure, the solar panel could be relatively easily stolen, and this had happed more than one in the community. Battery drainage has been addressed since by re-designs and selection of better quality batteries, and during the time of fieldwork a more secure solar panel bracket was being developed.

Overall, managerial stakeholders, in particular the COWSO, exhibit high demand for smart meters. They beneficially impact revenue collection, monitoring, and accountability, and bring high satisfaction.

5.4.3 User experience of smart meters

Impacts

The details of users survey participants (protocol C and E) are outlined in Section 5.3.2. 90% of users (protocol C) expressed that using the smart meters is positive overall. They are easy and quick to use and to collect water from, and any reservations are based on PWS failures such as tank emptying. The major impact for users is the reduced time now needed to collect water from

DPs. The removal of the short time-window of when the vendor was previously available from other activities (e.g. farming, church), which resulted in long queuing, has meant that access can be anytime of the day or night with no queuing. The reduction in queue time from smart meters is shown in Figure 5.3. Users expressed that *"…often they were not there, so we had to leave the bucket there for two or three hours*" (C16); *"…for many hours, with buckets in a row"* (E22); *"…the vendors argued and there was fighting"* (C15).

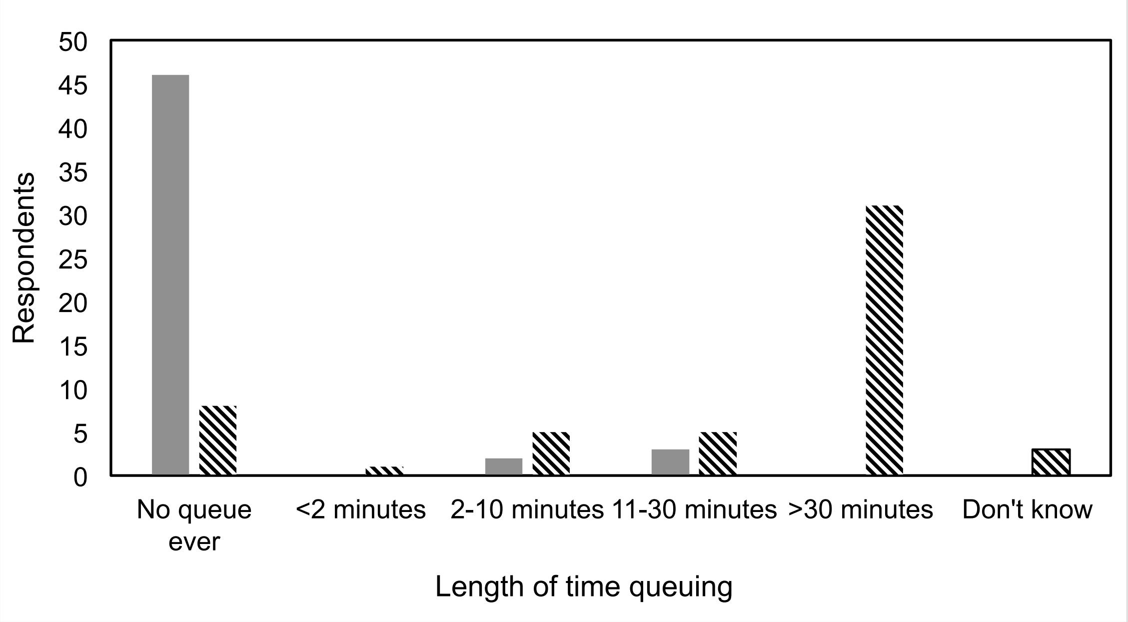

Figure 5.3 Comparison of user answers of length of time queuing at DPs before (dashed) and after (grey) smart meter installation

87% of users (protocol C and E) say there is now no queue ever, and observation during fieldwork also suggested this to be the case: *"I can even leave a pot on the fire, and the water hasn't boiled yet when I get back"* (C8); *"It's better to get water anytime you want, morning or evening. I can spend all day at the shamba* [farm] *and still not worry about water."* (C29). Some users still reported occasional queuing during very busy times of the day, and that higher flow rates reduce queuing time, and this emphasises the importance of the findings on flow rate reduction in Chapter 3.

User's answers of previous queuing time were added to the corresponding answers of how long travel and collection takes with smart meters now. This gives a good approximation of full length of collection time before smart meters. This is shown in Figure 5.4, and is compared against travel and collection times with smart meters.

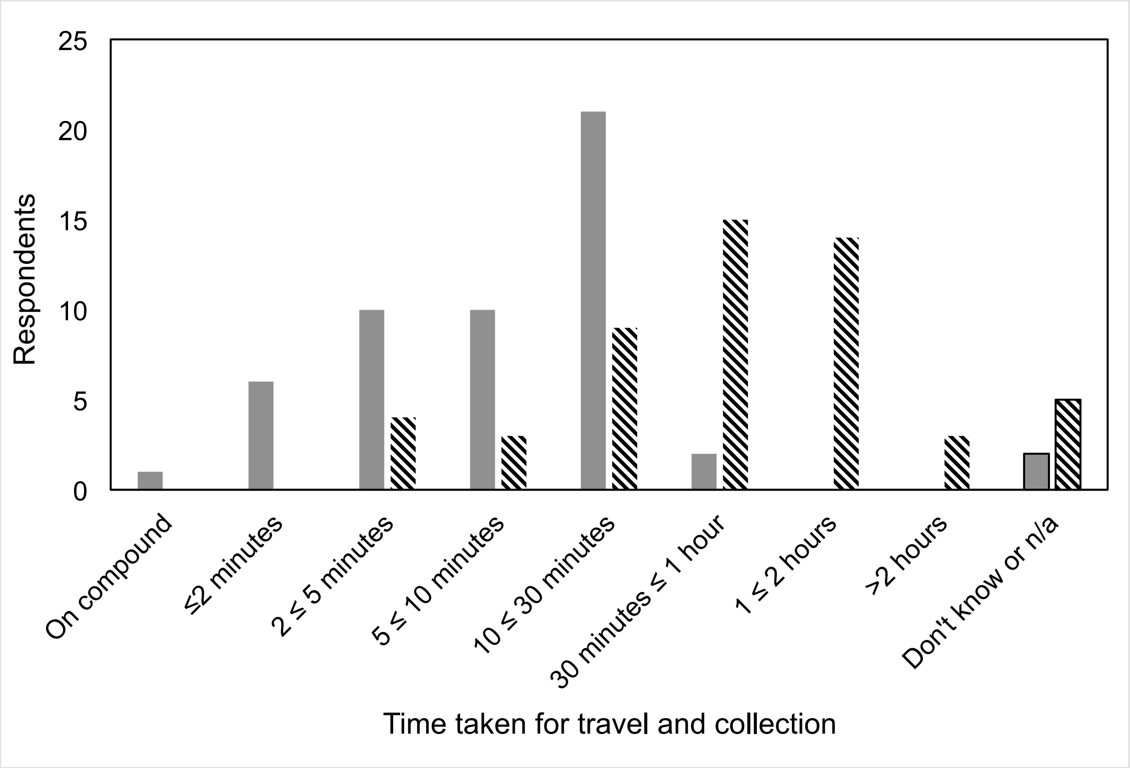

Figure 5.4 Comparison between collection times before (dashed) and after (grey) smart meter installation; precise answers were categorised to smooth out inaccuracies and variation

This quantifies a significant reduction in time taken for travel and collection with smart meters. Responses from the village council and COWSO support this finding that smart meters provide better service to users by allowing anytime access, and that this is especially beneficial to women and has contributed to better economic opportunity (see below): "*With extra time on the farm I can make more money. Our husbands stop asking questions and there are more school fees for children*." (MS2); *"there is more time…to cook and wash"* (MS3). Some users explain collection is quicker when they use a bicycle, or longer when children do it. Answers from Community A1 handpump users reveal that travel and collection is much longer there, typically longer than two hours: "*I go at eight AM and only get water at one PM."* (D3); *"…sometimes it is morning to evening waiting in line. There is no time for the shamba"* (D5). Here, the biggest problem is queuing (D2, D3, D4, D5).

56% of users answered that the smart meter they use is functional all throughout the day. The only understanding of non-functionality arose from unavailability of water from the PWS rather than smart meter failure, and this tends to occur later on in the afternoon (this and the time users collect water in the day is further examined in Chapter 6). There is variation between answers of number of times the smart meter itself has broken, between 'a few times' (34%), 'twice, once or never' (29%), and 'cannot remember' (34%); no respondents knew the cause apart from three who suggested the battery was faulty. It is difficult for users to distinguish between the smart meters and the PWS, and this is discussed below. Figure 5.5 shows that users believe repair times with smart meters to be relatively quick.

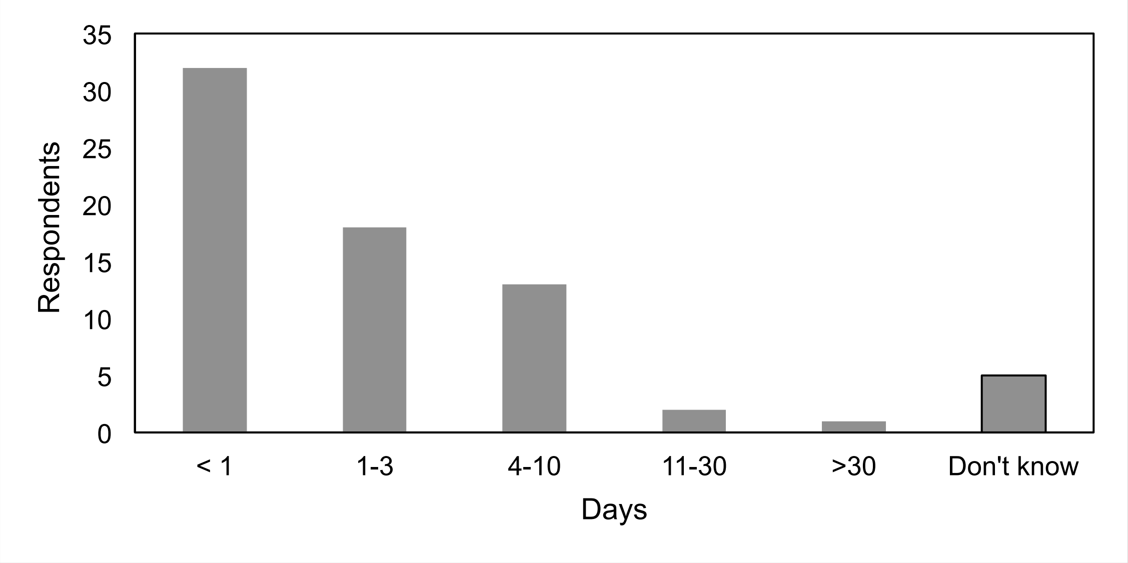

Figure 5.5 User's answers for length of time it takes for smart meter DP repair

This indicates that most failures are easy to repair by technicians in the community or district, such as battery replacements. 63% of respondents answered that repair of DPs is quicker than before smart meters, but this depends on the nature of repair, and spare parts can take some time. In comparison, handpump users in Community A1 explain that the handpump is *"used the whole time non-stop"* (D4) and it has broken *"many times"*; community members pay a subscription (~1,000 TSH; ~0.31 GBP) when it breaks and repair usually takes between one day and a week.

78% of users answered that the smart meters have benefited the health of the community, shown in Figure 5.6.

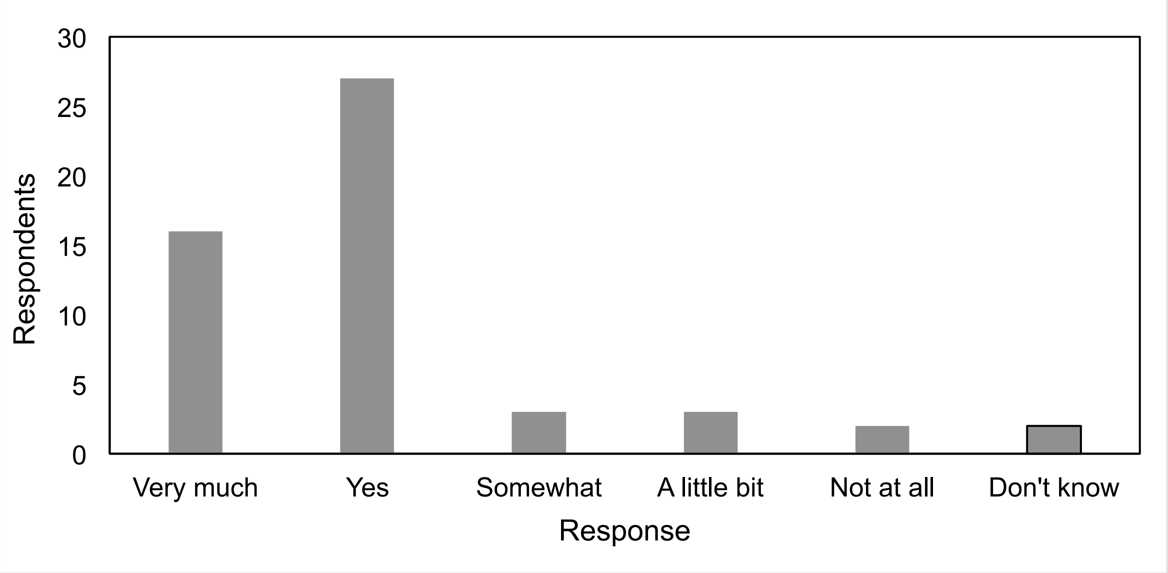

Figure 5.6 User's answers for if the smart meters have benefitted the health of the community

Users give a variety of explanations for this: *"*[smart meters] *reduce collection from wells"* (C1); *"It is clean water that doesn't need boiling"* (E6); the clinician outlined that *"At the clinic, records of diarrhoeal disease in children show decreases since the supply system was installed, and the [smart meters] does help this. Before, everyday five children were treated for diarrhoea but now there are less than two per week."* (C3), and this is substantiated by others: *"In two years* [since installation], *I have never heard of people suffering from diarrhoea"* (C10), *"…nobody complaining of stomach aches"* (C21). These explanations could be attributed to only the PWS, however other users outline that smart meters have further improved access to the clean DP groundwater beyond the PWS installation: *"*[smart meters] *allows people to get enough water"* (E10); *"Sometimes people queuing before didn't want to wait and so it was quicker to go to the riverbed, which is ill water."* (C31); *"People were dying, they find no vendor so go elsewhere to find water, to the dangerous cliff edges at dry river beds"* (C16). With smart meters, users *"don't have to travel far looking for water"* (C15). As such, the positive responses seen in Figure 5.6 that can be attributed to smart meters rather than just the PWS are significant factor. By comparison, community members in Community A1 who have to collect from the riverbed (by scooping below the dry bed) express that it *"…is difficult. Much* *worse in rainy season, it's hard to access."* (D6, D7, D8)[5]. Compared with this, the beneficial impact of shorter collection times from smart meters is significant.

Overall, this shows that users experience beneficial impacts of smart meters of quicker, anytime collection and improved service from faster O&M, and this is a supplementary benefit to health from improved access to clean DP water from the PWS.

Affordability

51% of users had a good understanding of the price charged per 20-litre container (25 TSH; ~0.008 GBP), and 23% understood imprecisely but of the correct value. Users consider payment and budgeting for water in different ways, for instance 500 TSH expecting to last for 20 containers. Those with poor understanding justify that, for instance: *"I just top up 1000 TSH and wait for it to run out, I have no idea of the number of buckets"* (C17); *"I just collect, I don't count"* (E27).

81% of users believe the price is 'roughly correct' for their household, and this mostly derives from the understanding that it was a community decision and users were therefore reticent to answer as individuals. The 17% who believe the price is 'a little too high' or 'much too high' suggest that it limits their use of DP water. 53% would pay more if it meant a better water service, but this was dependent on service provision. While most (73%, protocol C) users answer that they pay the same price as before smart meter installation, some users explain that "[I] *wasn't paying for handpumps before and there was no maintenance of the previous system"* (C10), or were not made to pay by vendors. One user felt that they pay *"less now because I hand over money less often"* (C31). Members of the COWSO perceive users to be happy with the price: *"People can afford, for two years users have bought credit no-problem…"* (MS1); *"…even those with low income can afford it…"* (MS7), and that the price was a community decision. Information from other managerial stakeholders suggests that price in Community A is half what is charged in other rural communities in Tanzania. Nine of the ten respondents in Community A1 would

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[5] The seasonality of collection from contaminated surface water sources is outlined and investigated in Chapter 7.

pay for water if it improved service, outlining that: *"If you get something for free you don't value it. Payment gives discipline of how to use water"* (D3).

Overall, the willingness to pay is high, with reasonable knowledge of cost. Affordability is sometimes measured as a proportion of household income with a range between 3% and 5% (Hutton, 2012b), however this has very limited empirical grounding, does not change the key result, and therefore was not used here (it also requires quantifying household income, which was avoided as outlined in the study approach in Section 5.3). Willingness to pay here finds additional relevance with the development of weather dependent pricing in Chapter 8.

User satisfaction

81% of users are 'happy' or 'very happy' with the availability of their DP (i.e. of water) with the smart meter, shown in Figure 5.7.

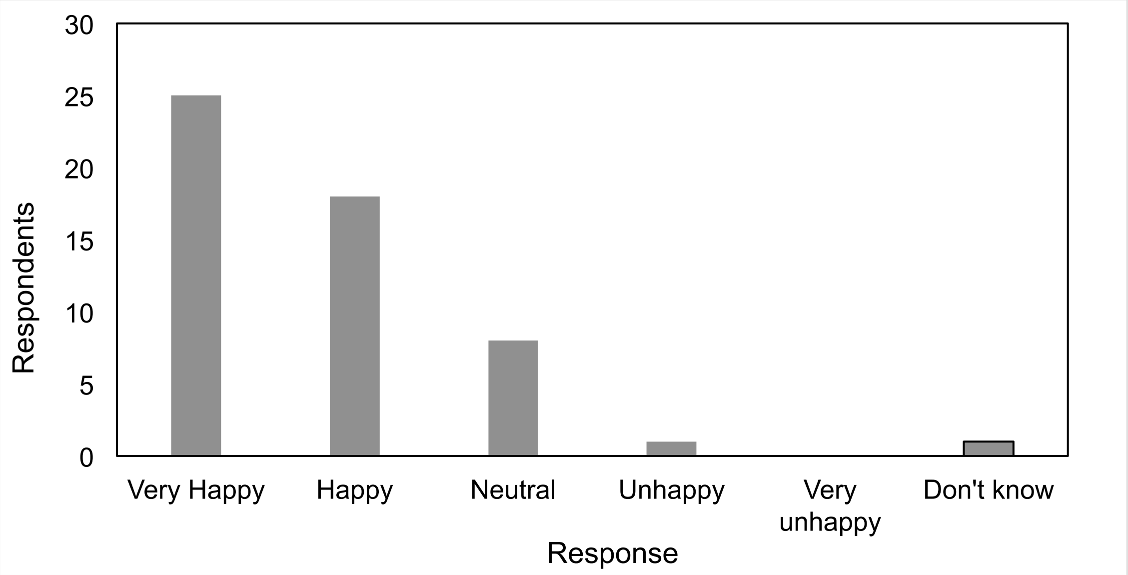


Figure 5.7 User's answers for satisfaction of availability of the DP with the smart meter

Users express that: "[availability is] *better even than in town"* (C10); "[we are] *lucky to have the technology in our village"* (C17). On the other hand, some explain that the PWS limits availability: *"There is a problem with the pumping system. If it would pump more that would be better"* (C21); "*I don't think the tank is big enough"* (C20). Community members of Community A1, by comparison, have less positive responses regarding availability, for example: "*I worry at any time the handpump can break."* (D3).

94% of users believe the smart meter system is 'better' or 'much better' than the previous system, shown in Figure 5.8.

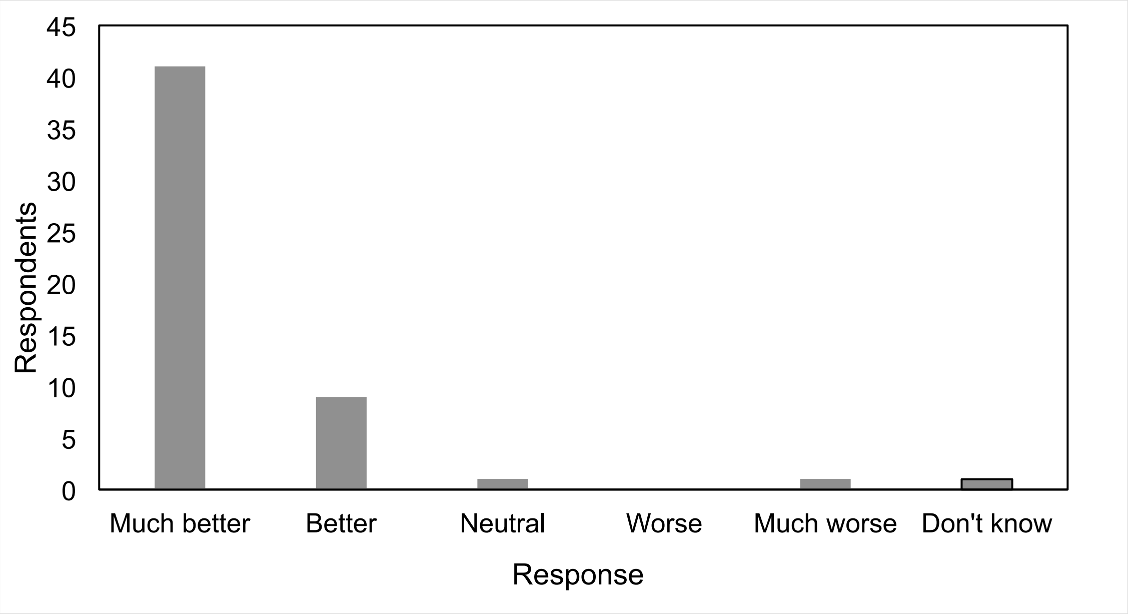


Figure 5.8 User's answers for satisfaction of the smart meter system compared with the previous system

Users provided a range of different explanations for their satisfaction. These mirror the beneficial impacts outlined above, for instance: *"Before, children would open and leave taps running. No respect for water use. The water vendor was not always there, or not for long."* (C14); *"People died* [collecting water] *on the riverbed before, they are scared to go there. You can't get clean water from the riverbed when it rains"* (E16); "[There is] *no non-revenue water any more"* (E8); *"It has simplified water service here"* (E10).

Users outlined significant satisfaction in the shorter and easier collection and the attendant socio-economic benefits of this. A number of users expressed economic benefits: *"I can make more income with the time saved, and spend it on food, the children's school…*[and] *spend more on water"* (C14); *"*[I] *use the extra time to graze cattle, and to find new grass areas for cattle. I feel I have a little bit more income from this."* (C31); *"I reinvest the extra income into the shamba"* (C29); *"It helps get more money to women, which can be spent on* *school fees"* (C18); *"I have more time for house activities"* (C13); *"There is now more spare time. I can plan for tomorrow's work. There's more income from the free time, for school fees"* (MS8). Significantly, these benefits have knock-on benefits to education, and to health, as evidenced: *"Children now have more time to study, to take the cows for grazing, for play and rest. Children don't get ill anymore."* (C26); *"It's good for my health to travel less"* (C12). The clinician supports this: "[Smart meters] *has made time more available for the community, for time on the farm, which means economic improvement. So people are paying more and are happier to pay for medicines"* (C3). Better accessibility of DPs makes it easier for users to choose to collect clean DP water rather than potentially contaminated water from alternative sources. Every COWSO member agrees that users are satisfied and happy with availability and shorter collection times.

Some dissatisfactions were also raised. One respondent (E4) became a non-user from annoyance at poor consistency of water supply from the PWS, representing a lost user because of an insufficient PWS. This has also been observed with pre-paid DPs in informal settlements in Kampala, Uganda, where users become tired of intermittent water supply and revert to other water sources (Nastar et al. 2019). Other users complain to managerial stakeholders (*Mwenye kiti*) when flow rate from the PWS is insufficient. One COWSO member explains that: "*They are satisfied when water is available all the time. They are not satisfied when water is not available*" (MS4). 23% of users do not believe the smart meters charge the correct amount of credit, and this is substantiated with occasional experiences of not getting expected volume of water for specific amounts of credit (as above). It was argued that: "*Generally* [users] *are satisfied and like the meters. There are some problems with tags, for example with one hundred working well and one working badly…the 'one' becomes significant!"* (MS1).

Overall, users generally see the smart meters as a great improvement to their lives, but have frustrations at occasional technical issues.

Likelihood of continued use over time

All users apart from one would be willing to keep paying for credit into the future. Reasons for this were given as: *"To keep the service good"* (C5), *"I look to the future"* (C9), *"…money is needed for repairs of the system when it breaks"* (C22). Other users pragmatically explained: *"We have no option if it's pre-paid"* (C7); "*You have to, you need water to survive"* (C11); *"There is no option"* (E30). These answers demonstrate understanding of the requirement of financial sustainability.

Four COWSO members suggested ideas of what might make users stop wanting to use the smart meters. These were: 1) users becoming too tired of more technical issues in the future, 2) continued theft of solar panels or other components, 3) another superior technology, or 4) extension of household connections (this is discussed in Chapter 9). None of these appear likely in Community A in the near future.

There are competing alternative water sources that could present a challenge to smart meter DP use and revenue collection (and a partial solution to this is presented in Chapter 8). These include the two handpumps (mapped in Figure 5.2), lined wells in individual compounds, rainwater harvesting, and surface water from scooping dry riverbeds. These are not likely to outweigh DP use, and the majority of drinking and cooking water is collected from DPs as shown above.

5.4.4 Accessibility of smart meters

Ease-of-use of smart meter tag

The smart meters are easy to use, and users find using the tag to automate opening much easier then turning a tap or using a handpump. This ease-of-use was confirmed by observation, and users across the demographic spectrum can collect water as evidenced below. Not having to pump avoids significant calorific expenditure (energy expenditure of handpump use has not been reported, but is high, particularly with deep groundwater and poorly-functioning handpumps). Good design of the concrete DP standpipe and apron is important for resting the heavy container at the correct height.

90% of users (protocol C) found obtaining a tag ‘easy’ or ‘very easy’ when the smart meters were installed. These were given for free and the COWSO charges (1,500 – 3,000 TSH) for replacements. Unaffordable new tag prices at urban pre-paid systems in Uganda have made users return to even more expensive water sources (Nastar et al. 2019), however only one user has demonstrated this in Community A. Almost all users have only one tag per household. 91% of users purchase credit from a reseller in person using cash, and only 8% know how to use mobile money for credit purchase. 82% of those who use cash find it easy, however there are some challenges: *“I need to go and find the reseller, or wait for him to come. I have to call him or walk to…wherever they are”* (C14); *“I have to find* [the reseller], *and sometimes I can’t top up…this has happened three times”* (C15); *“Sometimes he is not there, sometimes his phone has no charge for the top up...”* (C29); *“It is difficult when I’ve run out of credit after a long day, I have to go to the reseller”* (E27). This demonstrates that loading credit onto a tag can limit accessibility to some degree. Typical top-up values given by users divided by litres collected gives an approximate average time between top-ups of 6.1 days. This limitation is similar to an issue experienced in urban Ghana, were users who were not able to top up pre-payment cards on public holidays (Shang-Quartey, 2017).

Four users have experienced their first tag breaking, and 47% of users (protocol C and E) have lost a tag at least once, shown in Figure 5.9. Tag loss has no relationship with household size.

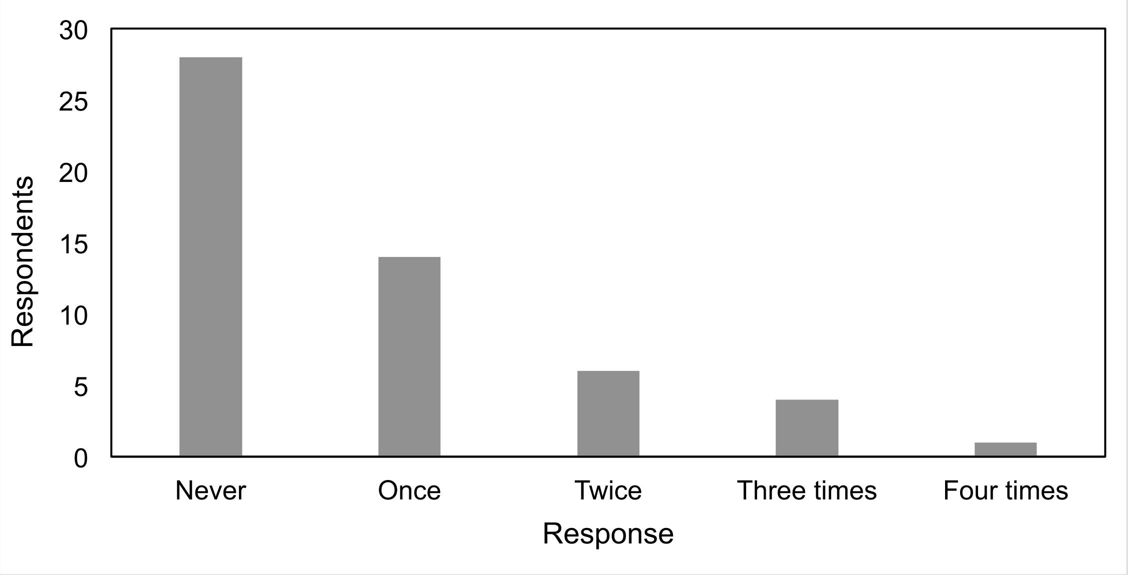


Figure 5.9 User’s answers for number of times they have lost a tag

83% of users (protocol C) believe good flow rate from the smart meter is either ‘important’ or ‘very important’ (most respondents did not understand the concept of ‘flow rate’ and so this required further explanation), mostly because it makes collection quicker: “*I can fill the bucket quickly, and get back home early*” (C15). On the other hand, excessive flow rate can cause spillage: *“…it doesn't all go in the jerrycan. This is lost credit”* (C29). One user explained that high flow rate is good because *“it's good to see that there is enough water in the system”* (C12). (This further emphasises the findings on flow rates in Chapter 3).

Equity of use

Because water collection is done on a household basis, there are not many individuals who are unable to collect water from the smart meters. However, only 43% of users (protocol C) believe ‘nobody’ in the community is unable to use the smart meters. For example, there are: *“Elders who cannot afford credit.”* (C7); *“Elders or those who are ill or disabled”* (C10), and who live alone and have no income. COWSO members suggested there are two or three such people in the community, and that they are given small amounts of free credit. Affordability is therefore a barrier to the most marginalised, as is the case with water supply without smart meters.

A large number of households have inequitable access and are marginalised by living far away from the DPs, with 42% of household’s interviewed further than

400 m. Five respondents who do not use DPs cite long distance as a reason (despite eight users still living further then them, i.e. >885 m, which demonstrates subjective priorities). Some users also expressed a desire for closer DPs. The mean distance of travel is 446 m, compared to 626 m for handpump users in Community A1. Distance of travel is further investigated in Chapter 6.

Either women or children are involved in water collection most often in every household interviewed, as shown in Table 5.3.

Table 5.3 Demographic breakdown of who collects water across households

Users	Households
Women and/or children involved	100%
Only women and/or children	89%
Only women and/or girls	55%
Only women	45%
Only children	19%
All household members	8%

This gender and age imbalance was evident during fieldwork observations, and the village council explained that women collect water for cultural reasons. This mirrors rural sub-Saharan Africa in general (as shown in Section 2.2.5), where the combined time spent collecting water everyday across 25 sub-Saharan African countries in 2012 was estimated as 16 million hours for women (62%), 6 million hours for men (23%), and 4 million hours for children (15%) (UNICEF and WHO, 2012). Approximately half of respondents reported that more than one household member is responsible for collecting water most often, which limited more detailed analysis.

Larger household sizes are slightly more likely to have woman and children responsible for water collection most of the time, shown in Figure 5.10, which is perhaps attributable to more children being available.

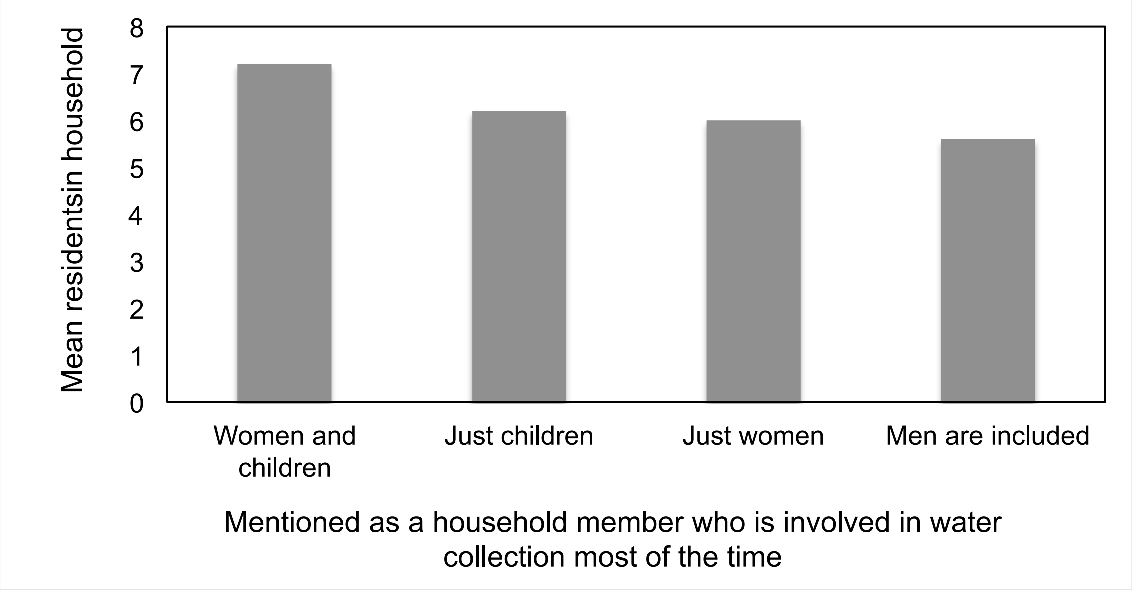


Figure 5.10 Household size of who collects water in the household most often

Who collects water most of the time is not a determinant for the time taken for each collection or the volume collected in these data. The average distance of collection is slightly longer when men are included as one the household members who collects water most often (mean of 508 m compared to the sample mean of 446 m), shown in Figure 5.11. This suggests that on average men collect from further away and children from closer. However these data show wide standard deviations and each household has different characteristics, and further statistical analysis is limited.

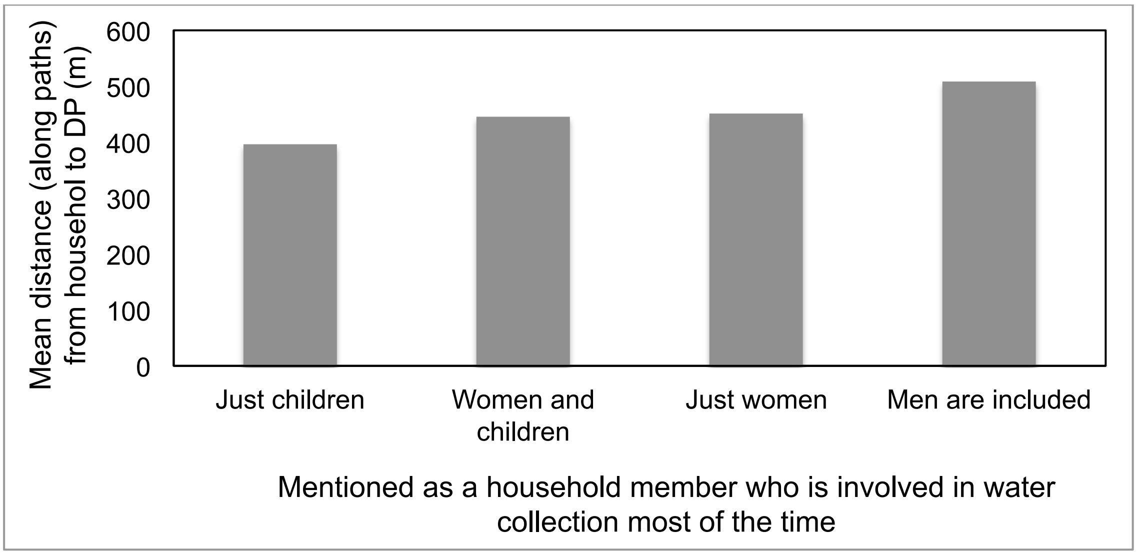


Figure 5.11 Average distance of collection of who collects water in the household most often

In general, despite minor differences, who collects water in the household does not significantly alter how different households access the smart meter DPs, or change equity of access beyond the pre-existing cultural behaviours.

The frequency that users lend their tags to other people varies more than other factors investigated here. This is shown in Figure 5.12.

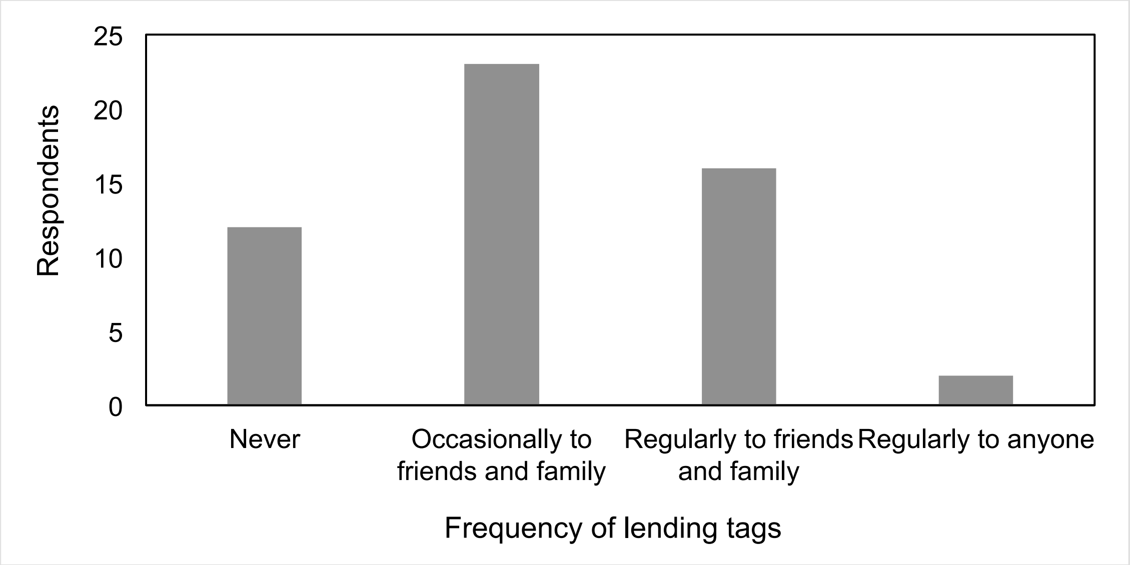


Figure 5.12 User's answers for how frequently they lend their tag to others in the community

Users explain that they share tags when others have run out of credit and cannot find the reseller. This could be characterised as a coping strategy of water insecurity. Reciprocal dynamics between family and friends has been found to be very important in studies of water sharing (Wutich et al. 2018). Here, the importance of social capital for maintaining equitable access to smart meters is demonstrated.

93% of users (protocol C) have no or extremely limited understanding of how the data and information on their water collection is used. One third do not mind: *"It's up to the managers, the COWSO to sort it"* (C2), *"So long as I can get water"* (C10). Half feel negatively about this: *"It's not good to use it without knowing what happens to the information"* (C7). The remainder expressed no viewpoint: *"I just know I need to add credit"* (C9). 70% of users (protocol C and E) have no understanding of what happens to their payments. The importance of openness regarding data in digital development was emphasised in the literature review.

5.5 Discussion

The study approach and methods have been shown to be very suitable for this evaluation. New information was uncovered from users and managerial stakeholders that relates to the socio-economic context. The requirements of the evaluation framework have been satisfied and voices from a diverse range of stakeholders were well represented. This has generated novel understandings of smart meter operation. These are developed in the following sub-sections and generalised beyond Community A. Rich qualitative information has helped frame understanding from the viewpoint of users. The evaluation went beyond simple binary metrics or common surveys of functionality, and benefitted from comparison against a control community.

The evaluation is summarised in Section 5.6 below. In general, the smart meters in Community A bring benefits to managerial stakeholders, users, and accessibility, and the above findings align with the three main findings from the evaluations in the literature review of improved revenue, management and access (Table 2.16). Beyond these established findings, this evaluation has also revealed novel information on: accountability, technical glitches, satisfaction, quantification of time saved, benefits of newly available time, improvements to O&M, community health, affordability, likelihood of continued use, ease of use, tag loss and sharing, and user comprehension.

This section discusses findings that relate to the improved access of users to clean water from DPs, as this is a significant impact of the smart meters under study in this context and is little-discussed elsewhere. In other parts of the world different technologies such as coin-operated water dispensers can allow users to access water without waiting for vendors. However, as already shown in Section 2.5.6, such technologies are unlikely to work effectively in rural sub-Saharan Africa for a number of practical reasons. The research here is therefore not a comparison against alternative technologies, nor an enquiry into alternative potential solutions. Consequently, the added-value of these specifically designed smart meters (beyond the PWS) in the socio-economic contexts such as Community A is the ability to have such improved access in the first place, which is facilitated by the combination of remote pre-payment, IoT monitoring, and automated dispensing; in tandem with the value of improvements to revenue and management as shown in this Chapter, and that of use of remote, high-resolution data used throughout this research.

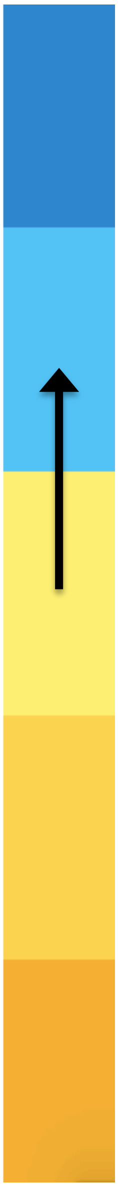
5.5.1 Impact on time taken for collection

The major impact of smart meters on users is the overall reduction in the time that users spend collecting their daily water. This is mostly from the removal of vendors from the DPs, who were often not available, which in turn caused long, variable queuing during windows of availability. With the smart meters there is anytime access to the smart meter DPs and queue time is virtually eliminated. 87% of users report zero queue time.

In contrast, people spend an average of 42 minutes per water collection trip in rural Tanzania (World Bank, 2018). Queuing is such a major part of water collection in rural sub-Saharan Africa that definitions of round-trips are based on “going to the source, waiting in line to collect water and coming back to the house” (Mandara et al. 2016), and queuing underpins the difference between different JMP service levels. In Benin, queue time is reported to be an average of ~29 times longer than the actual travel time to the water point in the dry season (mean = 313:11 minutes; ~8 times longer in the rainy season) (Arouna and Dabbert, 2010), and collection times in one study in Kenya were 2 to 3 hours (Cook et al., 2016). Very long queuing is also seen in Community A1, as shown above. Studies elsewhere take for granted the major inconvenience to users from unavailability of vendors at water points (for example in small-towns in Ghana; Kulinkina et al. 2016). Vendors delaying opening times or hastening closing times because of poor supply can also cause queuing (Oxfam, 2018).

The JMP service ladders for drinking water (JMP, 2017) are widely used benchmarks for comparing service levels. It is possible to map the improvement in total collection time resulting from smart meters that was shown in Figure 5.3 to different ‘rungs’ on the service ladder. The numbers of respondents who fit with each ‘rung’ are shown in Table 5.4. The DPs before and with smart meters are both ‘improved’ water sources.

Table 5.4 Improvement in JMP service level from reduced collection time with smart meters

Service level		Respondents per service level*		Rural Tanzania proportion *(JMP, 2019)*
		Before smart meters	**With smart meters**	
	**Safely managed** (drinking water from an improved water source is located on premises, available when needed and free from faecal and priority chemical contamination)	0	1	*(43% at least basic)*
	Basic (drinking water from an improved source, provided collection time is not more than 30 minutes for a roundtrip including queuing)	16 *(30%)*	49 *(92%)*	
	Limited (drinking water from an improved source for which collection time exceeds 30 minutes for a roundtrip including queuing)	32 *(60%)*	2 *(4%)*	*(14%)*
	Unimproved (drinking water from an unprotected dug well or unprotected spring)	0	0	*(24%)*
	Surface water (drinking water directly from a river, dam, lake, pond, stream, canal or irrigation canal)	0	0	*(20%)*
		n/a = 5	*n/a = 2*	

**excluding non-users and unquantifiable respondents*

This shows that reduced water collection time from smart meters has meant that 57% of users ‘progressed’ from ‘limited’ to ‘basic’ service. Put differently, the proportion of users who have basic service increased from 30% to 92% because of smart meters. Compared with the rural Tanzanian population, the improvement of those with ‘at least basic’ service has been from worse than average (43%) to much better than average. This novel formalisation of improved service is particularly relevant for planners who depend on such comparisons between service levels for decision-making. This is more convincing than evidence from other evaluations of smart meters such as numbers of users who report “saved time”.

The knock-on socio-economic benefits of shorter collection times raised by both users and managerial stakeholders are significant. Many users mentioned more income from being able to spend more time farming, and some said this went towards children’s school fees. The clinician explained that users are more willing to spend more on medicines. Elsewhere, quicker access to water sources has been demonstrated to improve family relationships in rural Kenya, with associated socio-economic benefits and potential positive feedback loops (Zolnikov and Blodgett Salafia, 2016). Data from twenty-six sub-Saharan African countries shows that a 15-minute decrease in one-way time to collect water is associated with a 41% relative reduction in diarrhoeal prevalence, improved anthropometric indicators of child nutritional status, and an 11% relative reduction in under-five child mortality (Pickering and Davis, 2012). Reduced collection times in rural Kenya have significant financial benefits because median costs from the otherwise long collection times amount to approximately 6% of household income (Cook et al., 2016). Longer times to the nearest water source reduce the probability of schooling as the main activity for children in rural Ethiopia (Cockburn and Dostie, 2007). Therefore, overall, the improved access to water from DPs with smart meters goes beyond SDG 6.1, and has a positive impact on poverty (SDG 1), health (SDG 3), education (SDG 4), and the local economy (SDG 8). This shows that smart meters can have systemic benefits on the socio-economic context (in line with the importance of systems thinking). This is more detailed than evidence from other evaluations of smart meters.

Another knock-on benefit of reduced time taken for collection is the inclusion of community members, discussed next.

5.5.2 Impact on inclusion of community members

Information from users and managerial stakeholders suggests that the reduced time taken for collection seems to decrease marginalisation of some community members.

Water access interventions are commonly assumed to uniformly benefit the community, but this is not the case in heterogeneous socio-economic contexts. Faster progress towards rural water supply is required among marginalised groups if the universal access enshrined in SDG6.1 is to be achieved, and ‘leaving no one behind’ is now a core focus of the international policy community (UN-Water, 2019). A focus on aggregate numbers hides local level inequalities (van Houweling et al, 2017). Geographic location, gender, wealth, and disability are common limitations to water access in Tanzania (Ezbakhe et al., 2019), and groundwater is often less available to the poorest (Komakech and de Bont, 2018).

The application of any technology cannot avoid exclusion at some level because access can never be totally uniform. For instance, research from Mozambique suggests that handpumps schemes can reinforce existing social, economic and political divisions within a population because access is never perfectly equal (Van Houweling et al., 2017). This risk of smart meters amplifying existing social divides is discussed in depth in Chapter 9.

However, the above results suggest smart meters in Community A instead improve access for marginalised populations. The reduced collection time from the DPs means that users who live further away have improved access. Shorter collection times make it more worthwhile for users further away, for instance at the extremities of the community, to travel to the DPs rather than other unimproved water sources, as evidenced by the responses from users and managerial stakeholders. Knowing there will be no queue makes users more likely to decide to travel to the DP and not to revert to an alternative free water source. Therefore, rather than physically reducing the inequities of distances (seen on the map in Figure 5.2 and further investigated in Chapter 6), improving time taken for collection can act to include further away households. Long distances are not the only reason non-users do not use the DPs, as shown above, therefore distance is not the sole obstacle to access, however it is a significant factor as shown elsewhere (Boone et al., 2011).

Women and/or children do the majority of the water collection from smart meter DPs as shown in Table 5.3. This reflects the general situation across sub-Saharan Africa (Graham et al. 2016). Any improvement in access to water, as elaborated above, therefore impacts women and children more than men, and consequently women and children are the main beneficiaries of smart meters. However, there is a risk that easier accesses makes it easier for women and children to take on more responsibility of water collection, who previously would not have been able to. This phenomenon has been postulated in one case study in rural Malawi with handpump installation (Rieger et al., 2016); elsewhere, improved water access in a remote community in Zambia ‘trivialised’ water access (by making collection easier), which led to more of the responsibility of collecting water being given to women (Mungekar, 2019). In Community A there is no significant evidence that improved access from smart meters has increased or decreased the burden of water collection on women and children. The positive responses received from women regarding more free time, and related socio-economic benefits, suggests that they do not take on more responsibility. However, this question requires further study as increased burden of collection could form a negative impact of both improved access to water points or increased volumes collected in future communities with smart meters.

Affordability could be a cause of marginalisation because, as users pointed out, the DPs are now unable to be used without a tag loaded with credit. One user did not want to pay for a new tag. In urban Ghana, ‘pricing out’ of the poorest with increasing costs because of expensive pre-payment water meters has led (along with technical problems) to major civil unrest (Shang-Quartey, 2017; Transformative Cities, 2019). In 44% of communities with new solar PWS schemes reviewed (UNICEF, 2016), the poorest 5% had to use free, unimproved water sources. Women in this context typically have less access to cash to pay for water credit (Korzenevica, 2019), and may therefore have more incentive to use unimproved water sources. Furthermore, approximately 32% of households use alternative water sources for different domestic uses (see Chapter 6), for example a nearby well for clothes washing. This suggests that there is a 'hidden affordability problem' (Komarulzaman et al. 2019). However, in Community A, overall, users and managerial stakeholders show that affordability and willingness-to-pay of credit is high, and that the small minority of poor people who cannot rely on family members receive credit from the COWSO. There remains a risk in other communities that financial marginalisation is 'locked in' by the new necessity of having a tag loaded with credit, however this is the remit of existing practice around pricing. Potential solutions to this could involve more formal 'lifeline' water allowances to the most economically marginalised.

Challenges to equity of access across the community have fundamental solutions not in smart meters but with installation of a greater number of DPs closer to user's homes, or of universal household connections; both of which will require substantially bigger PWSs. Consequently, these will have greater impacts on women and children.

Overall, the results from Community A suggest no evidence of entrenched divisions or marginalisation of specific groups resulting from smart meters. The major impact of reduced queuing seems instead to decrease marginalisation. This novel finding shows that, as above, smart meters go beyond SDG 6.1, and positively impact gender equality (SDG 5) and reduced inequalities (SDG 10). While this is significant, the positioning of DPs remains a barrier to equitable access to households, and this is addressed in the following chapter. In this sense, until Community A benefits from universal household connections (see Figure 5.16 below) rural water supply will remain inequitable. The smart meters therefore do not amplify existing inequalities, nor do they uniformly benefit the community.

5.5.3 Smart meters as part of the PWS

Smart meters are physically underpinned by the PWS. A fully functioning PWS is essential for effective smart meter operation. When the PWS fails to supply water the smart meters also fail, negating the above benefits. The above results show that the solar powered PWS in Community A (pictured in Figure 5.1) is subject to inadequacies, and supply cannot always meet demand. This explains the experiences of users of water running out in the evening (this is investigated in Chapter 6). Five potentially limiting factors of the PWS revealed by the managerial stakeholders are shown in Figure 5.13.

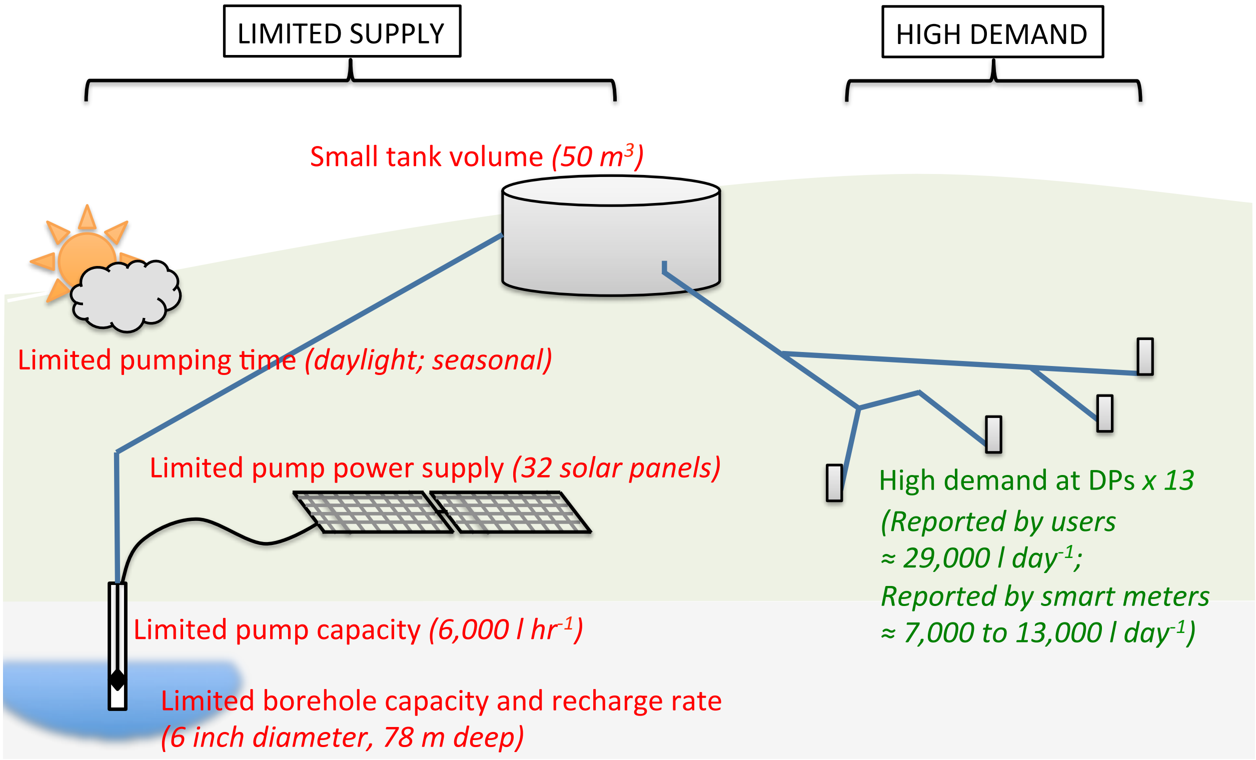


Figure 5.13 PWS with factors that potentially limit water supply (in red)

The borehole was drilled 78 m deep rather than a more appropriate 150 m due to geological problems. The pump choice was based on this potentially limited borehole capacity. A greater borehole capacity would have allowed a larger pump without danger of it breaking. Pump capacity is not sufficient meaning the pump runs non-stop everyday, and this has caused the motor to fail twice. The installation of the pump switch was done poorly, increasing the risk of overheating of the motor. The solar capacity can be limiting when there is not adequate solar radiation, such as during cloudy weather, which became evident on the first rainy season of operation after installation. The watchman is tasked with turning the pump on and off (there is no float-switch) but he has occasionally forgotten.

Water demand from the DPs is growing with increasing population while the PWS capacity remains the same. Approximate estimates of total demand calculated from users responses, and the range reported by smart meters (the difference between these estimates is addressed in Chapter 6), matches the testimony of managerial stakeholders that demand is greater than supply. One COWSO member explained that demand is growing and so a second borehole and pump would be useful (MS4).

Assuming that the tank rarely becomes full because of this demand, and the fact the 50 m^3 tank size would be sufficient for the estimated demand, the limiting factor is more likely to be the pumping capacity. Solar pumping PWSs are generally considered to be technically sustainable (notwithstanding theft and pipe breakages) and are more reliable than diesel-powered counterparts (Oxfam, 2018), however such PWSs still require design at sufficient capacity. This is a common challenge amongst practitioners. As shown by the information from the COWSO above, such infrastructure limitations cannot be addressed by regular O&M or be financed by revenue collection.

This evidence builds a picture of the smart meters in Community A having to rely on an unreliable PWS. In communities with smart meters where the PWS is well functioning, the smart meters can result in the benefits seen above and potential positive feedbacks (for example, willingness to pay has been shown to be higher when service and O&M is maintained; Olaerts et al., 2019; Koehler et al., 2015). Contrarily, where PWSs are unreliable, the benefits from smart meters are void. While this is an obvious point considering the nature of smart meters it has not received emphasis in other evaluations, despite being crucially important. This factor risks being missed or ignored because of the more enticing impacts of novel smart meters themselves. For example, smart meter installation programmes may receive backing from donors keen to see the benefits of the smart meters without full consideration of the underlying PWSs. Consequently, it is argued in Chapter 9 that ‘smart meter projects’ need to integrate with ‘PWS projects’. Consideration of the broader underlying system is an example of the importance of systems thinking outlined in Section 2.2.7. The effectiveness of the technology depends on the infrastructure and socio-economic context.

A well functioning PWS is also important for user perception. Some user responses showed that they do not differentiate between the PWS and smart meters, for instance not being sure which is responsible for non-availability, or conflating benefits. One user stopped using smart meter DPs because they believed the availability of water was unreliable. Similarly, other research has argued that it is difficult to distinguish the benefits of smart meters from benefits of PWSs (Komakech et al., 2020). The impact of limited supply on curtailed water collection by users is outlined in Chapter 6. However, distinct benefits of smart meters have been shown here, and these rely on well-functioning PWSs.

Smart meters might potentially work better if the PWS is part of a larger, centralised network that has a reduced risk of low service levels and more formalised service delivery. However, as such as system is likely to be less rural, this then introduces new challenges to the effectiveness of smart meters with complexity and competition from other sources. The suitability of different settings is more fully discussed in Section 9.4. Considering that the smart meters under investigation are more designed for rural settings, and that their benefits of access and improved service provision will be more useful in rural communities, the real solution is to ensure that the smaller de-centralised PWSs are well functioning in tandem with smart meters. This relies on quality constriction and groundwater development, and appropriate management systems.

5.5.4 Service provision and the COWSO

The limited capacity of the COWSO members to operate and sustain the PWS is a major limiting factor of rural water supply sustainability in Community A, and therefore of smart meters.

The COWSO members have relatively insufficient management capacity, evident during interviews and meetings, making accountable decision-making and efficiency a challenge. Some members miss meetings, and most members do not contribute to discussions. COWSO members are not professionals. Additionally, as seen above, the low price of water limits revenue and there is not much finance available. The importance of well-organised committees with good capacity ("around subjects such as payment perception, communication strategies, and conflict resolution skills") have been emphasised elsewhere, e.g. Uganda (Olaerts et al., 2019; Whave and University of Colorado Boulder, 2019). This mirrors the fundamental limitations of the community management model that were outlined in detail in Section 2.3.3, where too much responsibility is imposed on those with low ability to manage. The secretary-accountant is by far the most important member of the COWSO because of his motivation, access to information, links to the community, and control of the budget, without whom rural water supply would soon fail. Relying so much on one stakeholder means the sustainability of the RWS system is vulnerable.

The progression towards a service delivery approach, outlined in detail in Section 2.3.5, would be more compatible with smart meters than community management models. Professionalised service providers would be able to have better access to finance, perhaps from a clustered community model or investments, and have more capacity to use monitoring data from smart meters for planning and O&M. These contextual findings from Community A have great relevance for other smart meter communities, where management is a crucial systemic factor for success.

The potential for information from smart meters being used to empower poor rural communities by giving them more control over their water supply is not shown in these findings, beyond improved service provision, as smart meters act as more of a supplementary technology to improve service provision and access rather than a technology for control. It has been argued that certain open data from ICT-based water projects available to multiple stakeholders can strengthen accountability and inclusive decision-making (Welle et al., 2015; Schaub-Jones, 2013). Here, information on, for instance low volume collected, could be used as evidence by the COWSO to make the case to local government or NGOs for further improvements to rural water supply. However, compared to stretched resources and capacity of planners, this added evidence might be insignificant. Another side-effect of such action might be to make smart meter communities more ‘visible’ to authorities, potentially to the detriment of other deserving communities elsewhere.

5.5.5 Timeline of water supply in the community

Smart meters bring evident benefits but they are far from an ‘end goal’ of rural water supply. Other evaluations tacitly suggest that smart meters are approximate to a ‘solution’. In fact, they are only the next step towards universal access to clean water. This is discussed more in Chapter 9.

Smart meters may help address increasing demand by providing better access and service, however, as outlined above, if the PWS is limited then gains are unsustainable. This is what is seen in Tanzania on a nation wide level where gains in rural water supply have only been able to keep up with growing population and have therefore stayed proportionally at the same level (World Bank, 2018).

The major remaining limitation of rural water supply based on communal DPs is the need to travel to collect water, even when queuing is eliminated. While obvious, this deserves re-emphasis in the context of new technologies. Travelling for collection and carrying water have very significant negative health impacts. Of almost 1,000 respondents from Ghana, Vietnam and South Africa, those who carry water are much more likely to report pain related to compression from axial loading from carrying on the head (pictured in Figure 5.14) (Geere et al., 2018). Musculoskeletal disorders are one of the major causes of disability in developing countries. One-quarter of children in a study in Malawi reported that headaches and neck-aches are the most common health problem from carrying water (Robson et al., 2013). Additionally, water collection injuries are common, and 13% of a large-scale global study (n = 6,291) reported at least one such injury, largely from fractures or dislocations to lower limbs from tripping and falling, more often with women in rural settings

(Venkataramanan et al., 2020). Observation in Community A showed the majority of users collect without a bicycle or cart, and that this burden mostly falls on women and children. Smart meters do not mitigate these risks.

Figure 5.14 Woman carrying 20 kg of water by the head in Community A, which has a negative impact on health (source: the author)

Some users outlined a desire for piped household connections rather than communal DPs. The timeline of rural water supply in Community A is presented in Figure 5.15, with the potential of household connections in the future. This timeline illustrates the development of rural water supply from surface water and unimproved sources in the past, to the installation of handpumps, then the borehole pump, and then latterly the smart meters. This gives historical context to smart meter installation, and also demonstrates that unsustainability will result in reduced service levels. Such a timeline is representative of many rural communities across sub-Saharan Africa before smart meter installation. The potential competition to smart meters from household connections is discussed in Sections 9.3 and 9.4.

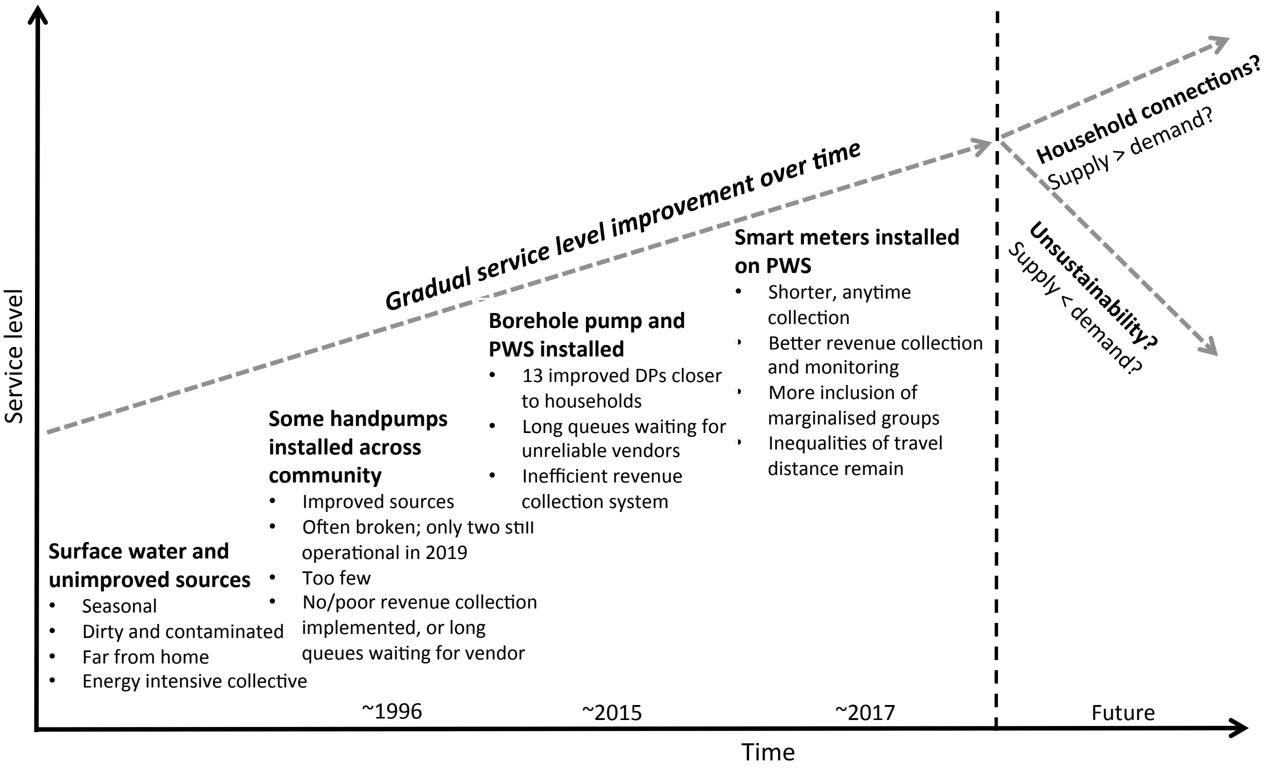


Figure 5.15 Timeline of rural water supply in Community A

The current limitations of communal DPs are little considered, but are important context for planners to remember. Other research has argued that smart meters are not panaceas because of poor implementation, business strategies, and costing (as shown in Section 2.5.6 and Section 9.5.1). However, here this same conclusion is reached from a more fundamental basis.

5.6 Summary of evaluation

In Table 5.5, the findings from the managerial stakeholders, users, and observation from Community A are combined with technical findings from Chapter 4, and presented for each of the evaluation framework criteria. In summary, smart meters in rural communities in sub-Saharan Africa are shown to have the potential to bring many benefits that extend beyond SDG 6.1 across the broader system. This goes beyond existing evaluations.

Table 5.5 Summary of evaluation of smart meters

Evaluation criteria	**Evaluation findings**
EF 1. Technical performance	
Accuracy of flow measurement	• Only marginally inaccurate in laboratory tests (average relative error +3.63%). Varying baseline flow rate does not significant affect this. A general calibration would bring >95% of measurements within ±5% error, which is taken here as a permissible range for operation in the field (van Zyl, 2011).
Restriction of flow	• The benefits of y-strainer outweigh any flow rate reduction, which are negligible for all gauze pore sizes until ~13 g of debris build up. Empirical findings here can provide a basis for gauze size choice, and novel predictive maintenance alerts.
EF 2. Demand from managerial stakeholders	
Impacts	• Smart meters are overall more financially effective for the COWSO and therefore O&M, with enhanced revenue collection from pre-payment, greater water use, less inefficiency because of automated operation (largely because there are no longer time-limited vendors), less non-revenue water, and accurate revenue tracking. Every litre is now valued economically, and theft of revenue and vendor payment are eliminated. Digital payment has made revenue tracking more accountable. Improved revenue is seen by the COWSO as the major benefit, and it partly bypasses capacity limitations of the COWSO. The low price of water still limits revenue, meaning still only small maintenance costs can be covered. Lack of financial records limits this analysis. • Monitoring of non-functionality is quicker overall as the COWSO can see on a smartphone when DPs stop dispensing water. This leads to quicker O&M. Some information is still through word of mouth. • Occasional mismatch between credit removed from tags and volume dispensed, because of software glitches, has led to lost revenue in some cases.
Satisfaction	• Occasional meter breakdowns, software glitches and tag failures are frustrating but are outweighed by the financial and accountability benefits. • The underlying capacity of the COWSO to conduct O&M remains a vulnerability to the sustainability of rural water supply (symptomatic of community management)
EF 3. User experience and demand	

Impacts	• Anytime access to DPs without vendors means that 87% of users experience ‘no queue ever’. Average time taken for collection is significantly reduced, and 92% of users now have collection times of less than 30 min, compared to 30% before smart meter installation. This effectively elevates Community A one level up the JMP’s service ladder from ‘Limited’ to ‘Basic’. More time is therefore now available for farming and other economic activity, which leads to more income, more schooling, and better health. • Replacement of vendors with automated collection also removes causes of arguments and problems of accountability. • Occasionally users have experienced inaccuracies with credit removal from tags. This has meant that they have paid too much or too little for water, or that tags and meters have stopped working, which has blocked access to water from the DP. • 63% of respondents answer that repair is now quicker. Quicker monitoring increases speed of O&M because technicians can be mobilised earlier and therefore improves service levels for users. • 78% of users answered that the health of the community has benefitted from smart meters. 97% of users use DPs as a main source of drinking water, and installation of a PWS alone brings major health benefits. Records of diarrhoeal disease in children have shown decreases since the PWS was installed, and, furthermore, better access from the smart meters has contributed to this. Enhanced access to water from the PWS because of smart meters means users are able to choose uncontaminated water from the PWS over surface water sources, and benefit from shorter collection times and more income. Users can also access greater quantities of clean DP water, which can be important for health.
Affordability	• Affordability of credit for using the DPs, and willingness to pay, are generally high, with only 17% of users considering the price of credit too high. The price was a community decision. This is the same price as before smart meter installation. Only 51% of users have an exact understanding of the price per litre.
User satisfaction	• 94% of users believe smart meters are an improvement for a range of reasons, mostly from the improved anytime access to water and quicker collection time from no vendors, and the extra time in the day now available. 81% of users are ‘happy’ or ‘very happy’ with the availability of water at the DP. • Problems with poor supply from the PWS and occasional inaccuracy of tag credit removal accumulate minor dissatisfactions resulting in a few (n ≤ 2) respondents reverting to unimproved sources. 23% of respondents have experienced inaccurate credit removal.
Likelihood of continued use over time	• The only points raised that may cause users (or managerial stakeholders) to stop using smart meters in the future are continued

	issues around incorrect credit removal, any limited access, or a better innovation in the future. Users are willing to keep paying for credit. Fundamentally, effective smart meters rely on a well-functioning PWS.
EF 4. Accessibility	
Ease-of-use of smart meter and tag	• The smart meter is easy to use. Users perceive high flow rate as important for quick water collection. • Some users explain that replacement cost of tags is too expensive. Approximately half of users have lost their tag at least once. The frequency of lending tags to other community members varies considerably. • Most users top-up credit from a reseller with cash. 82% of users find this easy, however this can be limited by access to a reseller.
Equity of use	• Respondents suggest that a small number of elder community members who live without dependents (and therefore have very limited money) are unable to pay (they are provided some free credit). • Women and children do the vast majority of water collection and therefore are impacted the most by the innovation. • Different households have different travel distances to DPs resulting in unavoidable inequalities in time of travel and therefore access (see Section 6.4.1). • Marginalised community members include those far from the nearest DP, too poor to afford credit, or those without tags. There is no evidence, however, that the new innovation has reinforced social divides or marginalisation. Instead, the reduced collection time incentivises users further away to choose DP collection over competing unimproved sources (e.g. riverbeds). • Understanding among users of what happens to data from their collections or money they buy credit with is very low.

5.7 Conclusions and novelty of work

Demand for smart meters from managerial stakeholders and users are shown to be high. Revenue collection, monitoring and service provision are improved. Improved access to DPs and quicker collection times has a significant positive impact on users, and benefits income, schooling and health. Affordability is good, and occasional technical problems do not significantly decrease satisfaction. Accessibility is high, in turn improving service to woman, children, and marginalised households.

Overall, smart meters (specially eWater taps) are shown to be highly effective in their socio-economic context in Tanzania. This has addressed the research gap identified in the literature review of the need for further independent, academic evaluation of smart meters beyond those presented in the literature review. The evaluation here has gone beyond linear evaluation and has drawn novel points of broader socio-economic impacts beyond established understandings, including the benefits of shorter collection times and the fundamental importance of well-functioning PWSs and community management committees. New detailed understanding of smart meter operation is uncovered which can provide evidence for decision-making.

Chapter 6. INSIGHTS INTO WATER COLLECTION PATTERNS FROM SMART METERS

6.1 Introduction

The previous two chapters have demonstrated that smart meters work effectively, record accurate data, and are beneficial to communities. This was important to establish first, as using smart meters for further research would otherwise be unethical and inaccurate. Now, new ways that smart meters can be used can be investigated.

The objective of the research in this chapter is to generate understandings of how smart meters can provide new insights into water collection.

To do this, remotely collected data from eWater taps in rural Tanzania and The Gambia are combined with results from the surveys and interviews from Chapter 5 to investigate new insights into water collection patterns from DPs. Distance users travel to DPs, times of day users collect water in the day, volumes collected by users, and the relationship between volume dispensed and location of DPs are investigated using the novel approach of combining newly available smart meters data with user interviews. Factors influencing water collection from PWSs are thereby identified, and relevance of findings for management and planning is outlined.

This addresses the research gap stated in Section 2.5.7 of the need to go beyond shorter-term benefits of smart meters and monitoring, and develop new opportunities and methodologies that ‘use’ the long-term data collected from smart meters. There is untapped potential for using this newly available, high-quality data to understand patterns of water collection in communities. Understanding collection patterns is important for planners.

This chapter, and Chapters 7 and 8, present new ideas of how smart meter data can be harnessed to help improve rural water supply and smart meter effectiveness, and in so doing moves beyond only evaluation. This is based on the idea that there are now 'research instruments' continuously collecting data in the field, which has not yet been well developed.

The novel contribution of this research is:

- Longer-term use of smart meter data to understand water collection patterns from PWSs
- Combination of smart meter data with user experiences (interviews)
- Demonstration of the usefulness of smart meters as novel research instruments

This research has been published as a journal article:
Ingram, W., & Memon, F. A. (2020). Rural Water Collection Patterns: Combining Smart Meter Data with User Experiences in Tanzania. *Water*, 12(4), 1164.

6.2 Background

SDG 6.1 requires better understanding of water supply at the village level. Specifically, complex patterns around rural user collection behaviours are not well understood (Thomas et al., 2019; Elliott et al., 2019). When in the day do users collect water? How does location of water point impact collection? How much water do users and households collect from different sources, and why? Answering these questions can bring evidence for planning and policy, and help reduce the risk of marginalised people being left behind (UN-Water, 2019; Ezbakhe et al., 2019; Graham et al., 2016). Research on household water demand in developing countries has previously focused on urban contexts (Nauges and Whittington, 2010), and exceptions in rural settings have mostly relied on household surveys due to lack of piped connections (Mu et al., 1990). Most attempts to estimate household water demand in developing countries has relied on data from household surveys. While water collection patterns can be determined from surveys and manual meters, this is much harder, less accurate, more expensive, and lower time resolution. Now, smart meters represent a new opportunity.

Households typically use more than one water source for the range of domestic uses, and determinants such as price, distance, quality, and specific use are complex and have been explored in focused literature (Nauges and Whittington, 2010; Hope et al., 2020; Coulibaly et al., 2014). Evidence suggests that improved water sources are commonly used for drinking and cooking, with unimproved surface water or wells being used for non-consumptive uses (Elliott et al., 2019), and this was shown to some degree in Section 5.4.1. Seasonal rainfall also impacts the choice of source as investigated in Chapter 7. While information on different sources are gathered from the interviews here, the novel contribution of this study comes from the high-resolution smart meter data, only available from PWS DPs, and its combination with the interview data. The emphasis is therefore narrowed to collection patterns from PWSs, but this remains important as information on PWS planning can find more direct use than information on other alternative sources. Overall, while alternative sources account for some collection of more non-consumptive domestic water, as expected, DPs are the most significant, as shown in Section 5.4.1 (only four users out of 53 interviewed do not use a smart meter DP as their main source of drinking water). The focus on the PWS here is justified.

Consequently, water quality of alternative sources beyond the PWS is not investigated in this study. Water quality challenges of surface water or shallow dug wells typically originate from contamination from run-off, or groundwater contamination if in proximity to latrines or other sources of pollution, and can result in microbiological risks. Such water quality issues can manifest in taste, smell or aesthetic concerns for users; and this is likely to be a driver behind user preference for the PWS, along with convenience and knowledge of the benefits of clean water. There is a risk in the context under study that deep groundwater, i.e. PWS water, also has water quality limitations despite being microbiologically safe, which could be caused by geogenic contamination of e.g. Iron or Fluoride, which can also affect taste, smell, and aesthetics, or work to corrode rising mains and pipework. In Community A there was no indication of any groundwater quality concerns from users or managerial stakeholders.

This is in line with the general acknowledgement that deep groundwater tends to be of satisfactory quality, as outlined in Section 2.2.5. Further detailed investigation would be required to determine exact water quality of the PWS groundwater and of alternative water sources in this particular setting. Water quality challenges relating to seasonality and rainfall are discussed in detail in Sections 7.1.2 and 7.1.3.

Furthermore, a significant water quality health risk comes from contamination during the transportation of water and storage in homes. Interviews and observation conducted in the previous chapter showed that users in Community A almost universally collect, transport and store water from DPs in 20-litre containers with lids, either on foot or using bicycles, carts, or donkeys, however storage is more variable. The lids reduce contamination risk as they block access of contamination (e.g. children's fingers or animals), and piped water has been shown as less likely to be contaminated compared with other water supply both at the source and once transported to the household from DPs (Shields et al., 2015). Therefore access to DPs is likely to reduce this risk compared to alternative sources.

In the developed world, smart meters in municipal systems have been used for decades to provide information on consumer behaviours (Cominola et al., 2015). In rural sub-Saharan Africa, understanding collection habits and needs can help practitioners and service providers visualise and predict demand. This is pertinent for the supply-demand challenge outlined in Section 5.5.3. It also furthers general understanding of rural water supply useful for larger scale research and policy across the sector and different settings, and of the complex system of rural water supply outlined in Section 2.2.6 and Section 2.4.7. Demonstrating the potential of smart meters for this now is important considering the projected increase in smart meter deployment.

6.3 Study approach and methods

Previous studies on PWS water distribution in sub-Saharan Africa have had to rely on conventional meters of uncertain accuracy and reliability, with low temporal resolution manual readings that are laborious and costly (e.g., Kulinkina et al., 2016), and are therefore restricted in detail. Here, data is now available from each DP on: time of use, the water volume dispensed per use (therefore the flow rate), the availability of each meter (i.e., functionality of the DP or meter), and the ID number of each tag being used to operate the smart meter. The accuracy and precision of these automated measurements is high, with time measurements in real-time and the impeller flow meter with very low error as established in Section 4.6.1. The exact GPS location of each DP is also known to within approximately 2 m. Data is accessed via an online dashboard where geographic and temporal scales can be selected. This represents a new opportunity for long-term monitoring of PWS use at fine temporal and spatial resolutions, such as hourly volumes dispensed. Matching user ID number to individual uses is not possible here due to sharing of tags and anonymity. Other novel technologies share some of these data categories to varying degrees.

Here, the 13 smart meters in Community A, which was described in Section 5.2, are used to investigate collection patterns. These are supplemented with the 10 smart meters in a rural community 40 km to the west of Community A (Community A2), and with 28 smart meters in a rural community in The Gambia, Community B. This allows for investigation of patterns across different settings. Distance users travel to DPs, times of day users collect water in the day, volumes collected by users, and the relationship between volume dispensed and location of DPs are most relevant to the study objective and have good quality data available. Data between November 2018 and August 2019 was gathered so as to align with the fieldwork timeframe (February 2019 to April 2019) and negate seasonality. Interview data and information from users and managerial stakeholders outlined in Section 5.3 are used, along with household GPS location data. In addition to the description in Section 5.3, the user surveys also included questions on water collection patterns, e.g.:

- ‘What time does your household collect water?’
- ‘Why do you collect water at this time?’

- ‘How long does the travel and the collection take from this water point, including queuing?’
- ‘What is your household’s main water source for drinking/cooking/washing/ bathing/domestic animals?’).

Factors were analysed individually and together, using quantitative methods involving descriptive statistical and mapping techniques, including measures of central tendency and dispersion, frequency distribution, time-series analysis, and uni- and multivariate regression, with presentation in graphs and maps. Detailed statistical modelling was not appropriate for investigating these new descriptive collection patterns. Specific detail is outlined with results below. Visualisations, including animated mapping, are employed where relevant to make patterns more generally understandable (Mannschatz et al., 2015). Qualitative data was processed as in Section 5.3. Interviews were not possible in Community A2 or Community B.

As argued in Section 3.1 regarding the analytical framework, the infrastructure of rural water supply is often treated as a separate issue to the socio-economic context (Whaley and Cleaver, 2017). Here, the combination of smart meter data with quantitative and qualitative information from interviews allows limitations of each method to be addressed and can provide more contextualized insight (Turman-Bryant et al., 2018; Andrés et al., 2018b; Anthonj et al., 2018). This allows for a better representation of the reality of rural water collection. Primarily, it minimizes the risk of missing information from only using the remotely collected data. Inversely, the availability of high-accuracy and high-resolution data on water usage adds detail and accuracy to findings beyond conventional survey approaches. This combined approach engages with the understanding of rural water supply as systems, outlined in Section 2.2.6 (Casella et al., 2015; Valcourt et al., 2020; Huston and Moriary, 2018; Liddle and Fenner et al., 2017) and aims to progress beyond technocratic approaches (Di Baldassarre et al., 2019). Demonstrating the benefits of a combined approach at this stage is important, considering such innovations and availability of data in general will be more common in the future across rural water supply systems.

A similar triangulated approach has shown success with other research problems, without remote data collection. For instance, in indigenous communities in Australia, researchers have combined water use data loggers and supplementary qualitative surveys (Beal et al., 2018). Others have combined structured questionnaires, direct observation, and water quality testing in large-scale surveys (Giné-Garriga et al., 2013). Outside of water supply research, sensor data has been successfully combined with interviews to impartially evaluate an improved cook stove intervention in Uganda (Sundararaman et al., 2016), and toilet use frequency in India (O'Reilly et al., 2015).

6.4 Results

6.4.1 Distances users travel to DPs

'Distance' is often used rather than 'time taken for collection' as an indicator in definitions of rural water access. 42 out of 45 national-scale water access indicators include definitions based on distance (Martínez-Santos, 2017; Kayaga et al., 2009), and so this is an appropriate choice of metric to investigate patterns here. Tanzanian national policy has a threshold of water access based on one water point serving 250 people within a 400 m radius (Mandara et al, 2016; Mwamaso, 2015), and DP locations are dictated during planning phases of PWSs based on household proximity and other hydraulic factors (e.g. topography, pressure, volume).

In Community A, 58% of respondents are within 400 m, as shown in Figure 6.1 (distance measured along paths is used for analysis, as explained in Section 5.3.2). The mean distance of travel for respondents is 446 m (a round-tip of 892 m), and there is wide distribution of households (std. dev. = 338 m). Household density is higher in the South of the community, following the road. A large number of households have marginalised access by living far away from DPs, as discussed in Section 5.5.2. 91% of users use the DP that is closest to their household most often. The remainders use DPs only marginally further away, never more than 50 m, and cite reasons of personal preference of paths, choosing not to collect near a school, or no particular reason beyond habit (water quality is uniform across the PWS). This is a similar value to the 89% found in Mali (Martínez-Santos, 2017), where taste, affordability or other personal preferences influence this decision. Community A has uniform quality (i.e. taste) and cost. In Community A1 that neighbours Community A, where there is no PWS, the mean distance to a handpump is 626 m (std. dev. = 236).

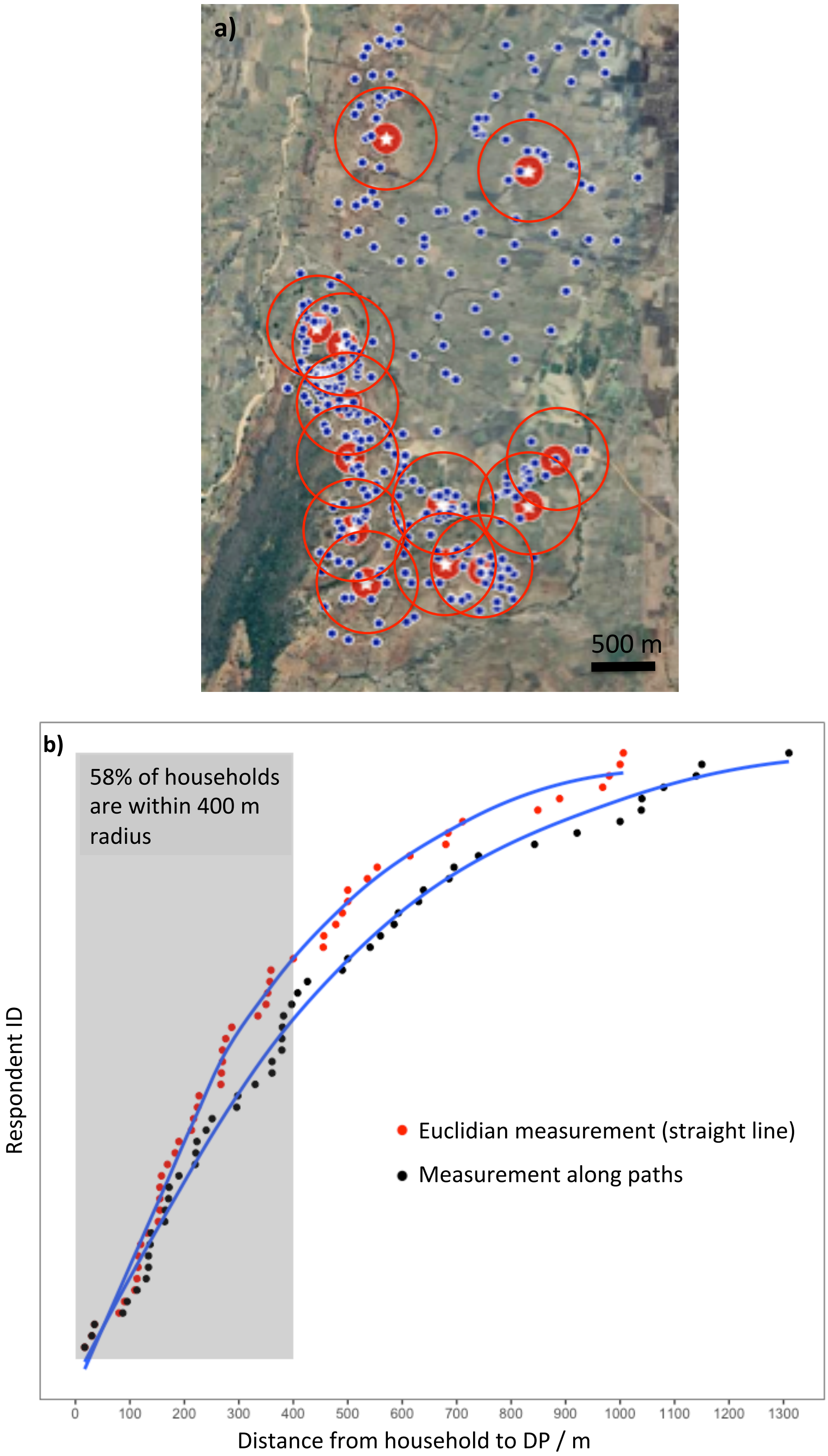


Figure 6.1 a) DPs in Community A showing 400 m Euclidian radius (red) and all household locations (blue); b) Distribution of distances between households and DPs for sampled user households.

Five of the nine respondents who do not use DPs cite long distance as a reason (mean distance for these respondents is 885 m, and eight users still live further away). This behaviour is seen in rural Madagascar where some households are less likely to choose an improved water source if it is further away than unimproved alternatives (86% use the option that is the closest available, which have a mean of 193 m distance) (Boone et al., 2011). Some users in Community A also expressed a desire for closer DPs.

Answers of time taken for water collection from users (as multiple choice of different time categories) were combined with the recorded location data to verify the expected positive relationship in Community A between distance and time taken for collection. This is shown in Figure 6.2. Different modes of collection such as using bicycles (faster) or young children (slower) reduce the significance of this relationship and explain outliers (goodness of fit is not appropriate for ordinal data here). Experiential findings are more appropriate here than combining distance with an average walking speed.

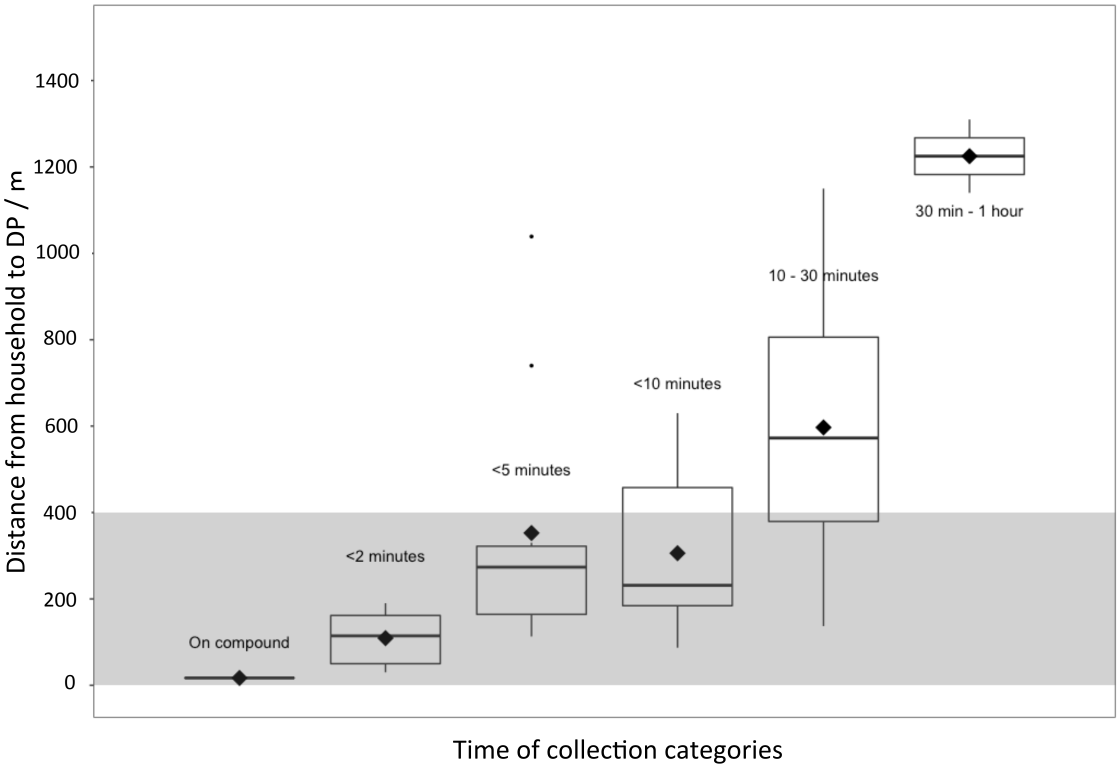


Figure 6.2 Distances from user households to DPs with reported times taken for collection (excluding non-quantifiable responses; outliers represented as dots).

Overall, the relatively clear relationship in Figure 6.2 demonstrates that shorter distances result in quicker collection times, and vice versa. This is significant because elsewhere variable queue time negates this relationship between distance and time taken for collection, for example in Madagascar (Boone et al., 2011). This provides new numerical evidence to the relationship between distance and time in a relatively novel setting where queue time is no longer significant (because of smart meters), and further demonstrates the impact of elimination of queuing as discussed in Section 5.5.1. This finding quantifies in this setting a previously anecdotal assumption. This evidence is in line with early evidence from rural Kenya where time taken for collection has been shown to influence the choice of water source (Mu et al., 1990). Here, the elimination of variable queue time in Community A shown in Section 5.4.3 has meant that distance is the major factor for time of travel, which in turn is dependent on DP positioning. Frequency of water collection and volume collected per trip was not included in the protocols because at the time of protocol design it was not considered to fit within the ‘right-sized’ research approach (see Section 5.3) because of hypothesized wide variability. There is a possibility that closer households are able to undertake more frequent collection trips than those further away, and this opens up interesting new research questions for further work.

6.4.2 Times users collect water in the day

As far as evident, understanding of time of collection of water in the day in rural sub-Saharan Africa remains largely based on anecdote or assumption. One analysis of solar pumped water kiosks in Kenya found that 55% of users collected water in the morning (Oxfam, 2018), and it is generally understood that each context and household will have different collection routines. Patterns in time of collection have great relevance for how communities interact with rural water supply, and high accuracy smart meters now make detailed investigation of this possible.

Answers on time of use from the first interview group were recorded. When users gave less precise times these were compiled into two-hour ranges to accommodate daily variability. The number of respondents who answered for each time range are plotted in Figure 6.3a. This shows the number of households that collect water at each time as a distribution across the day, and suggests that there are two collection peaks in the morning and afternoon. Average hourly combined usage data (litres) from all 13 DPs over November 2018 to April 2019 are plotted alongside this frequency distribution for comparison on the same axis (Figure 6.3b). The timespan used corresponds to the fieldwork outlined in Section 5.3 while reducing seasonal effects, and is disaggregated monthly with an average across months.

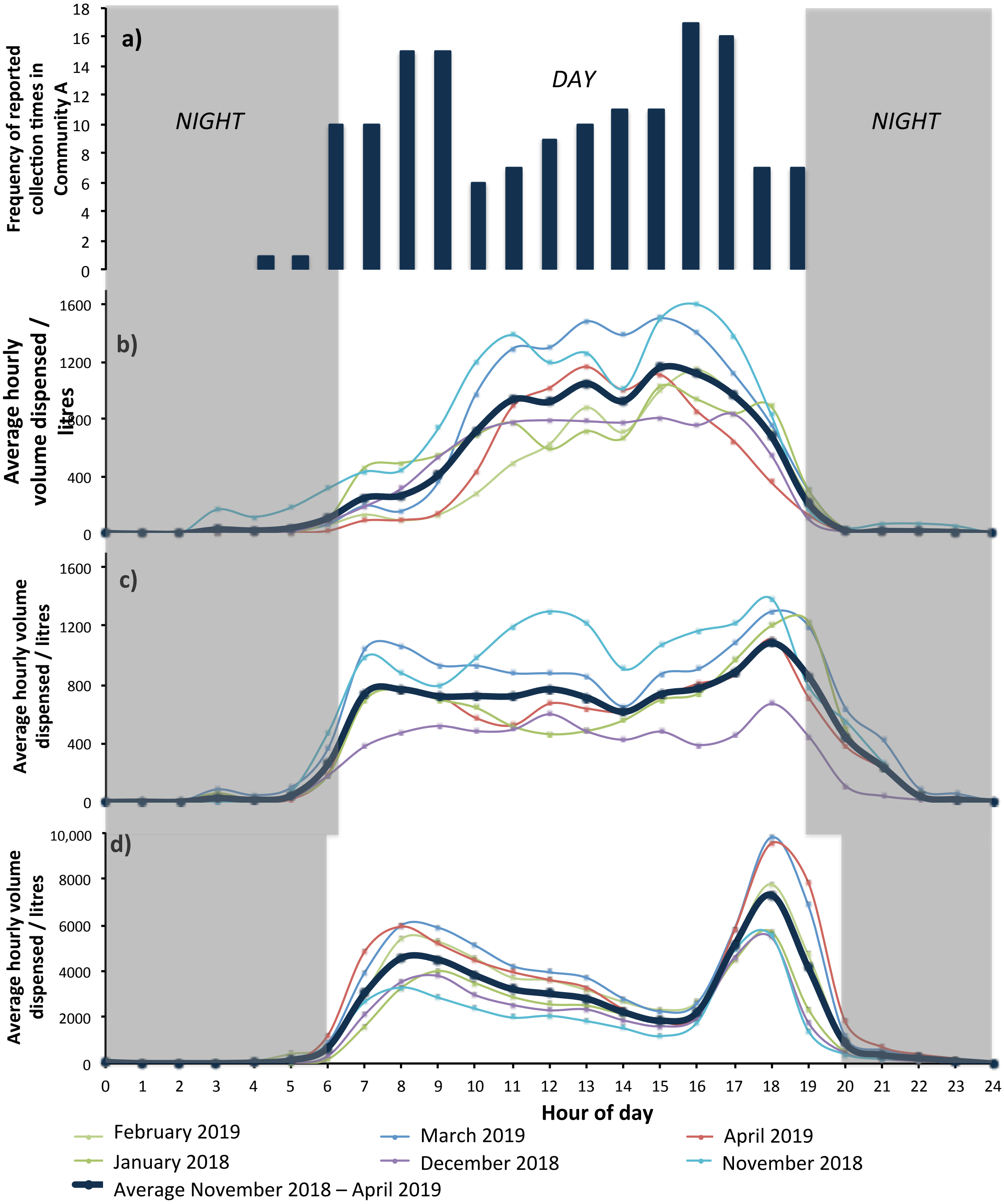


Figure 6.3 a) Cumulative frequency distribution of reported collection times of households in Community A; b) Usage data of combined average hourly use from all DPs in Community A for the period November 2018 to April 2019, c) Community A2 and d) Community B.

The variance in times of collection reported shows the differences in collection schedules between households in Community A. There appears to be no period in daylight when collection is not done, with a general preference for either morning or afternoon, or both. Qualitative explanations given by users for these quantified times vary. Times are limited by, for example:

- when water supply is available from the PWS, specifically in the morning when solar pumping has not filled the tank, or in the evening when the tank has become empty
- when users have time free from other activities
- when it is less hot
- farm work in the morning and rest time in the evening
- when the children return from school to do the collection (approximately 16:30).

No users interviewed collect at night either because of schedules and security, but more commonly because of lack of water availability. Households further from DPs showed a minor preference for morning collection, perhaps because closer households may feel more comfortable waiting until the afternoon; however this trend is not very significant with these data.

The DP usage data from the smart meters maps to the reported times of collection for the time period (Figure 6.3a,b) within a reasonable margin of error considering variability of daily schedules, aggregate DP usage data, and imprecision of time recall. The afternoon peak is mirrored in both data sets. The weaker match in the morning is likely attributable to households collecting lower volumes at these times. A slight increase in volume dispensed over the afternoon compared to the morning likely demonstrates the time spent on farming activities in the morning mentioned by users. The sharp reduction in usage between 17:00 and 19:00 (Figure 6.3b) demonstrates supply running out by evening. Such limits to supply were discussed in detail in Section 5.5.3; users outline that supply often abruptly runs out later in the day, and often attribute this to days of reduced sunlight when solar pumping capacity is limited, and managerial stakeholders explained that water supply from the tank and the rest of the water distribution system cannot always match demand. Research in urban Sri Lanka has shown that if service from a piped connection is available for longer throughout the day, volume collected increases (Nauges and Van Den Berg, 2009). However, this is by a negligible amount of 2% for every extra hour of availability, and in a very different setting and does not merit comparing here. There is no relationship between: time of use (of DP) and time taken for collection (travel); time of use and main source of water for specified uses; or time of use and user satisfaction. No DPs appear to be used more at different times of the day.

Community A2 (Figure 6.3c) shows a greater variation of times of collection throughout the day compared to Community A. This is perhaps due to the more dispersed nature of the community and longer collection distances. The mean distance between DPs is 1.0 km, compared to 0.48 km in Community A. It also suggests that water is more available in the PWS as supply lasts longer into the evening and remains until the morning. The storage tank of the piped water distribution system in Community A2 is larger (70 m^3) than in Community A with a population of a similar size that is more dispersed.

More consistent usage times across all months is shown in the average hourly usage data in Community B in The Gambia with 28 DPs (Figure 6.3d). Here, the start and end of collection with sunrise and sunset are relatively precise. Comparing this community (and Community A2) is useful here to reveal that Community A exhibits relatively inconsistent patterns. Attempts to explain the differences here are inappropriate without socio-behavioural understanding of Community B in a very different context (further research incorporating use of water for religious reasons in this largely Muslim setting would be particularly interesting). However, the larger number of DPs, larger population, greater volumes dispensed, and nucleated distribution may have a levelling and smoothing effect on the data (mean distance between DPs is only 93 m).

Some degree of seasonality of collection from DPs is evident across the different months in all three communities. Reduced collection from piped supply due to free rain and surface water in rainy seasons is a common feature of rural water supply in sub-Saharan Africa. This does not drastically influence time of collection here (this phenomenon is fully investigated using smart meter data in Chapter 7).

6.4.3 Volumes collected by users

Users in Community A were asked the volume they collect from DPs in the interviews, giving a mean total volume of 133 litres per household per day (std. dev. 72 litres). 12 respondents' answers are unquantifiable because of the imprecision of the user's response, and one represented a school teacher's collection combined with school collection and was therefore not representative. 133 litres is equivalent to approximately 6.5 20-litre containers per day. Division of household collection volumes by household resident number gives an approximate mean of 25 litres per person per day from DPs. Volume is not influenced by the household member responsible for collection, suggesting that children collect approximately the same volume of water per day (within one std. dev.) as adults. Carrying such heavy water loads has been shown to be particularly damaging to child health (Geere et al., 2018).

Larger household sizes decrease the volume of water per resident. Figure 6.4 shows this in Community A, with estimates calculated from the surveys. The mean values of the daily volume collected per person show a strong overall negative univariate relationship against household size (R^2 = 0.78). Multiple determinants that influence volumes collected, such as household volume requirements, distance (as above), different water sources, and other socio-economic factors, weaken this relationship. No influence of household size was observed in Mali (Martínez-Santos, 2017), where this trend was fully obscured by these other variables. However, less water per resident with larger household sizes is generally seen in the developed world because of shared water use activities in households (e.g. Schleich and Hillenbrand, 2009; Arbues et al., 2010), and also in some developing world urban settings (e.g. Cheesman et al., 2008). In Community A, the most likely explanation is that larger households have more children who do not use domestic water for the full range of uses.

Further relationships between volume per capita and: a) distance to DPs and b) time taken for collection, were also investigated using uni- and multivariate regression models, and while no significant univariate relationships were found for these data, co-variants of household size and distance to DP increased the strength of the relationship (R^2 = 0.85, with no significant interaction).

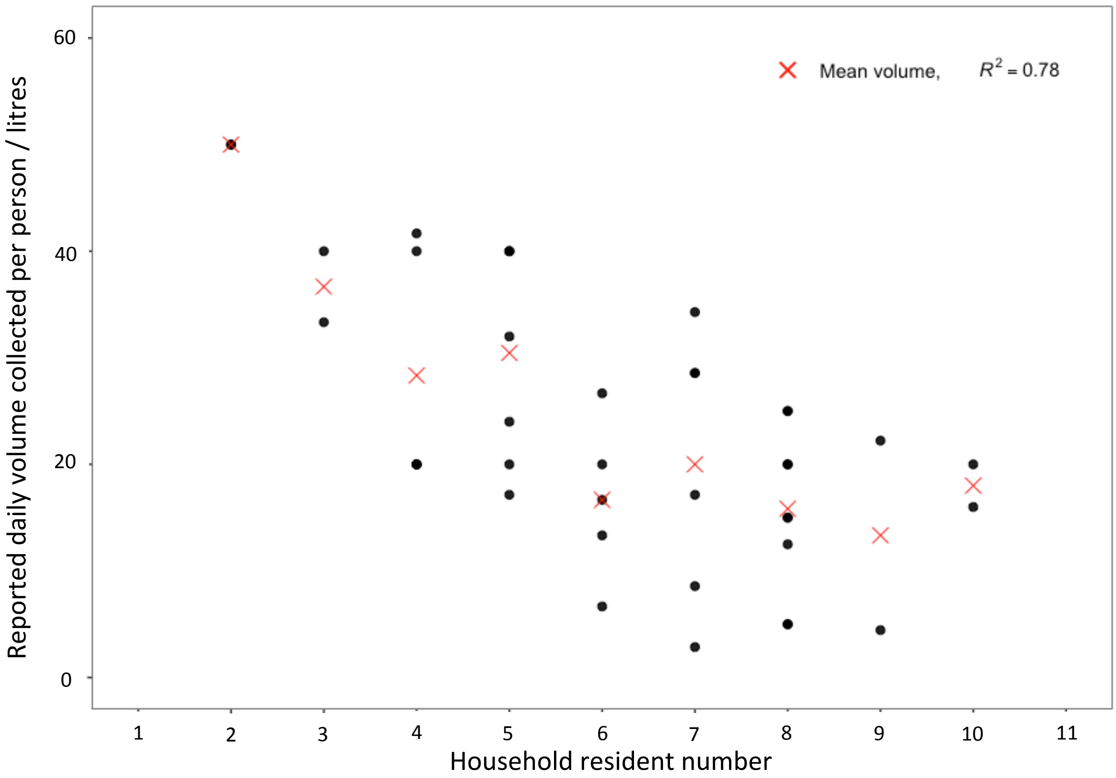


Figure 6.4 Average volume collected per day per person from DP against number of residents per household (not including n = 12 unquantifiable volumes and one outlier of 80 litres per day).

Individual water collection events can be identified from the DP usage data using the time of use and tag ID number. A commonly observed pattern is users first collecting small amounts of water (~1 litre) by briefly applying their tag before collecting lager volumes to fill up containers. This was often observed during fieldwork in Community A for washing out of containers. Long gaps are evident between collections, and this adds evidence to users' answers that there are no queues at DPs, which was shown in Section 5.4.3. The majority of collections shown in Community A have maximums of 18–20 litres. The most commonly used container is 20 litres. This supports findings from Section 5.4 that users value every litre and waste less because of pre-payment. Users tend not to collect more than three buckets (~60 litres) at a time. This remote analysis is supported by fieldwork observation.

There is a mismatch between the mean volume users answered they collected daily from DPs per household (133 litres), and the remotely collected data. If the number of households in Community A that use DPs is underestimated at 250 (non-user households not included), then dividing the mean daily total volume dispensed between November 2018 and August 2019 (11,736 litres; std. dev. = 3,070 litres) gives approximately 47 litres per household. The discrepancy is more likely to originate from overestimation by users of the volumes they collect from DPs, or reporting of maximum volumes. Additionally, water from alternative sources like lined wells in household's compounds or rainwater harvesting may have been included in users' totals, despite specification of DPs in the protocols, because of daily variability of collection and water use (Elliott et al., 2019). Smart meters measure volume accurately as demonstrated in Section 4.6.1, and are not subject to subjective estimations. These low collection volumes are consistent with expectations from rural water points away from households across the developing world (Nauges and Whittington, 2010).

6.4.4 Relationship between water volume dispensed and location of DP

It is understood that households in rural sub-Saharan Africa tend to collect less water when distances to water points are greater (Cook et al., 2016; MacDonald et al., 2019), and in some cases distances provide robust forecasts for volume dispensed (e.g. $R^2 > 0.93$, better than affordability or water quality; Martínez-Santos, 2017). It has been theorised that when a water point is over 100 meters away (or more than 5 minutes) the volume of water collected tends to significantly decrease, plateauing between 100 and 1,000 meters, after which volume decreases again (WELL, 1998). In Community A, distance of household to DP shows only a minor negative relationship with volume collected (as reported by households). Here, the influence of distance is weakened by multiple factors, e.g., some users transporting more water further by cart, bicycles and donkeys, and the relative proximity of DPs compared to communities without PWSs.

Smart meters allow location of DP and volume dispensed to be further examined using data from the individual DPs, along with household location. It is useful to have accurate understanding of which DPs get used the most. The variable volume dispensed from each DP over November 2018 to August 2019 can be visualised in a moving image, represented in Figure 6.5. Monthly aggregations are used here, as they are not disrupted by brief non-functionality events. These dynamic maps give geospatial context to DP location (Mwamaso, 2015; Mannschatz et al., 2015; Kwakkel et al., 2014).

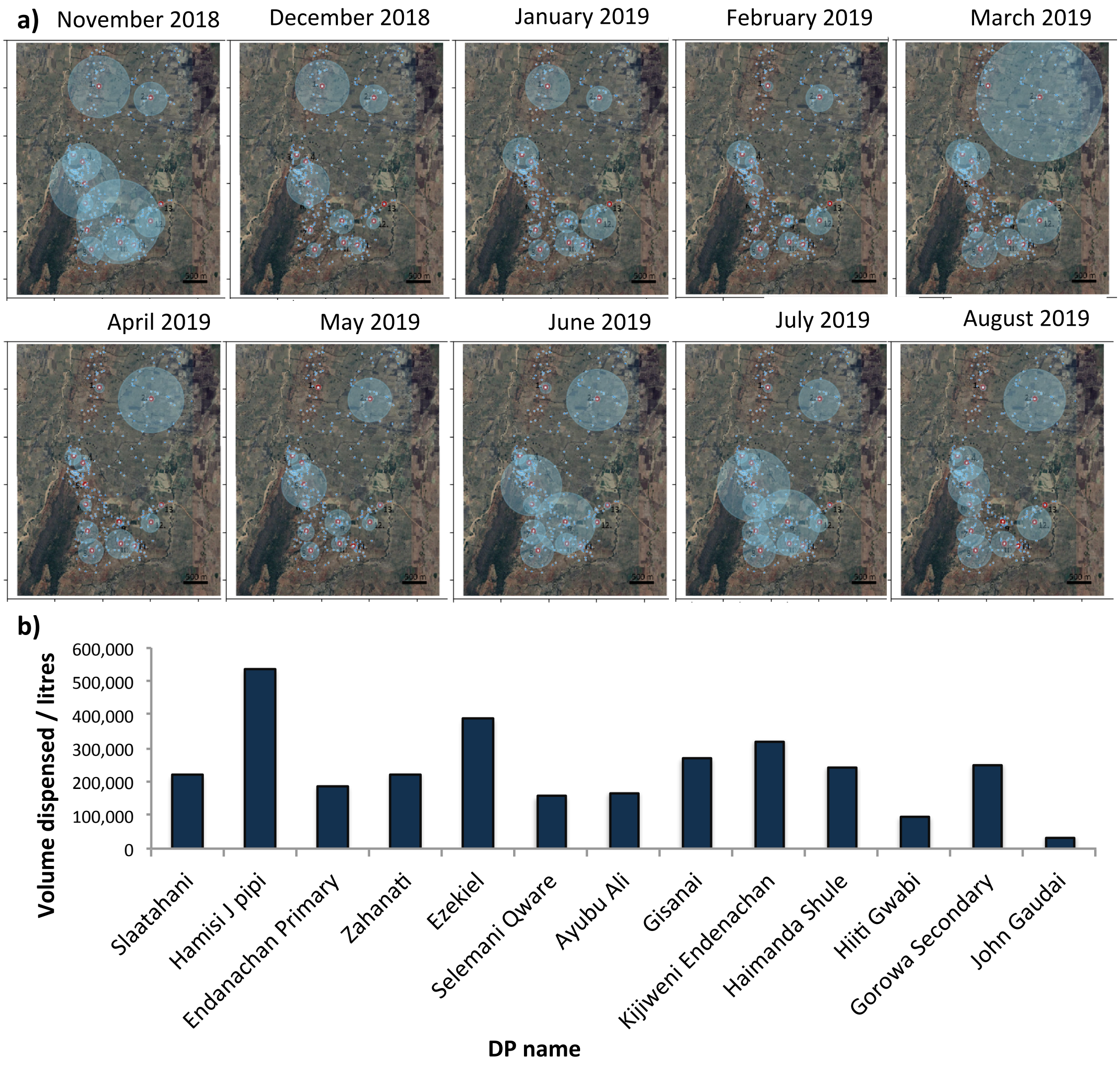


Figure 6.5 a) Frames of a moving image showing volume (radius of blue disc) dispensed from each DP in Community A (November 2018 to August 2019), mapped for each location. Blue dots represent all households. Each frame represents one month. These can be watched for November 2018 to August 2019 for Community A and Community B for the same time period at: https://streamable.com/nob82y; https://streamable.com/z72l4i; b) Total volume dispensed for each named DP over the same time period.

These visualisations (Figure 6.5a) present a clear way to show that use of individual DPs in Community A does not have uniformity or regularity across time or DP location. For example, monthly volumes dispensed from DP 'Ezekiel' vary by a factor of 11, and 'Kijiweni Endanachan' by 30. The range of coefficients of variation (standard deviation divided by mean) across each DP is wide (0.28 – 1.1; mean = 0.60). Months that exhibit an overall high volume across all DPs are partially skewed by specific DPs. This variation of usage over time originates from unpredictable and dynamic collection behaviours, and the impacts of seasonality. There is no relationship between distance of DP from tank and volume dispensed, nor with periods of non-functionality. The complexity and lack of any discernible regularity is an interesting finding, discussed below, and limits further analysis here beyond visualising the unpredictability of volume dispensed. However, Figure 6.5b does reveal some differences of volume dispensed between DPs:

- ‘Hamisi J pipi’ is shown to dispense the highest volume overall (but not every month)
- ‘Selemani Qware’, ‘Ayubu Ali’, ‘Hiiti Gwabi’, and ‘John Gaudai’ show low volumes dispensed every month
- Water volumes dispensed from the remaining eight DPs do not show very high or low volumes dispensed (staying within one std. dev).

The reasons for these observations are explored in relation to how many households are nearest to each DP. Higher numbers of households that use each water point in small towns in Ghana results in greater volumes being dispensed (Kulinkina et al., 2016). A Voronoi-type mapping shows the number of households that are nearest to each DP, which are then plotted against total volume dispensed from each DP over November 2018–August 2019 (Figure 6.6). Nearest-neighbour analysis (Vasiliadis and Kobotis, 1999) to analyze how clustered DPs are did not give not appropriately high significance.

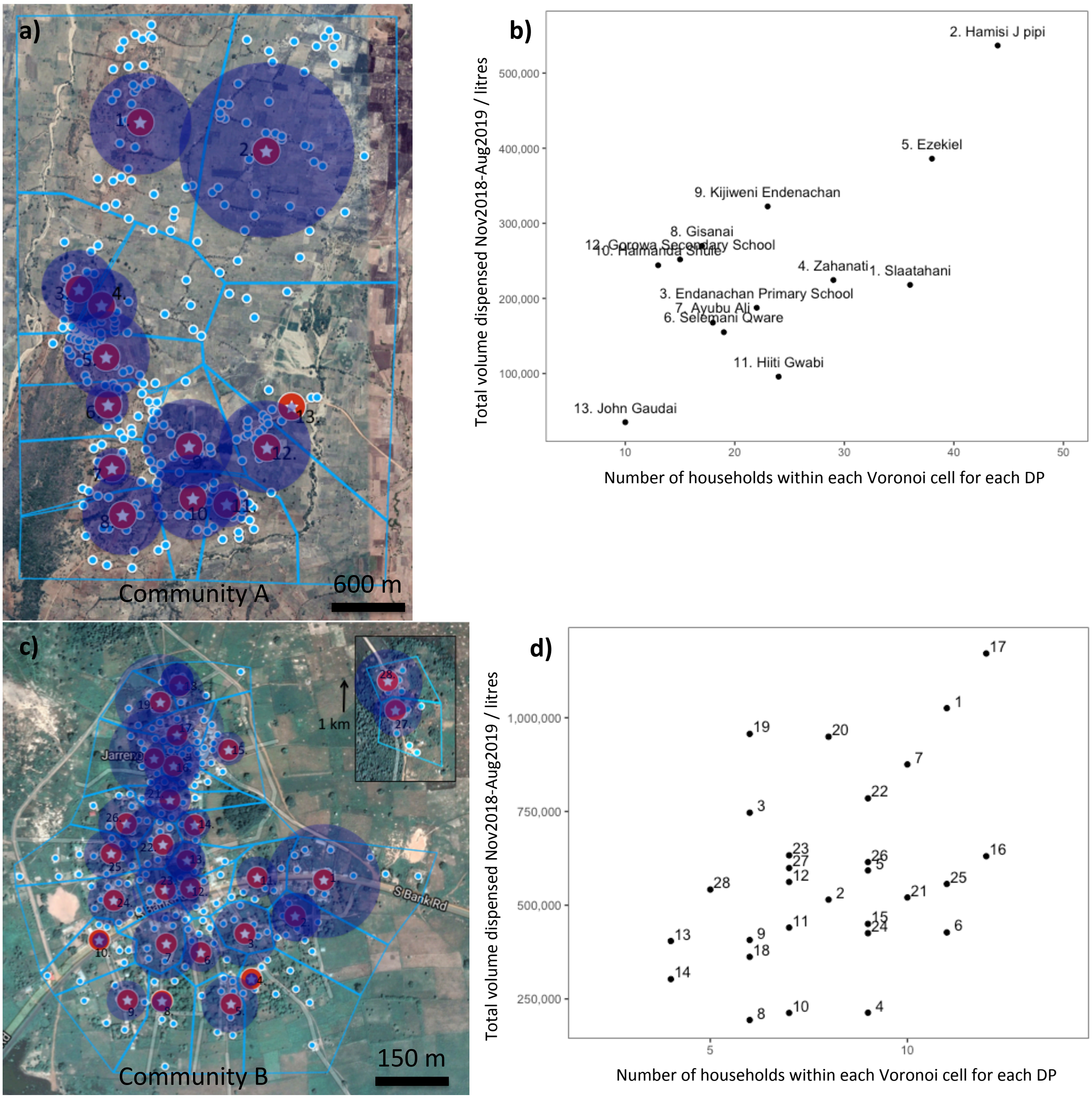


Figure 6.6 a) DPs (red) and location of all households in Community A (blue dots) with total volumes dispensed over November 2018–August 2019 as radius of disc (blue) where 500 m radius = 150,000 litres, showing Voronoi cells for each DP; b) Number of households in Community A that are nearest to each DP against total volume dispensed over November 2018–August 2019; c,d) Community B, as for a.b) with 100 m radius = 400,000 litres.

The general positive relationships shown in Figure 6.6b,d confirm that DPs that have more households that are nearest to them tend to dispense more water, due to greater total usage. Furthermore, comparison against the location of DPs in the community and the density of households in Community A shows that the total number of households appears to be a more important factor than household density. For instance, households in Community A around ‘Hamisi J pipi’ (North-Easternmost DP) are more dispersed with users having further distances to travel (mean ≈ 630 m). DPs in central locations in the community do not dispense more water. Greater number of DPs in this analysis would give a better representation of this trend, however the key finding is evident. This finding is supported by the 28 DPs in Community B (in The Gambia) over the same time period, shown in Figure 6.6c,d. These DPs also show significant variation and irregularity of volume dispensed, which is significant considering that Community B saw a much more regular time of collection pattern (Figure 6.3d). Community B has a significantly higher density of households (n ≈ 227), with the majority within 100 m of DPs. Its PWS dispenses approximately 2.4 times more water than Community A's (over the same period).

6.5 Discussion

6.5.1 Collection patterns from smart meter DPs

Many rural households in sub-Saharan Africa collect water from more than one source, which can improve resilience of water supply. Different sources are commonly used for different purposes, and respondents report this is also the case in Community A. Specifically, alternative unimproved sources are reported to be used more for non-consumptive uses where quality and payment are less critical factors, indicating some preference for cleaner DP water for consumption. Alternative sources may influence DP use, however here this is considered less significant and the focus in this study on collection from PWS DPs is justified: 97% of users report DPs as their main source for domestic water and only a small minority of the community do not use DPs, as was confirmed in Section 5.4.1.

The surveys have shown that approximately 58% of households are within 400 m of a DP, the nationally mandated distance for water service (Mandara et al, 2016; Mwamaso, 2015). Unsurprisingly, users who live further away generally report longer time for overall water collection trips. This is a relatively clear trend across the community because it is not influenced by time spent queuing as it is elsewhere without smart meters. As discussed in Section 5.5.2, on one hand, therefore, the elimination of queuing has resulted in access to water from communal DPs being unavoidably unequal, because some households remain further from DPs. On the other hand, the reduced overall collection time from the DPs means users who live further away have improved access, making it more worthwhile for them to travel to the DPs rather than other to unimproved water sources. Distance (and therefore time taken) for collection will grow in importance because economic losses associated with time spent collecting water are projected to increase in sub-Saharan Africa as GDP grows (Fuente et al., 2020).

These results show that households in Community A collect water from the DPs at different times of the day. Time of water collection in the day has been examined with relatively high accuracy and precision. Preferences are partly influenced by when children return from school, time free from farming and other activities, and temperature, as explained by users. Collection is seen to stop in the smart meter data, and managerial stakeholders confirm that this is when availability of water in the PWS runs out. This hydraulic limit constrains users' collection schedules. Community A2 (and Community B) use their DPs later into the evening. This suggests that preferred collection behaviours, depending on the setting, depend on supply being greater than demand at all times. This reinforces the information from managerial stakeholders (discussed in Section 5.5.3) that demand for water is outstripping supply, due in large part to population growth, and that, as shown, limitation of the PWS negates the anytime-access of DPs, which negates the benefit of the smart meters.

The mean volume collected recorded from smart meters is ~47 litres per household per day (lpd) (average household sizes gives approximately 8 litres per person per day). This falls below recommended water requirements for human activities and consumption, especially considering larger households are shown to have less volume per-capita (Figure 6.4). 'Basic' access is categorized as 20 lpd (50 lpd = 'intermediate'; 100 lpd = 'optimal') (Howard and Bartram, 2003), or as 50 lpd (Gleick, 1996). Any additional water from alternative sources is more likely to be contaminated. Despite the improvement in service from the PWS with smart meters, this situation remains far from an acceptable level of supply of clean water.

The smart meters reveal high unpredictability of volumes dispensed from different DPs across time (days, months), and location, which is unexpected. It was hypothesized that more centrally located DPs would record greater volumes dispensed. The slight positive relationship between household number closest to each DP and total volume dispensed explains some of the variation, however the significance of other variable factors beyond distance, such as how much volume each household collects, is shown in the wide data spread for these relationships. Detailed explanations of this are not possible without additional research questions. However, visualising the unpredictability of volumes dispensed is useful itself in showing that assumptions of more regular water collection patterns resulting from installation of 'formalised' PWSs in rural communities are not necessary correct. This is in contrast with urban piped systems with household connections, where the large scale has a levelling effect on the regularity of patterns.

If evenness of water distribution across DPs (and therefore revenue collection) is a planning aim for PWSs, the positioning of DPs in PWS across sub-Saharan Africa could be better based on Voronoi-type mapping of households rather than density of households or community centres. This may be more objective and less influenced by social pressures, and could also increase access of more marginalised households. This general relationship could also guide operation and maintenance of existing PWSs. For example, in Community A an extension of 'John Gaudai' pipework northwards by 300 m would bring the DP in range of more distant households in the agricultural plain area. This would reduce the burden on 'Hamisi J pipi' and therefore balance the vulnerability of heavily used DPs breaking down. This could also increase access of more marginalised households. This general understanding that volume dispensed from each DP depends more on the number of households could help inform planners about different DP use on any existing PWSs across sub-Saharan Africa where smart meters are not installed, with relevance to revenue collection.

Analytic information from PWS water collection patterns for the purposes of management, beyond DP siting, has the greatest potential for indicating overall volume dispensed (particularly across the day) as this could support COWSO decision-making regarding pump use and PWS capacity. Relationships with groundwater depletions would be useful further work, as discussed in Section 10.2.1.

Overall, there is limited indication of strong patterns of water collection. The variance in household collection from DPs across times of day, volume collected, and time taken for collection that is seen in the data from smart meters and users emphasise that understanding collection patterns cannot be based on linear assumptions. This reflects the wider rural water supply system, and its complexities and heterogeneities described in Section 2.2.7. Nonetheless, without an optimally functioning PWS with water available whenever required, i.e. with a tank size, pump, and borehole yield of sufficient capacity, users will have to adjust their water collection and use practices. This could involve relying more on unimproved alternative sources.

6.5.2 Benefits of remote data collection and combination with interviews

Smart meters provide high resolution, accurate, and objective data on volumes and times of water dispensed from DPs over long periods relatively easily, cheaply, and at the required scale, without the need for inaccurate modelling or estimations. Interviews and surveys provide information and explanations not available from smart meter data. Accordingly, a more rounded understanding of water collection patterns from PWSs has been possible here beyond a reductionist one based only on DP data. For example, simply viewing times of collection remotely provides accurate information on total volumes dispensed at different times. However, collecting additional responses on when users collect water from DPs has revealed a wide variance between households. It also explains why some users prefer certain times, in particular when children return from school, or when they have free time from farming. There is a reasonable match in times between the two sources of information for the timescale studied. Additionally, this combined approach allows discrepancies to be revealed between remotely measured and self-reported information. Measured total volume dispensed is estimated at ~47 litres per household per day, while the mean self-reported volume collected is ~133 litres per household per day. This is evidence that self-reported volumes are less accurate with different sources of water not distinguished. This demonstrates the value in objectively establishing reality.

Matching specific users with tags for detailed investigation of household patterns and payments is not accurate enough here. This is because of lending of tags (described in Section 5.4.4), some registration inaccuracies, and the logistics and ethics of matching households to tags. Even if this data were available for use, it would still require combination with survey and interview protocols for the reasons given above.

While this study is limited to a snapshot using one monitoring technology, data from an increasing number of DPs are continually being collected across sub-Saharan Africa using similar technologies, as outlined in Section 2.5. After installation, economic costs of the remote data collection are negligible from smart meters compared to manual meter reading, which requires individual readings by staff and is subject to human error. This represents an opportunity to benefit from even ‘longer-term’ use of these data, which is a gap highlighted in Section 2.5.4. Here, this research has demonstrated how this gap can be addressed, and the value of doing so.

6.5.3 Relevance of findings to practice and policy

Better information is needed on how communities use rural water supply projects if they are to be sustainable and resilient. The World Bank has called for more resources to go towards data collection for water management in Tanzania (World Bank, 2017c). Remotely collected data from PWSs using smart meters or similar Internet-of-Things technologies listed in Section 2.5 can contribute to this data collection. Combining remote collection of data with ‘on the ground’ knowledge generation is generally applicable across anywhere such technologies are deployed.

Community A holds general similarities with other rural communities across sub-Saharan Africa, such as domestic water use, agrarian livelihoods, and demographics. Findings here around irregularity of PWS use and location of DPs with regard to household density can help service providers plan new and existing PWSs elsewhere more sustainably, for example by building in additional capacity to PWSs to accommodate unpredictability of water collection, and DP location. PWSs are of increasing popularity across rural sub-Saharan Africa (as shown in Section 2.3.1), and they often provide better and more sustainable service, higher water quality, and are more economically favourable compared to handpumps, and can facilitate better revenue collection (Pezon, 2015). Understanding water collection patterns specifically from PWSs, within the context of alternative sources, is of increasing relevance and can form part of the move away from handpump-scale community management models and support the service delivery approach.

General unpredictability in demand across different DPs and different times is likely to be a common attribute across other rural communities' PWSs. A rural water supply system that is resilient to shocks and changes must accommodate for wider variability in demand. This is pertinent considering climate change. For example, potential interventions on a PWS could be focused on ensuring supply across a whole community rather than at specific DPs, which could reduce use of unimproved alternative sources.

Solar pumping is increasingly seen as the best option for PWSs (World Bank, 2018b). Understanding the continual demand across mornings and afternoon–evenings in small rural communities can inform pump installation and solar panel requirements. In Community A, the mean daily total volume dispensed between November 2018–August 2019 was 11,736 litres (std. dev. = 3,070 litres), and as shown in Section 5.5.3 this remotely collected data shows that the tank size is probably not the limiting factor in supply. Rather, solar pumping appears insufficient. Combined with a low productivity borehole, supply lags behind demand, and the tank runs empty over the evening.

6.5.4 Limitations of the study and further work

This study was able to address the objective well and has generated understandings of how smart meters can provide new insights into water collection. Similar to Chapter 5, this research would be more representative of water collection patterns across rural communities in general if user experiences from more communities were available. This would require further fieldwork. Additionally, longitudinal study of how water collection patterns change over the long-term would be interesting; this is partly addressed in Chapter 7 regarding seasonality. Overall, this has demonstrated the potential for a new research approach in this area.

Additionally, other research on water demand in developing countries has included variables relating to household characteristics, specifically income, wealth, and education. Including these may have revealed further interesting relationships. However, it has been shown that income doesn’t have significant influence (Mu et al., 1990), and would have added unnecessary questions contrary to the ‘right sized’ approach (Section 5.3). Additionally, investigation of frequency of water collection throughout the day across different variables would be an interesting topic of further study.

The methodological limitations of the interviews were outlined in Section 5.3.4 and remain pertinent for the analysis here. However, as in Chapter 5 these do not significantly alter findings, and the sample size is large enough to give reasonable quantitative data and useful qualitative information. As shown, the omission of alternative water sources is not significant as the majority of users answered that they use DPs for the majority of domestic water, and it is the PWS and smart meters that are under investigation.

Smart meter data on water collection patterns from PWSs could potentially find application in analysing and managing groundwater resources, as suggested in Section 2.5.2. Interesting further research could focus on the relationship between volumetric use and aquifer depletion over time and space. Including multiple smart meter PWS systems across a district in such as study could be used to investigate groundwater resources on a fine spatial scale across the same aquifer, which might indicate groundwater flow, inter-community resource equity, or suitable borehole siting locations; at the moment, the scale of smart meter rollout limits this.

6.6 Conclusions and novelty of work

Patterns of water collection from a PWS in a rural Tanzanian community have been provided to a new level of detail by combining remote data collection from smart meters with the experiences of users themselves.

This study adds value by showing that:

- 97% of users use DPs as their main source for domestic water, and distance from households to DPs is highly variable and is one constraining factor of access to water regardless of queue elimination from smart meters.
- Users collect water at different times of the day, depending on when water is available at the DPs and other behavioural factors explained in interviews such as when children return from school or free time from farming. Water supply running out over the day is another constraining factor.
- Volumes collected show wide variability between households. Remotely collected data shows mean volume collected per household per day is approximately 47 litres, contrasting against mean volume of 133 litres given by respondents. This shows the importance of objective smart meter measurements.
- Different DPs across the community distribute unpredictable and variable volumes over time. DPs at locations in community centres or higher household densities do not consistently distribute more water. Instead, a higher number of households that use each DP is a better indicator of greater volumes dispensed, and this can contribute better to DP location planning than, for example, community centres. However, there are multiple unpredictable factors that influence volume dispensed.
- Fundamentally, while collection patterns result from socio-economic factors and behaviours, the functionality and good operation of the PWS (including supply of water that meets demand) underpins collection.

These findings are generalisable to other rural communities with PWSs with or without smart meters. The same methods can be applied in other communities with smart meters. Smart meters are therefore shown to be useful not just for the reasons shown in Chapters 2 and 5 (i.e. improved service provision, monitoring, access, revenue collection, et al.), but also as a research tool that can help uncover new findings about how communities access rural water supply. This goes some way to address the limited longer-term use of this kind of monitoring data. Use of smart meters for research purposes is a growing opportunity.

Chapter 7. INSIGHTS INTO SEASONALITY OF WATER COLLECTION FROM SMART METERS

7.1 Introduction

So far, it has been demonstrated in Chapters 4 and 5 that smart meters can be beneficial to communities and technically robust. It was then shown in Chapter 6 that they can successfully be used as research instruments to reveal useful water collection patterns. This chapter follows the same concept as Chapter 6 in developing new ideas of how smart meter data can be harnessed and used in the longer-term. This principle is extended to investigate the environmental factor of seasonality by combining smart meter usage data with meteorological data.

The objective of the research in this chapter is to generate understandings of how smart meters can provide new insights into seasonality. This chapter investigates how weather and seasonality influence water collection in rural communities in sub-Saharan Africa, and adds to the existing understanding of this relationship that has been derived from other methods. This addresses the research gap outlined in Section 2.5.7 of better understanding the impact of seasonality using newly available smart meter data, and better longer-term ‘use’ of data.

The novel approaches of the work in this chapter are:

- Use of smart meter data for combination with weather data, rather than other sensor or manual data; and therefore focus on increasingly popular rural PWSs rather than boreholes or handpumps
- Inclusion of three independent meteorological data sets rather than just one
- Longer time-series data sets of approximately three years rather than one or two
- Investigation of seasonality of rural water collection in Tanzania and The Gambia.

Based on the findings presented here, Chapter 8 next investigates how smart meters can mitigate the adverse effects of seasonality of water collection with weather dependent pricing.

7.1.1 Background to seasonality and rural water supply in sub-Saharan Africa

Different locations in sub-Saharan Africa experience different lengths, intensities, and numbers of seasons, however seasonality is typically characterised by rainy and dry periods. In the dry seasons, the ratio of Tanzania's national water demand to available supply is approximately 150% (World Bank, 2017c), and it has long been understood that seasonality influences water points in sub-Saharan Africa (e.g. White et al., 1972). Individual water points are classified as 'seasonal' if a seasonal interruption of more than one month is reported (Giné-Garriga et al. 2013), and in rural Tanzania water quality at 19% of improved water points has been recorded as seasonal (Jimenez Fernandez de Palencia and Perez-Foguet, 2012). In central Tanzania, 24% of the water points are reported to change seasonally from providing a sufficient to an insufficient amount of water (Twisa and Buchroithner, 2019). Across sub-Saharan Africa, access to groundwater with PWSs often allows continuous access to clean water through dry seasons.

However, in keeping with the complexity of rural water supply outlined in Section 2.2.7, the influence of seasonality extends beyond water points, with multiple impacts across different factors. These include the availability of alternative water sources, affordability, user behaviour, revenue collection, and the ability to conduct O&M. For example, it has been shown that rainy seasons reduce the ability of communities in Zambia, Ghana and Kenya to mobilise resources for O&M (Kelly et al., 2018). In coastal Kenya, revenue collection at handpumps collapses during the rainy season below a 60% revenue collection threshold (and remains more resilient in the dry season with reinforcing growth dynamics once about 40% of users are paying) (Foster, 2017). In Benin, 66% of users who purchase water in the dry season are reported to switch to combined purchased and free water in the rainy season (Arouna and Dabbert, 2010).

Seasonality is shown to be a significant factor for users in Kenya who want higher prices and faster repairs of handpumps (Hope and Ballon, 2019).

Some breakdowns of PWS infrastructure are more common with either rainy or dry seasons (WaterAid, 2018). Seasonality tends to be a major factor in the availability of cash or other capital in communities. Lack of capital can contribute to decreased sustainability, or community members mobilising other forms of asset such as manual labour if needed (Behnke et al., 2017). Many of these seasonal challenges are rooted in the limitations of the long-prevailing community management approach (Chowns, 2015) outlined in Section 2.3.3 where non-professional community members have too much responsibility for O&M of rural water supply.

Studies have tended to examine the influence on water source choice of either the wet season or the dry season, and findings from both groups are consistent with each other. For instance, in drought season in Ethiopia (the inverse of rainy seasons) springs, hand-dug wells, and surface sources showed large reductions in availability, putting more pressure on deep motorised boreholes (MacAllister et al., 2020). Here motorised boreholes are further away from households. Generalisation is limited, as shown by comparison in one study where Uganda fitting the pattern of lower functionality in the rainy season, but Liberia showing lower functionality in dry season due to decreased groundwater availability (Foster, 2013).

7.1.2 Influence of rainwater on collection

Rural households tend to collect water from multiple alternative water sources away from the home, as was shown in Section 5.4.1 and Section 6.5.1. Increasing evidence shows that this behaviour is partly determined by rainfall variation and the resulting availability, quality and affordability of different sources (MacAllister et al. 2020; Hope et al., 2020; Majuru et al., 2016; Hoque and Hope, 2019). An historic focus on ‘main drinking water source’ in programme data collection has obscured this. Furthermore, different sources have been shown to find different uses in the household, in particular unimproved sources for non-consumptive uses and improved clean sources for drinking and cooking (Elliott et al., 2019). Use of alternative sources is a common coping strategy to water source unreliability (Majuru et al., 2016), and choice of alternative source is influenced by income and nature of unreliability; however most of the evidence for this is from urban settings.

Generally, rural users tend to spend less time and money on water collection from improved water sources in rainy seasons because seasonal water sources are more available, for instance from rainwater harvesting, streams, ponds, and tube wells (Kelly et al., 2018). In one study in Kenya, most households (n = 387) report that most of their water comes from rainwater in the rainy season, with 96% reporting they collect rainwater at this time (Cook et al. 2016). 41% of households in a study in Rwanda used rainwater as their primary water source in the rainy season, compared to 27% who used improved wells (Hopkins et al., 2004). Likewise elsewhere in Kenya, the rainy season sees an increase in the number of households who harvest rainwater from 0% to above 50% (Hope et al., 2020), with a gradual increase in scooped water collection, a decrease in handpump and water vendor use, and a sharp drop in hand-dug well use. Rural households in Benin that pay for water (rather than collect free) were observed to collect less water in the rainy season than dry season by about 14% (Arouna and Dabbert, 2010).

7.1.3 Negative impacts of seasonal use of contaminated water

There is an increase in many water-related illnesses during rainy seasons. This is largely due to increased use of contaminated sources of water. Seasonality is known to influence water quality globally, and the rainy season is shown to increase faecal contamination even of improved water sources in both rural and urban contexts (Kostyla et al., 2015). For example, diarrhoeal disease in children peaks during the rainy season in Senegal (Thiam et al., 2017), and this is speculated to arise from greater pathogen growth and infection from contaminated water. Decreased rainfall and increased temperature during dry seasons has also been linked with increased diarrheal prevalence, which is related to domestic water use and increased rotavirus insulation (Bandyopadhyay et al., 2012). In the dry season, households in rural Tanzania and Uganda are shown to move towards water sources with lower risks of water-related illnesses (Pearson et al., 2016). Seasonal shifts to surface water sources also increase risk of parasitic infection, for instance schistosomiasis (Braun et al., 2018), which has some evidence of seasonality (Grimes et al., 2015).

Quality of harvested rainwater and other seasonal rainfall sources tends to be worse than groundwater. Formal rainwater harvesting, which is more often the focus of research, typically consists of well-constructed permanent storage tanks and pipework. In the setting under study here described below, rainwater harvesting is more typically an open container beneath the corner of a tin roof. Rainwater harvesting is generically categorised as an ‘improved source’ (JMP, 2017a) (unprotected well, spring, river, and surface water are ‘unimproved’ sources). Additionally rainwater harvesting can fit in the ‘safely managed’ category of the JMP service ladder outlined in Section 2.2.1. However, quality of harvested rainwater is dependent on many factors, including environmental and meteorological conditions, birds and rodents, as well as roof and guttering construction, openness of collection containers, and treatment applied (Despins et al, 2009). Even in developed countries where it is more often easier to limit contamination, rainwater harvesting has still been shown to contain a diverse range of pathogens (Dobrowsky et al., 2014). Although rainwater harvesting can provide greater volumes of water, which can be beneficial for health though improved hygiene, it also brings significant infection risks (Baguma et al., 2010). ‘Waterborne’ and ‘water-washed’ diseases are responsible for the greatest disease burden in this instance and mostly result in infectious diarrhoea. Children under five, and other vulnerable groups such as pregnant women, immunocompromised, or older people, are particularly susceptible, which is pertinent in these domestic settings. Harvested rainwater is significantly more likely to be contaminated with faecal indicator bacteria than borehole groundwater (Bain et al. 2014; Hamilton et al., 2019), especially in this context where there is likely no protocol for disposal of the ‘first flush’ or infrastructure for filtration.

In comparison, groundwater is generally considered good quality (Katuva et al. 2019) especially in comparison to surface water vulnerable to contamination in the unsaturated zone (Lawrence, 2001). Borehole PWSs like those in this study tend to rely on groundwater of even deeper and higher quality water than handpumps, often from confined aquifers. Microbiological water quality is highest in boreholes, i.e. PWS or handpumps, followed by protected springs and rainwater harvesting, open and covered hand dug wells, and finally open water (Parker et al., 2010). Rainwater harvesting was shown to have a significantly higher number of *E. Coli* thermotolerant coliforms (indicator for faecal contamination), but approximately equivalent turbidity as groundwater. Studies across sub-Saharan Africa have shown that most groundwater from handpump-boreholes fits within the WHO water quality standards (Lapworth et al., 2020). Recent findings from Malawi show that groundwater from handpumps shows negligible change between seasons and alternative sources are higher risk (Ward et al., 2020). While most water suppliers and public health agencies fail to test for water quality frequently enough or to WHO standards (Peletz et al., 2016), and despite some geogenic contamination (i.e. originating from the geology) from arsenic, fluoride and iron, groundwater use results in better health outcomes. An important factor remains contamination after collection from open containers. However, piped water is shown as less likely to be contaminated compared with other water supply both at the source and once transported to the household from DPs (Shields et al., 2015). Overall, groundwater from PWSs has reduced risk of contamination and is a safer option of water supply than rainwater harvesting.

Regular use of unimproved water sources by populations in developing countries goes unreported, and detailed surveys suggest this is done by an average of 5.5% more than official estimations (Vedachalam et al., 2017). Furthermore, health seeking behaviours are reported to reduce in the rainy seasons (Sauerborn et al., 1996), when rural households have less cash for healthcare and greater opportunity costs from productive work. During the dry season in Ethiopia, water use drops to less than 10 litres per person per day with use for hygiene reducing most significantly (Tucker et al., 2014). Along with health impacts, reduced seasonal collection impacts year-round and long-term sustainability of rural water supply. Less revenue collected reduces financial sustainability and O&M capacity. Willingness to pay also generally decreases when these free alternatives are available. In Kenya’s Kitui County (Nyaga, 2019) even when all piped water systems are functional operators have to close operations in the rainy season due to users going to alternative, free water sources, making the businesses unviable. Even smart meter kiosks are seen to close during rainy seasons (Komakech et al. 2020).

Put together, this evidence emphasises the need for seasonal interventions that improve clean water use and public health.

7.1.4 Existing quantification of seasonal reduction in clean water use and novelty of approach

Recent research has used different monitoring techniques to quantify the impact of rainfall on use of improved groundwater sources. One study of PWSs in four small towns in Ghana used manual flow meters to infer that a 100 mm increase in monthly rainfall (ground-measured 5-15 km from the communities) correlates to an average 16% decrease in monthly water dispensed from communal water points (Kulinkina et al., 2016). Another study in Kenya used data from ‘Smart Handpumps’ (n = 266, ~±15% accuracy of volume measurement; Thomson et al., 2012; see Section 2.5.5 and Section 4.2) across one year to show an average 34% reduction in handpump use when it is rainy season (Thomson et al., 2019). The researchers used rain gauges on location to show that individual heavy rainfall events can result in a 68% reduction in handpump use on the day, with a lag in re-uptake over the following two days. Here, days with the greatest 10% of rainfall (mm) were shown to have the greatest influence. Preference for rainwater harvesting and surface water collection meant only 6% of households used handpumps as their only water source in the rainy season, compared with 86% in the dry season. Other work presents similar findings using ‘Sweetsense’ sensors (also included in Section 2.5.5) to measure pumping at motorised boreholes (n = 221) over eighteen months in arid regions of Kenya and Ethiopia, and their response to drought emergencies (Thomas et al., 2019; Turman-Bryant et al., 2019). Borehole runtime was combined with one satellite-based rainfall estimate (5 km resolution, CHIRPS), and aggregated weekly. An increase in borehole runtime of 22.3% was observed following weeks with no rainfall compared to weeks preceded by some rainfall. Borehole pumps were found to be used an average of 0.38 hours less in the rainy seasons. Daily rainfall estimates gave poor prediction of volume dispensed in this context.

These studies quantified reductions in clean groundwater use using new IoT monitoring technologies. Next steps are to extend this to examine the impact on use of rural PWSs using smart meters, rather than just handpumps and boreholes, and to develop management strategies to address reduced use. PWSs are of increasing popularity compared to handpumps (Pezon, 2015). The research presented in this chapter uses the same smart meters from Chapters 5 and 6 for accurate remote data collection at rural PWS distribution points (DPs) themselves. Fine spatial resolution daily time series of three individual rainfall estimates, with one temperature estimate, are analysed over three rainy seasons in Tanzania and The Gambia. An added value from this approach is that volume dispensed is measured from the point of collection of domestic water across the communities, bringing the investigation closer to users' realities and representing the whole community rather than individual handpumps or boreholes. Volume is also more accurately measured remotely with direct flow measurement (as established in Section 4.5.1) rather than via proxy sensors, and variabilities, inaccuracies, and missed readings from manual collection are avoided. Here, these meters aid investigation by remotely reporting on water collection over multiple years. This aims to be part of the move towards longer-term use of these data. This partly answers the call from other researchers for "collection of more detailed data on seasonal variation and management" (Anthonj et al, 2018). This research is not an attempt to forecast volumes dispensed, as suggested in other research based on weather and other variables (Check et al., 2017), but instead provide a basis for the timing and magnitude of price changes for weather dependent pricing (Chapter 8).

Significantly, while other studies have measured and described seasonal changes and the associated policy implications, research has yet to go further and illustrate how novel smart meter technology can be used as a new tool to help mitigate use of contaminated water sources. Smart pre-payment meters open the possibility of remote financial management in response to weather. A novel weather dependent pricing mechanism is outlined and developed in Chapter 8.

7.2 Study context, approach, and data

Data was collected from two rural communities with smart meters installed on DPs of PWSs in northern Tanzania (Community A; ~300 households, 13 DPs) and central Gambia (Community B; ~230 households, 27 DPs). These are the same as in Chapter 6. Volume dispensed from individual DPs varies widely as established in Section 6.4.3; therefore data on volume dispensed from individual DPs are combined as this was considered to better represent trends in community-wide water collection. Both are supplied by a borehole and elevated tank. Domestic rainwater harvesting when present (see below) is informally done using bucket containers beneath tin roofs, with no communal rainwater harvesting. Alternative seasonal water sources, specifically riverbeds and wells, are spaced heterogeneously across the communities. Measurements of borehole pump use or tank level are not available. The relationship of volume dispensed data with weather data is investigated.

Data from rain gauges were not available in either community. Meteorological stations in Tanzania, used in other studies (Twisa and Buchroithna, 2019), are dispersed across hundreds of kilometres and therefore not representative. Despite being more accurate at the location of deployment, the density of hydro-meteorological stations across Africa is eight times lower than the minimum density recommended by the World Meteorological Organisation (Resende et al., 2019). Monthly rain gauge data from a town 15 km from Community A are available from 1971-2019, however are unusable as 40% of data points from 1999 are missing. Instead, satellite measurements of weather provide homogeneous spatial coverage (Sun et al., 2018). Three satellite-based daily rainfall estimations (mm) were discovered to be available for the two locations. These provide an observational range shown in Figure 7.1.

I. The Global Precipitation Measurement (GPM) is a constellation satellite mission that uses a package of radar and microwave sensors, and currently provides one of the best-regarded space-based precipitation measurements (Skofronick-Jackson et al., 2018; Hou et al., 2014). Precipitation data resolution is available at 0.1 decimal degrees, approximately 11 km^2 at the study latitudes. The data were available via the Giovanni online data system, developed and maintained by the NASA GES DISC (Acker and Leptoukh, 2007);

II. University of Reading's TAMSAT (Tropical Applications of Meteorology using SATellite data and ground-based observations) uses infrared measurements to provide rainfall estimates across Africa with finer resolution of 0.0375 degrees (Maidment et al., 2017; 2014; Tarnavsky et al. 2014). Daily estimates are disaggregated from 5-day totals, and show similar estimation to other daily rainfall estimates;

III. CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) uses infrared cold cloud duration measurements to provide rainfall data at 0.05 degrees resolution (Funk et al., 2015). It was developed for USAID to support the Famine Early Warning Systems Network (FEWS NET).

Differences between satellite rainfall datasets are primarily due to different sensor inputs, algorithmic assumptions, and calibrations against ground-based measurements. It is not appropriate here to discern the most reliable or accurate option. All three estimates show clear and regular rainy seasons in both communities, shown in Figure 7.1 and Table 7.1. Rainfall throughout the rainy seasons is shown by all estimates as highly variable (both intensity and day), and both communities are characterised by some days of extremely heavy rainfall, which is examined below. There is some minor variability between estimations of intensity of rainfall (mm) and timing (day) of rainfall events. Community B experiences more rainfall than Community A (by: GPM = 24%; TAMSAT = 59%; CHIRPS = 49%). TAMSAT and CHIRPS measure marginally longer rainy seasons than GPM in Community B and Community A respectively. TAMSAT shows slightly less sensitivity to rainfall intensity, and CHIRPS measures fewer days with rainfall > 0 mm.

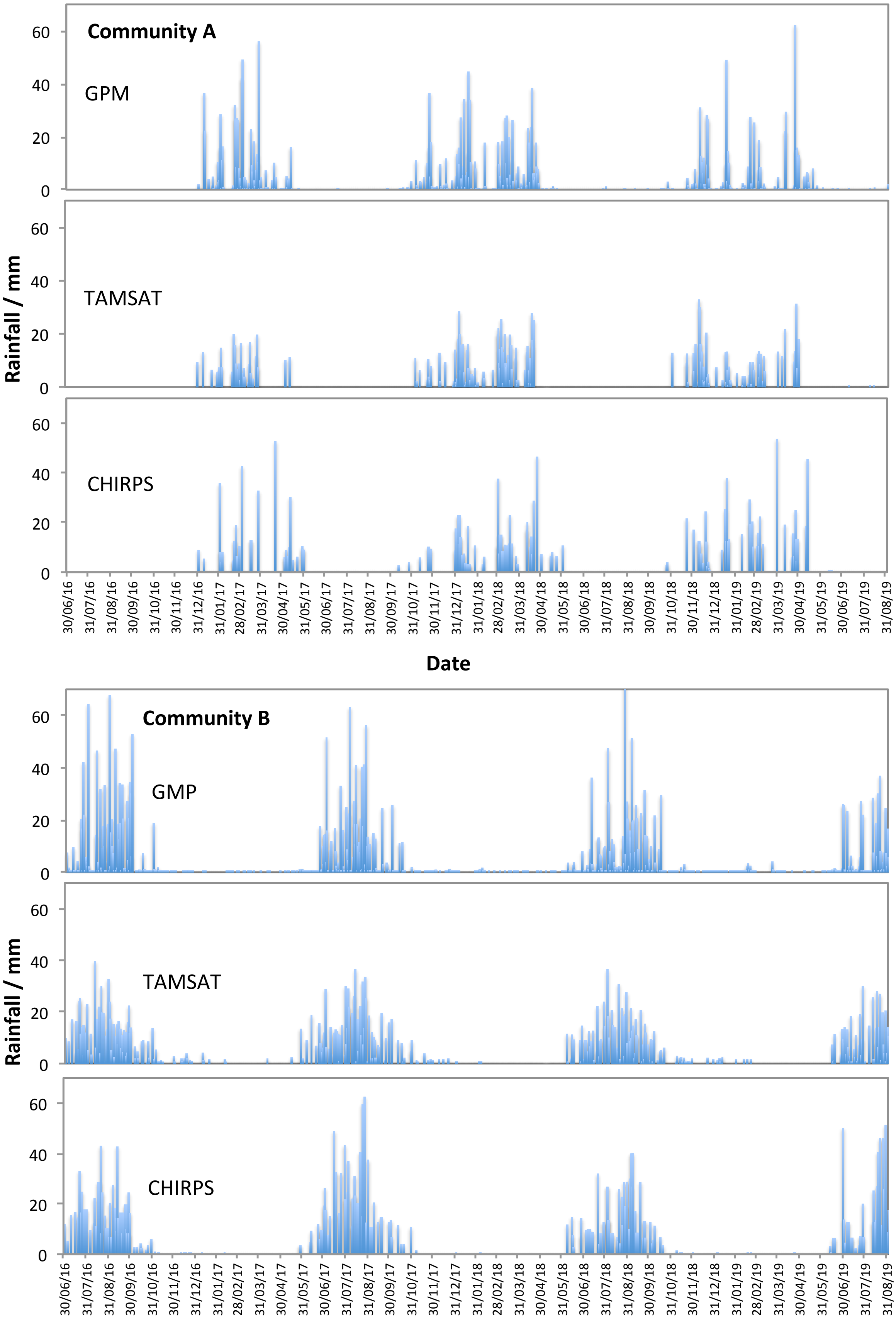


Figure 7.1 Rainfall from three available daily satellite rainfall estimates (GPM, TAMSAT, CHIRPS) for Communities A and B.

To avoid the imprecision of defining rainy season start and end dates from these data, months are assigned as ‘rainfall’ or ‘dry’, as shown in Table 7.1. This gives robust approximations and better represents uncertainties and variabilities around the onset and length of rainy seasons, such as from the observed ‘Eastern Africa paradox’ mismatch between modelled and observed meteorological patterns (Wainwright et al., 2019). The ‘long’ and ‘short’ rains experienced in East Africa are combined for this analysis as they are not particularly evident in Community A. Such ‘unimodal’ rainfall is also reported for an adjacent Tanzanian region to Community A (Twisa and Buchroithna, 2019). This allows for general comparison with other communities across sub-Saharan Africa including Community B.

Table 7.1. Comparison between rainfall estimates

	Rainfall months	**Dry months**	**Total rainfall days** (A: out of 814; B: out of 945)		
Community A	Nov-Dec-Jan-Feb-March-April-May	June-July-Aug-Sept-Oct	> 0 mm	> 0.5 mm	> 1.0 mm
GPM mean rainfall	3.53 mm	0.04 mm	254	179	157
TAMSAT mean rainfall	2.92 mm	0.00 mm	143	135	131
CHIRPS mean rainfall	3.05 mm	0.04 mm	106	100	100
Averaged mean daily rainfall	*3.17 mm*	*0.03 mm*	*168*	*138*	*129*
Community B	June-July-Aug-Sept-Oct-Nov	Dec-Jan-Feb-March-April-May	> 0 mm	> 0.5 mm	> 1.0 mm
GPM mean rainfall	4.49 mm	0.07 mm	443	201	170
TAMSAT mean rainfall	4.42 mm	0.13 mm	235	224	200
CHIRPS mean rainfall	4.92 mm	0.01 mm	156	141	141
Averaged mean daily rainfall	*4.61 mm*	*0.07 mm*	*278*	*189*	*170*

Corresponding temperature data were also included in analysis, estimated at two-meters altitude from Atmospheric Infrared Sounder (AIRS) available from the same source as GPM. These are included in Figure 7.2 below. There is minor warming towards the end of each dry season in both communities, particularly in Community B. Community A mean = 24.2 ^{o}C (range = 10.0 ^{o}C). Community B mean = 30.4 ^{o}C (range = 13.6 ^{o}C). Irradiance from Ozone Monitoring Instrument (OMI) was examined but is excluded from further analysis due to strong and significant negative relationships with rainfall and temperature from the obvious link with sunshine.

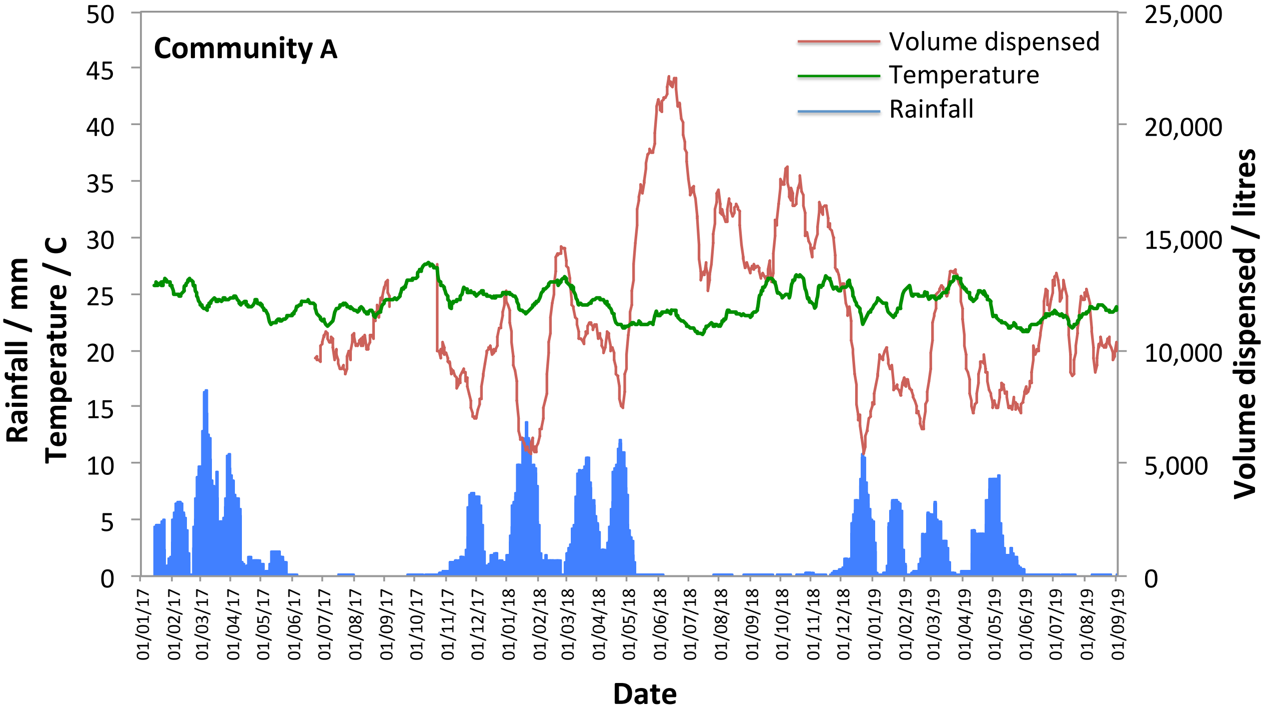
In addition to these data sets, community members in Community A were asked questions as part of the protocols in Chapter 5 that relate to rainwater harvesting and collection behaviours in hot weather. There were no price changes, droughts, or other influential factors over the period to the author's knowledge.

In the following sections the relationship between volume dispensed and weather data is investigated at different time resolutions, in the order of: 1) seasons, 2) daily and 14-day, and 3) days of heavy rainfall. Different statistical techniques including single and multivariate regression and analysis of time lags were employed to derive the influence of weather on volume dispensed from DPs, along with comparison of data sets with measures of central tendency and dispersion. Further analytical techniques are outlined with relevant results below. Other statistical analysis using, for example, panel data techniques (Taylor and Ortiz, 2009) or forecasting were not required for the objectives here. Importantly, findings are 'ground-truthed' with the experiences of community members for the same reasons as outlined in Section 6.3.

7.3 Analysis and Results

7.3.1 Influence of rainy seasons on volume dispensed

Volumes dispensed from the DPs are shown in Figure 7.2 (A = 814, B = 946 days). Rainfall (GPM) and temperature are included for comparison. Daily values are smoothed using a 14-day moving average to present the overall trends, discount brief data gaps, reduce the influence of outliers and autocorrelation, and better represent seasonal changes. Daily mean volume dispensed is approximately three times greater in Community B than Community A (A = 11,700, B = 35,200 litres). The volume dispensed, rainfall and temperature all show high daily variability (coefficient of variation: A = 0.41, B = 0.59), which is explored below. There are periods when collection drops close to zero, for instance October 2017 in Community A. These are attributable to non-functionality of the PWS, and do not form a significant number of data points (A = 59, B = 16 days), and are therefore cleaned from the data rather than filled with a dummy variable. The overall increase of volume dispensed in Community B reflects an increase in water collection from more DP meters coming on-line over the period.



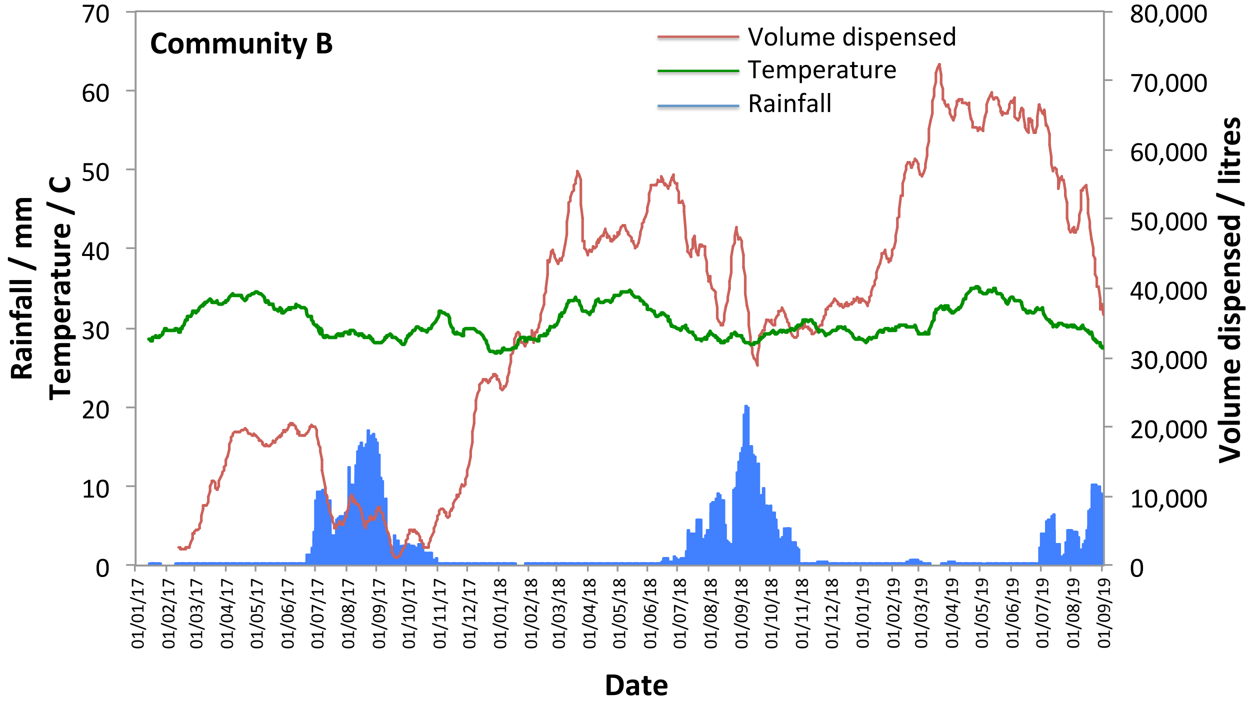


Figure 7.2 14-day moving averages of: volume dispensed from DPs (red), GPM rainfall estimates (blue), and temperature (green). Greater granular details of rainfall months can been seen below in Figure 7.5.

A general relationship between volume dispensed from the DPs and rainfall and temperature in these two communities is evident in Figure 7.2. Volume dispensed is higher overall in dry months, aligning with periods of rainfall. Specific sub-seasonal peaks of rainfall correspond with troughs of volume dispensed.

This apparent influence of rainfall months is tested using the dry and rainfall month designations from Table 7.1. Figure 7.3 and Table 7.2 show that volume dispensed is significantly less in rainfall months in both communities. Kruskal-Wallis tests confirm this is statistically significant, showing volumes dispensed during rainfall months are strongly non-identical to dry months. In general, an average of approximately 20% less water is dispensed in rainfall months compared to dry months. (Adjusting for the overall increase in Community B gives an average decrease across the three seasonal changes of approximately -12%).

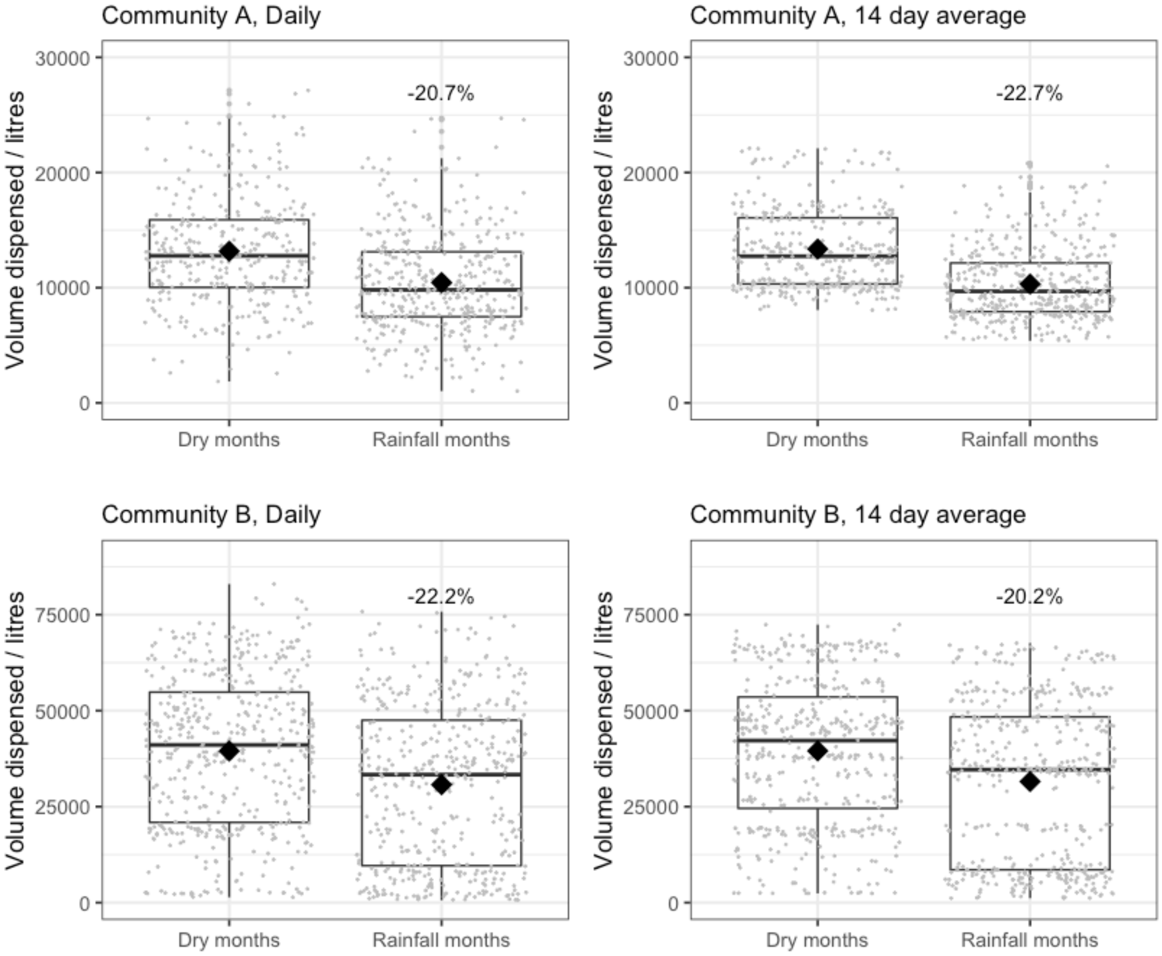


Figure 7.3 Difference in volume dispensed from DPs between dry and rainfall months, showing individual data and mean.

Table 7.2. Impact of rainfall months on volumes dispensed

	Community A (daily)	*Community A (14-day moving average)*	Community B (daily)	*Community B (14-day moving average)*
Dry months				
Mean daily volume dispensed (litres)	13,167	*13,360*	39,488	*39,517*
Standard deviation	4,770	*3,504*	19,843** (5,764)	*18,752*
Per household approximation* (litres)	44		172	
Rainfall months				
Mean daily volume dispensed (litres)	10,448	*10,318*	30,725	*31,547*
Standard deviation	4,344	*3,151*	20,727** (9,032)	*20,456*
Per household approximation* (litres)	35		134	
Comparison				
Decrease in volume dispensed in rainfall months	20.7%	*22.7%*	22.2%	*20.2%*
Kruskal-Wallis*** χ2	62.9 (p << 0.001)	*143.5* (p << 0.001)	41.1 (p << 0.001)	*35.2* (p << 0.001)

** based on rooftop counting estimates with fieldwork calibration; A ≈ 300 and B ≈ 230; as described in Section 5.2*

*** these large standard deviations in Community B are from gradual increase over timespan. Values in brackets are standard deviations of residual variance from 14-day maximums, which give a better representation over the shorter-term.*

**** Kruskal-Wallis tests statistically determine that the medians between groups are different, in this case between dry and rainfall months, and are used here as a non-parametric alternative to ANOVA. The p values are less than the significance level 0.05 and so we can conclude there are significant differences between the dry month and rainfall month groups.*

Rainfall months in both communities show higher variance of volume dispensed compared to dry months. Coefficient of variation for *rainfall months:dry months* is 0.42:0.36 for Community A and 0.67:0.50 for Community B. This indicates relationships exist at a finer timescale than seasonally, and this is investigated below.

Overall, this analysis shows that users' collection of clean water from DPs significantly drops by approximately one fifth over rainy seasons in both communities. This is consistent with the findings from research elsewhere presented in Sections 7.1.1 and 7.1.4 (e.g. Kulinkina et al., 2019; Thomson et al., 2019; Thomas et al., 2019. Reductions in volume dispensed follow changes in rainfall and temperature. Dry months are treated as a baseline and therefore not included in analysis herein.

7.3.2 Influence of weather on volume dispensed at higher time resolution

Next, the influence of rainfall and temperature on volume dispensed in the two communities is investigated on finer timescales, specifically daily and 14-day moving averages, with an aim of investigating how well volume dispensed can be predicted by these weather variables on these timescales. 14 days is selected as a central estimate between daily and monthly. Daily variability is plotted in Figure 7.4 for the three rainfall estimates. Significant clustering around low rainfall values, i.e. dry days, is removed by only including values above 0.5 mm.

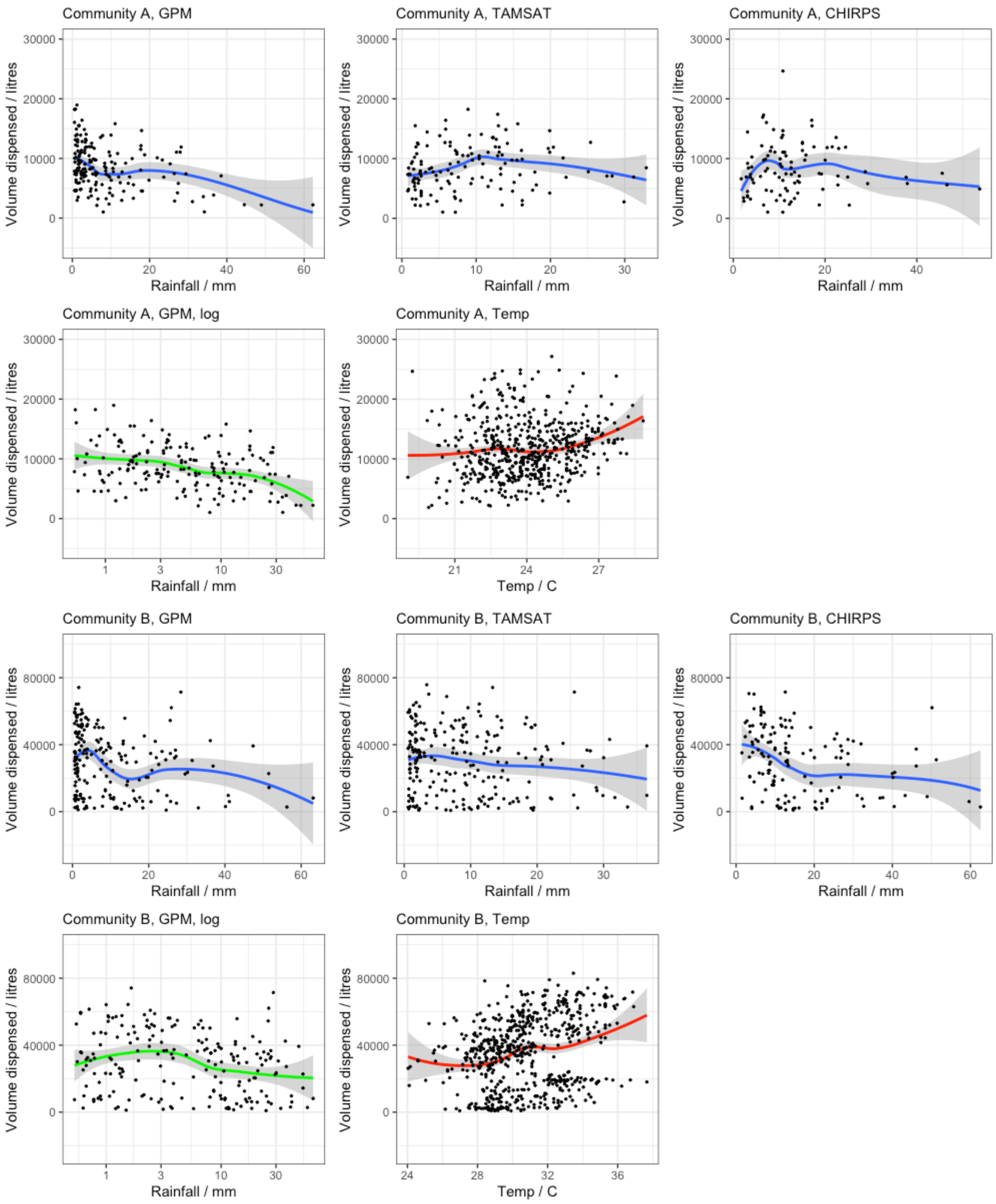


Figure 7.4 Trend of decreasing daily volume dispensed from DPs with increasing rainfall and decreasing temperature estimates for Community A and B; > 0.5 mm. The ‘gap’ for temperature in Community B originates from missed temperature measurements from the orbiting satellite at these coordinates. R^2 values are presented below, and in Table C.1, Appendix C.

Negative relationships between rainfall and volume dispensed are evident as expected, mirroring the seasonal differences seen above. Uncertainty increases with higher rainfall values however an overall trend is clear. 14-day moving averages (not included) exhibit the same trends with narrower uncertainties.

Plotting on a $\log_{10}$ rainfall scale (shown for GPM in Figure 7.4, with a threshold of >0 mm) shows these trends are stronger beyond a rainfall threshold of between 0.1–1.0 mm. Satellite rainfall measurements are liable to inaccuracies at low rainfall level. Therefore, rainfall values close to zero have insignificant influence (this is further support that dry months are irrelevant in this analysis). Overall, this suggests that the impact on water collection is more significant when rainfall is heavier.

The positive relationship between temperature and volume dispensed shows an increasing gradient at higher temperatures in both communities. This suggests that very hot days are more likely to see greater volumes dispensed. This is more pronounced in Community B, where it is hotter with extreme days up to daytime averages of 37 ^{o}C.

The relatively wide spread of volume dispensed data across Figure 7.4 is indicative of the multiple factors exerting influence on household water collection volumes beyond weather, as established in Section 6.5, especially towards the more numerous lower rainfall estimates. This univariate regression shows that rainfall and temperature estimates on a daily timescale therefore only account for a small proportion of change in daily volume collected. This is marginally improved when 14-day moving averages are used.

In order to better account for volumes dispensed on these timescales, considering rainfall and temperature are not fully independent, multivariate regression models including rainfall and temperature estimates (7.1) were used:

$$\mathrm{x}_{\mathrm{A,B}} = \beta_0 + \beta_1\,(\text{Rainfall estimate, mm}) + \beta_2\,(\text{Temperature estimate, }^{o}\text{C}) \qquad (7.1)$$

Where $\mathrm{x}_{\mathrm{A,B}}$ is the volume dispensed (litres) from all DPs in the community, β_0 is the intercept, and β_1 and β_2 are the coefficient estimates of the independent variables. An interaction function between β_1 and β_2 is not included because interactions between temperature and rainfall estimates were shown to be statistically insignificant (noncollinear) throughout the tests using ANOVA type-II, which confirmed that variance is significantly accounted for by both temperature and rainfall. Temperature estimates correlate weakly to rainfall estimates in these settings. The available temperature data is based on orbiting satellite measurements and has regular missing days, however enough data remain to be representative, regular, and significant. It was also confirmed that dry months significantly decrease model predictions, and therefore remain excluded. Other determinants uncovered in Chapter 5 such as household size are not included because the objective here is to determine the influence of rainfall and temperature on volume dispensed across the whole community (data is also not available in a comparable disaggregation). Results for these models for both communities are presented in Appendix C, Table C.1. Models are included that combine the three rainfall estimates for daily and 14-day moving averages, along with three rainfall thresholds (≥0.0, >0.0, and >1.0 mm).

These results generally confirm the trends seen in Figure 7.4 that lower volume dispensed relates to higher rainfall and lower temperatures in the two communities. There is a wide variation between the model fit of different combinations, with a maximum adjusted R^2 value of 0.29 in Community A (from using daily GPM estimates with rainfall > 1.0 mm), and 0.16 in Community B (14-day GPM estimates > 0.0 mm). Previous attempts to model volume dispensed using household characteristics surveys and distances from household have also given very low adjusted R^2 values (e.g. below 0.15; Mu et al., 1990), demonstrating the limitations of modelling this highly complex system. Direct correlation between variables here is also weak. Different thresholds of rainfall give variation. The range reflects the observational uncertainty between different rainfall estimates. R^2 values between daily and 14-day models are similar. Overall, inclusion of the GPM estimates with temperature gives the best estimate in Community A. There is little difference between estimates for Community B. In general, the significance of the fits is very high ($p << 0.001$) even where data points are excluded below thresholds. Using logarithmic values of rainfall estimates does not increase model fits. Further examination did not reveal any non-linearity.

Lag functions for one and two days were tested for these models. This was to account for the potential of users storing water in containers after heavy rainfall, as seen with handpump users in Kenya (Thomson et al., 2019), and Tanzania

(Farré, 2017). Lag functions in most cases decrease the model fits in this context, suggesting that any collection lag is outweighed by other factors. Collection from DPs occurs from morning to evening as shown in Section 6.4.2, and so any rainwater harvesting in the morning may impact afternoon collection. If morning collection from DPs is unaffected by rainfall later in the day, then this is likely to also be another factor in the low model fits, as rainfall estimates are daily totals.

Overall, it is apparent that rainfall and temperature estimates are not good at predicting volume dispensed on a daily or 14-day timescale. However, these two weather variables can still explain up to almost one third (29%) of the variation in volume dispensed. This shows that rainfall and temperature remain very important factors. The observational uncertainty from the different rainfall estimates suggests that inaccuracy of rainfall measurement also inhibits accuracy of prediction. Nevertheless, multiple factors, such as diverse household water collection behaviours and availability of water in the PWS tank appear to have overall greater influence. These extraneous factors are largely unquantifiable, and are otherwise visible in the wide spread of volumes dispensed across the dry months where rainfall remains at 0.0 mm. An additional factor that limits the predictive power of rainfall and temperature at short timescales is that alternative water sources are not always available in the rainfall months. Some users in Community A report not being able to collect water from riverbeds when they are flowing, which are a widely used source in the dry months. These limitations make more precise statistical predictions based on rainfall and temperature, such as employing artificial neural networks (Walker et al., 2015) or further calibration and sensitivity analysis of models, inappropriate here. The inappropriateness of modelling on daily time resolution also negates any potential autocorrelation in the time series data sets.

7.3.3 Influence of individual weather events

Next, the influence of individual rainfall and temperature events in the two communities are investigated. It is hypothesised that days of relatively heavy rainfall correspond to significantly reduced volumes dispensed, and high temperatures with increased volumes dispensed. This follows the apparent influence shown in Figure 7.4, and from the experiences reported by users. 79% of respondents in Community A report rainwater harvesting when asked where they collect water when it rains heavily (and 8% from wells). It is also based on observations of heavy rainfall making water collection from DPs more difficult along paths and unpaved roads. Degradation of transport infrastructure with rainfall impacts water collection in rural communities elsewhere in sub-Saharan Africa (Behnke et al., 2017).

Days of extreme rainfall and temperature characterise both communities. Rainfall seasons for the two communities are plotted as individual days in Figure 7.5. The most recent rainy seasons with complete data (Community A: November to May 2019; Community B: June to November 2018) are used for illustrative purposes, and an average of the three rainfall estimates is used because each indicates the days of heavy rainfall.

Daily mean rainfall in Community A during all rainfall months from the available data (2017-2019) is 3.17 mm (GPM = 3.53, TAMSAT = 2.92, CHIRPS = 3.05 mm). 26% of days in rainfall months have rainfall above the mean. Temperature is more normally distributed, with mean temperature of 24 ^{o}C; 27% of days have temperatures in the upper quartile (26-28 ^{o}C). Daily mean rainfall in Community B during rainfall months (2017-2019) is 4.60 mm (GPM = 4.49, TAMSAT = 4.42, CHIRPS = 4.92 mm), with a wider distribution than Community A. 22% of days in rainfall months have rainfall above the mean. Mean temperature is 30 ^{o}C, and 25% of days have temperatures in the upper quartile (31-35 ^{o}C).

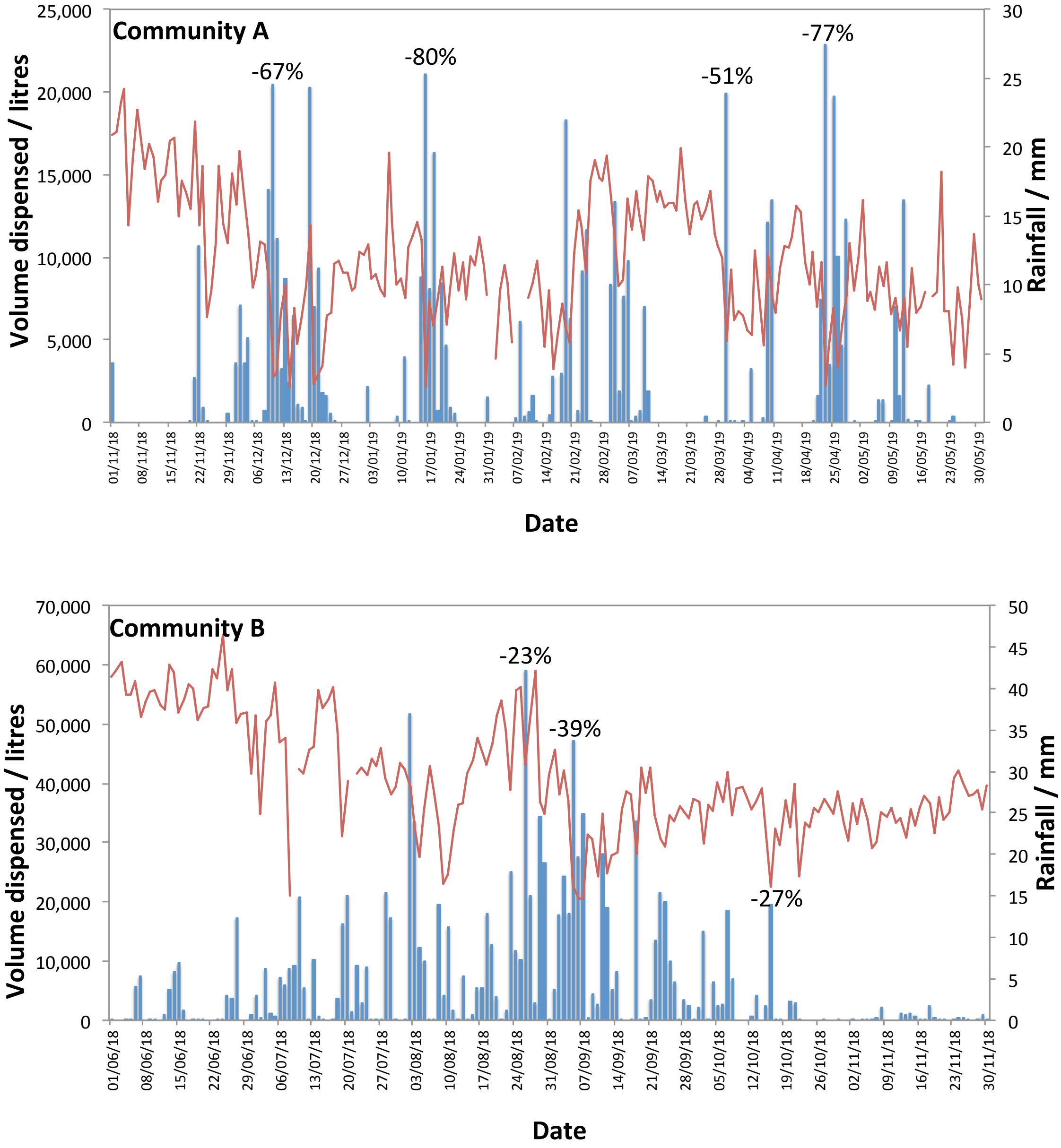


Figure 7.5 Daily rainfall (averaged estimates) over rainy season with volume dispensed (red line) in Community A and B, showing notable daily percentage drops in corresponding volume dispensed compared to previous day.

Figure 7.5 shows that on days (single or grouped) of heavy rainfall there are sharp reductions in volume dispensed. For example, in Community A the day of heavy rainfall on 16/01/2019, which has 25 mm of rainfall, sees an 80% reduction in volume dispensed compared to the previous day. The mean reduction from previous days across days with >8 mm of rainfall is 32% (median = 23%). In Community B, 07/08/2017, which has 7 mm of rainfall, saw an 81% reduction. Here, mean for >8mm = 24% reduction (median = 19%). No significant trend is apparent for either community between reduction from previous day and rainfall, which suggests that days of ‘heavy rainfall’ have a binary influence. This phenomenon is more apparent in Community A.

These observations are confirmed by running the multivariate regression models again with different rainfall thresholds (including all rainfall months, 2017-2019). Testing segments above specific thresholds was deemed more appropriate than ‘stepwise regression’ due to the poor fits of the ‘first step’ revealed above. Testing for generalised segments above thresholds also eliminates inherent uncertainty from differences between rainfall estimates. For Community A, a threshold of >8 mm of rainfall using averaged estimates gives a relatively high model fit ($R^2 = 0.45$, $p < 0.001$). The model improves with an increasing threshold until too few days remain for any meaningful significance. This estimation is significantly better than those that include lower rainfall amounts. 8 mm represents rainfall approximately 2.5 times heavier than the mean in the rainfall months. Total volume dispensed on these days is approximately 31% less than the total across the time period. Approximately 9% of days across this period have rainfall >8 mm. Using days of unusually heavy rain gives a reasonably good estimate of when volume dispensed reduces; heavy rain appears to overcome the other determinants of collection. Changing water demand behaviour with perceptions of rainfall, rather than accurate rainfall measurements, may account for remaining weakness of this model. For Community B, setting rainfall thresholds shows no significant improvement to the models. High thresholds, especially using GPM estimates, give high R^2 values (0.55-0.73), however significance is weak and therefore cannot be taken forward as representation of reality.

Thresholds of temperatures in Community A, without thresholds for rainfall, do not give better model fits. However, higher temperatures can refine the previous rainfall threshold of >8 mm: a combination with >24 ^{o}C gives a reasonably good fit ($R^2 = 0.59$, $p < 0.001$). This temperature threshold is approximately the mean temperature across rainfall months (24.3 ^{o}C). Therefore, this suggests that the majority (59%) of the variation to volume dispensed is accounted for by rainfall 2.5 times above the daily average, when temperatures are higher than average. In reality, because of the relationship between rainfall and temperature, this combined threshold model would be impractical to apply to any daily management (let alone with weather forecasting), and temperature and rainfall will have different impacts on different days. With Community B, temperature thresholds on their own have no impact, and nor combined with any rainfall threshold. For either community, a lag function in the regression models of one, two or three days with these thresholds had no significant impact of model fit.

Overall, it appears that heavier rainfall events have a significant impact on volume dispensed in Community A, but less so in Community B. This influence of heavy rain could be explained by it being more worthwhile or unequivocal for users to try to harvest rainwater from their roofs on these days. Low rainfall could not be worth the time and effort.

7.3.4 Results and explanations from users at the community level

Next, the experiences of users themselves are used to scrutinise the findings from the above analysis. Experiences of users in Community A support the observation of reduced collection from DPs during rainfall. Only about 21% of users did not report rainwater harvesting, which is typically done from household metal roofs. For most respondents this is for non-drinking uses, and drinking water is still from the DPs. Those who do not harvest rainwater give different reasons, for instance the roof is not suitable (e.g. grass, flat), or the water is too cold and therefore believed to cause illness. 8% of respondents answer they collect from wells when it rains. Two respondents explained that wells become contaminated by animal effluent run-off in rainfall months and they prefer rainwater harvesting. 73% of respondents also answer that hot weather means they use more water. This is for the range of domestic uses, and also for domestic livestock watering and small-scale irrigation. This supports the inclusion of temperature in this analysis. Managerial stakeholders also explained that users collect water from alternative sources more in the rainy season because it is free, and most users collect from rainwater harvesting. They explain there is rainwater harvesting on days of very heavy rainfall. This suggests that the main shortfall in collection of clean DP groundwater is from rainwater harvesting, at least in Community A, that there are therefore significant health impacts as described above.

The volume of rainwater that could be harvested from rooftops in Communities A and B is approximately calculated in order to give a rough comparison against the shortfall of volume dispensed from DPs over rainfall months, and therefore corroborate the influence of rainwater harvesting. The rainwater harvesting capacity for each household depends on rainfall intensity, roof area, storage capacity, and run-off coefficient (a factor of the roof construction material), calculated using the equation (Ishaku et al. 2012):

$$V_R = \frac{R \times H_{RA} \times R_C}{1000} \tag{7.2}$$

V_R: daily volume of rainwater per household (m^3 per day); R: daily rainfall (mm per day); H_{RA}: household roof area (m^2); R_c: runoff coefficient (dimensionless). Values and results are presented in Table 7.3.

Table 7.3. Rainwater harvesting approximated capacities

		Community A	**Community B**
R (mm per day)	Mean daily rainfall averaged across the three estimates for 2017-2019 rainfall months	3.17 mm	4.61 mm
H_{RA} (m^2)	Estimated from satellite imagery and fieldwork. Households in the centre of Community A are more likely to have metal roofs and larger/multiple buildings. Almost all buildings across Community B have metal roofs.	20–40 m^2	35–60 m^2
R_C (dimensionless)	0.85 is a commonly used value for hard roofs in humid tropics (Ishaku et al., 2012). Conservatively adjusted here because of inefficient roof use and guttering, and lower quality material.	~0.3	~0.5
V_R (litres per day)	(79% in Community A refers to respondents who report rainwater harvesting.)	~19–38 litres per day (x 79% = 15–30 litres)	~80–139 litres per day

The approximated V_R values in Table 7.3 would compensate the deficit in volume dispensed from DPs (shown above in Table 7.2) by a factor of 2–4. Therefore, easily enough water could come from the rainwater harvesting described by users to explain the seasonal reductions in volume dispensed from DPs. In reality, this theoretical capacity is likely smaller. Fieldwork observation showed that often less than half of the roof space was used, containers were temporary (e.g. pots, plastic buckets), and rainfall is highly variable with collection occurring more with only heavy rainfall events. Rainfall variability and lack of local skills and institutional support have been listed as limitations to the implementation and sustainability of rainwater harvesting infrastructures in Tanzania (Pachpute et al., 2009).

Overall, this local 'ground-truthing' helps confirm the hypothesis that days of heavy rainfall influence volume dispensed from DPs, and that this is a direct demonstration of the influence of availability of free rainwater.

There are potentially other ways in which seasonal weather influences the volumes dispensed from DPs. Time spent collecting water, access to different sources, and expendable wealth are known to be important seasonal determinants (Arouna and Dabbert, 2010). However, in this study focusing on Communities A and B these factors will not apply is the same ways due to the central importance of the PWSs (as established in Section 5.4.1). The availability of free water, mostly from rainwater harvesting, is assumed to be the most significant determinant, as evidenced above. This phenomenon can also be viewed inversely to an increase in DP usage when alternative options are no longer available, such as is reported in drought conditions in Ethiopia (MacAllister et al., 2020). However, PWS water is less susceptible to seasonal availability and is more appropriate to use as a baseline.

7.4 Implications of findings and limitations

The objective in this chapter has not been to build a perfectly representative predictive model for volume dispensed, which is futile in these complex socio-economic contexts, but to help explain the influence of rainfall and temperature in Community A and B. Overall, a similar relationship as seen in previous studies is confirmed with water collection, but here from PWS DPs; volume collected drops significantly over rainfall months, and on days of heavy rainfall. This provides a basis for weather dependent pricing in Chapter 8. It is also shown that daily time resolution weather is not a good predictor of collection, which is also suggested elsewhere (Turman-Bryant et al., 2019). Numerical modelling in this context is unlikely to give very accurate and precise predictions. The weaknesses of correlation attests to the complexity of rural water collection patterns (as shown in Chapter 6), which is the case in other models of water demand anywhere that are based on variable socio-economic factors (e.g. Griffin and Chang, 1991).

This research has added value by using greater accuracy direct flow measurement from DPs on PWS themselves, over longer time periods, with more comprehensive weather data than previous studies. It has also been further shown here that smart meters can be a useful instrument for investigating long-term questions at high-resolution as also shown in Chapter 6. As such, the significant advantage of using this newly available smart meter data for descriptive and analytical investigations has been shown. It is now the case that in certain communities in rural sub-Saharan Africa there is a new monitoring infrastructure (and there will be more in time) that can provide daily or sub-daily data on volume collected from individual DPs, and this has great potential for detailed analysis beyond what has been begun here. Being able to use this data for analysis is a major advantage of having it, beyond immediate management uses.

Importantly, this research provides further evidence that even well functioning PWS systems in rural communities do not guarantee year-round health outcomes. In addition, these findings show that volumes collected from PWS DPs increases as the dry season starts. This suggests that a good time to install new PWS projects would be just before dry season onset, as this would capture the incoming increase in demand, resulting in immediate gains to revenue.

The analysis has some limitations, however these do not significantly impact the main findings:

- The available volume dispensed, rainfall and temperature data is subject to high variability, particularly the volume dispensed, seen in the imperfect fits of the models. This reflects the complexity of variable determinants of water collection and the influence of weather.
- No data is available on the borehole use or tank levels, which could enable a verification of volumes dispensed. However, volume dispensed from DPs gives an equally good measure of users' collection, and borehole data is rarely available in this context let alone for three continuous years on a daily time resolution.
- The PWSs showed short periods of non-functionality, however these were insignificant across the study timeframe and cleaned from the data.
- Temperature values have days missing due to the AIRS satellite operation (Community A = 228 days; Community B = 329), which partially reduces the accurate attribution of volume dispensed to temperature.
- Fieldwork in Community B was not possible, and would have given richer understanding of how water collection behaviours differ between communities.
- Binary distinction of dry and rainfall months may have introduced some minor inaccuracies of start and end dates of rainfall periods depending on the year, however was necessary for analysis.

An interesting strand of further research would be determining the degree that the specific aquifers used by such communities are recharged and depleted with rainy and dry seasons, and investigating the seasonal relationship between this groundwater resource and PWS use. While flow rates at DPs will not change because these are determined by the unchanging elevated tank and piped network, data on PWS pump use (specifically length of pumping use and power consumption required) is likely to vary seasonally. Pumps are likely to be used for longer towards the end of dry seasons when the saturated zones of groundwater are more likely to drop in depth because of the lack of replenishment from rainfall (this is a highly variable phenomenon and depends on multiple interacting aquifer characteristics). In some cases, an increase in pumping combined with decreased volume collected from DPs might provide a remote indication that groundwater supply has become insufficient. Integrating pumping data with smart meter data collection would aid this enquiry. Regardless, correct borehole development (that is well sited, deep enough, correct diameter and media choice etc.) should account for seasonality in groundwater resources anyway.

Additionally, the advantage of newly available smart meter data can allow further detailed investigation into seasonality and rainfall in the future. This could include determining a relationship between heavy rain and volume collected on a sub-daily timescale; for instance, users may be seen to collect in the mornings still, despite heavy rain over afternoons (which can show regularity e.g. over parts of East Africa), and with a lag of collection until the following afternoon. This analysis would be made more effective with commensurate sub-daily rainfall data; while satellite-based estimates and therefore the analysis here are limited in resolution and accuracy, ground-based weather stations could be employed for this purpose. This was beyond the scope of the research here. Alternatively, individual DPs across a community may show different seasonal trends of use than others. This could be potentially influenced by seasonal alternative sources close to certain DPs such as rivers or ponds, or social changes like seasonal migration or farming.

7.5 Conclusions and novelty of work

The conclusions from the research in this chapter are as follows:

- Smart meters can be a useful long-term ‘research instrument’ for understanding the relationship between water collection and environmental factors, in particular weather.
- The use of more than one set of weather data contributed to understanding.
- Water collection from PWS DPs shows a similar relationship with weather and seasons as from other water points.
- Collection of clean DP groundwater significantly drops by approximately 20% over rainy months in both communities studied.

- Weather is not a good predictor of volume dispensed on a daily or 14-day timescale because of the multiple other determinants of water collection, however can still explain up to almost one third (29%) of the variation in volume dispensed (in Community A), showing that rainfall and temperature remain very important factors.
- Heavy rainfall has a significant impact on volume dispensed in Community A (but less so in Community B), with days of up to 80% reduction (25 mm) from the day before. The majority (59%) of the variation to volume dispensed in Community A can be accounted for by rainfall 2.5 times above the daily average and higher than average temperatures.
- Users corroborate these findings by explaining they (79%) undertake rainwater harvesting from rooftops. Households have ample capacity to meet the shortfall from DPs by rainwater harvesting. This likely has negative health impacts.

These findings, specifically the timing and magnitude of reductions in volume collected, provide a firm basis for the price calculations for weather dependent pricing undertaken in Chapter 8.

The novel contribution of the work in this chapter has been:

- Use of smart meter data for combination with weather data rather than other sensor or manual data, and a focus on rural PWSs rather than boreholes or handpumps.
- Inclusion of three independent meteorological data sets rather than just one.
- Longer time-series data sets of approximately three years rather than one or two.
- Investigation of seasonality of rural water collection in Tanzania and The Gambia.

Chapter 8. WEATHER DEPENDENT PRICING USING SMART METERS

8.1 Introduction and background

In Chapter 7, it was shown that volume of clean groundwater collected from smart meter DPs drops significantly during rainfall months, and on days of heavy rainfall. As shown, seasonal availability of alternative water sources is recognised as a major determinant for collection from clean water sources, and this has major health implications. However, efforts to mitigate this negative effect have been limited or non-existent.

The objective of this chapter is to investigate how smart meters can mitigate these adverse effects, specifically how collection of clean DP groundwater can be incentivised over contaminated free rainwater. A novel mechanism called ‘weather dependent pricing’ (WDP) is conceptualised, developed, and validated here. A decision support tool is presented, and sensitivity and uncertainty analysis is conducted. It is shown that WDP can be a new off-the-shelf health intervention with good value for money that can help realise gains of smart meter projects, strengthen rural water supply systems, contribute towards climate change resilience, and be supported with 100% efficient finance transfers.

This addresses the need outlined in Section 2.5.7 of developing new appropriate management strategies based on the novel pre-payment capabilities of smart meters. Smart meters have not yet been used as tools for seasonal management.

8.1.1 Outline of WDP

In this chapter, it is shown how WDP could help sustain the use of clean water from smart meter DPs throughout rainfall months and heavy rain periods, and therefore reduce the health risks that come from potentially contaminated rainwater, and improve revenue collection.

WDP is based on remotely reducing the price of water from the DPs using the (pre-payment) smart meters investigated in this research in conjunction with the impact of weather defined in Chapter 7. Water tariffs are powerful management tools (Boland and Whittington, 2000). Here they are tailored to a new objective beyond traditional cost-recovery, economic efficiency, equity, or resource conservation. Currently, prices in rural sub-Saharan Africa tend to be set at a uniform rate throughout the year.

The overall objective of WDP is to incentivise users to avoid contaminated water sources and maintain use of clean water DPs. The health benefits of transferring away from contaminated water were introduced in Section 7.1.2 and are well covered elsewhere (Hutton, 2006). They include averted cases of diarrhoeal diseases (the second leading cause of death globally for children under five), malnutrition-related diseases, and health-related quality of life impacts, with knock-on benefits such as higher school attendance rates and student learning capacity. While clean water can lead to health and economic benefits, WDP must be considered within the context where e.g. diarrheal disease also often result from other factors such as poor food quality, poor sanitation and hygiene, and interaction with livestock. This is an important consideration, showing that improved seasonal access to clean water is not guaranteed to have measurable impacts on health proposed in this Chapter (see discussion of relative risk in Section 8.3.2). With this in mind, WDP is proposed to go some way to reduce the seasonal peak in health risks caused by alternative water sources, rather than eliminate the total base-load of diarrhoeal diseases in communities. Importantly for service providers, WDP also has the potential to improve annual revenue for service providers.

WDP is informed by the real-life findings from Chapter 7 alongside findings from other studies and detailed econometric and behavioural science considerations. Users choose what water source to collect from based in part on the influences of price, cost, and value (Hope et al., 2020). It is important to remember that simple assumptions and intuition around pricing can lead to incorrect outcomes

(Nauges and Whittington, 2017). With this in mind, the following are considered in the development of WDP:

- Water pricing structures and impacts elsewhere, including with pre-payment meters
- The magnitude of required pricing changes for the desired demand change, in accordance with the price elasticity of demand
- Relative health risks with and without WDP
- To what extend reduced prices in this context are likely to incentivise users to choose to change their behaviour
- Hypothetical value for money, cost-benefits, sensitivity to different variables, and uncertainty of outcomes
- How financial transfers can now efficiently subsidise lost revenue from reduced prices, and what WDP would mean for climate change resilience.

WDP is possible due to the novel remote pricing capabilities of the smart meters that: can be done in real-time to reflect short changes in weather (unlike any seasonal pricing without smart meters); is accountable to service providers and users; and avoids the common complication to water pricing management of users failing to pay. Here, smart meters present an opportunity to address the need of designing new services based on local demand characteristics in a targeted manner. It has already been argued that PWSs could allow for more advanced tariff setting structures than handpump schemes (Aguaconsult and WaterAid, 2018).

8.1.2 Use of structured pricing incentives elsewhere and novelty

Water is recognised as an economic good, as enshrined in the Dublin Principles (ICWE, 1992), which also emphasise that economic valuation needs to take into account affordability and equity criteria. Tariff setting for water is often political and controversial. Tariff design aims to address the criteria: cost recovery for sustainable service provision; equity between different groups; affordability; economic efficiency, i.e. minimising other financial sources (e.g. taxes) when tariffs account for less than 100% cost recovery; and simplicity. These criteria are subject to trade-offs, hence tariff design is very contextual (Nauges and

Whittington, 2017; Banerjee and Morella, 2011; Kayaga and Smout, 2014). Tariff setting can also play a role of sending signals to users about water use and provide financial rewards for desired behaviour. Water pricing mechanisms for managing water demand around the world have typically been employed to promote efficient use of limited water resources, for instance in water scarce regions (e.g. Rogers et al., 2002, Inman and Jeffrey, 2006; Garrone et al., 2019; Rinaudo et al., 2012; Nauges and Whittington, 2010).

Two-part and increasing block tariff (IBT) structures are commonly employed by utilities. For instance, IBTs based on increasing prices for increasing volumes supposedly improve equity by providing ‘lifelines’ to the poor at below cost. They are common globally, and 85% of utilities surveyed in sub-Saharan Africa used one (Banerjee et al., 2008). Volumetric band tariffs have been proposed for different handpump use in Kenya to increase fairness for users (Thomson and Koehler, 2016). Some researchers have questioned assumptions about the effectiveness of block tariffs in urban utilities (Nauges and Whittington, 2017; Boland and Whittington, 2000). IBTs are now seen to introduce inefficiency, inequity, complexity, lack of transparency, instability, and difficulties with forecasting, and have adverse effects on poorer households, in particular larger households. Blocks are often set at the wrong levels, often from political interference, so richer households also benefit from low prices, which reduces revenue thereby disfavouring poorer households. Another common misconception is that household wealth is strongly correlated with volume of water consumption. This means that WDP is unlikely to impact different wealth households differently.

Some utilities do use tariff structures in a seasonal way with greater prices over a period of peak usage to incentivise water conservation, for instance in summertime in Spain (Molinos-Senante, 2014), France (Rinaudo et al., 2012), and the USA (Polebitski and Palmer, 2010). One water company in the UK increases prices by 6% between June and September from a baseline price (Kayaga and Smout, 2014). Some researchers have also proposed tariff changes in relation to the marginal cost of water scarcity, which could be seasonal (Monteiro and Roseta-Palma, 2011). Another proposal involves adjusting billed prices *ex-post* on a monthly basis for municipal water supply in

Belgrade, Serbia, relative to precipitation and temperature in the catchment, where a correction factor based on the monthly variance from a 30-year average would be used to adjust the price (Pesic et al., 2013). This idea is based on an assumption that users will not know their monthly bill *ex-ante* and so with knowledge of this pricing scheme they will act to reduce water consumption on specific days they perceive as warm or dry, i.e. water scarce. These proposals all aim to improve water resource use efficiency rather than incentive clean water use.

Water pricing research has focused on utilities in the developed world (Fuente, 2019), partly because of reduced complications from multiple alternative sources (see Section 5.4.1) meaning that pricing measures have been easier to deploy uniformly. Smart meters in rural sub-Saharan Africa now allow for more sophisticated tariffs. Inversely to pricing structures that promote water conservation, WDP aims to incentivise greater use of clean water. As far as evident, pricing is not recorded anywhere as being used as a direct tool to incentivise the use of clean water sources in this manner, nor as a dynamic response to weather. Another way to see WDP is as the inverse of the deleterious situation where efforts to improve cost-recovery through raised tariffs causes users to turn instead to alternative poor-quality free sources, resulting in attendant negative health impacts (such as reported in South Africa; Cardone and Fonseca, 2003). Overall, the idea of price discounts over rainfall periods appears to be novel.

8.1.3 Pricing management with pre-payment meters elsewhere

Using smart meters as a tool for managing demand is not new, however it is not well developed. Smart meters in urban households in the developed world have improved residential water demand characterisation, and promoted behavioural changes, in particular (and apparently exclusively) water saving attitudes (Cominola et al., 2015). Researchers have pointed out that smart meter enabled sub-daily dynamic pricing could help level out peak demand and reduce operational costs (and the burden on water resources) in large-scale municipal supply (Rougé et al., 2018).

‘Off-grid’ smart meters enable decentralised variable pricing (i.e. ‘third-degree price discrimination’). In India, ‘water ATMs’, which are kiosk-based smart meters operating on a similar principle as the smart meters investigated here, charge higher prices in cities and significantly lower prices in small villages (Schmidt, 2020). This shows that context can be a suitable determinant for variable pricing. This mirrors off-grid metered electricity tariffs around the world that can be variable depending on circumstance (e.g. Sidhu et al., 2020).

Overall, WDP shows another added value of smart meters in rural sub-Saharan Africa, and that modern, ‘smart’ water demand management can also be applied in this context.

8.2 Details of weather dependant pricing

Here, details of WDP are based on the findings in Chapter 7 for Community A and B. WDP is conceived as applicable to any rural communities in sub-Saharan Africa with smart meters and a PWS (i.e. into the future).

8.2.1 Willingness to pay in Communities A and B

Firstly, understanding users’ current willingness to pay will inform the potential efficacy of WDP. In general, current willingness to pay in Community A was shown to be high in Chapter 5 (subject to varying motives; Hope and Ballon, 2019). 81% of users asked answered in the protocols (Section 5.4.2) that the price is ‘roughly correct’ for their household. Most users explain that they are satisfied with this price because the community has agreed it on. 17% said the price was ‘a little too high’ or ‘much too high’. However, users consider payment and budgeting in different ways, and only 51% have a precise understanding of price per volume: e.g. *“I just top up one thousand shillings and wait for it to run out, I have no idea of the number of buckets”* (C17); *“I just collect, I don’t count”* (E27).

Fundamentally, however, users in Community A and B are currently demonstrating by the drop in demand that they have *de facto* lower willingness to pay for clean DP water when rainwater is available. This is in keeping with existing empirical evidence that monthly willingness to pay (in Zimbabwe) rises over the course of dry seasons (Waughray et al., 1997).

Affordability tends to be dependent on variable availability and quality of different sources throughout the year as much as income-expenditure ratios (Hoque and Hope, 2019). WDP therefore addresses the ‘hidden water affordability problem’ (Komarulzaman, 2019), which is shown by the use of free alternative water sources, by reducing obstacles to payment of clean water from DPs. Users in this agricultural setting tend to be poorer during rainfall months (verified by members of the COWSO in Community A), and the opportunity cost of time required for fetching water is larger (Arouna and Dabbert, 2010). Reduced pricing in rainfall months could therefore also help alleviate these affordability barriers. Overall, there is evidence that users would react to the WDP pricing incentives.

8.2.2 Selection of timing of pricing blocks

Selection of *when* in the year WDP should be applied is guided by the influence of: 1) rainfall months and 2) days of heavy rainfall that were found in Section 7.3. Three WDP pricing blocks are proposed:

Block 1 (p_1): baseline applied over dry months, equivalent to ‘normal’ pricing.

Block 2 (p_2)***:*** applied on each rainfall month, i.e. over the length of the rainfall season. Start and end dates therefore have flexibility subject to annual variation. Designated rainfall months from Table 7.1 constitute approximately half of the year in Community A (58%, 212 days) and Community B (50%, 183 days).

Block 3 (p_3)***:*** applied only on days where rainfall is very heavy. In the case of Community A, this would be days where rainfall exceeds ~8 mm, or greater than 2.5 times average, as shown in Section 7.3.3 (based on averaged GPM, TAMSAT and CHIRPS rainfall estimates). This would account for approximately 32 days per year in Community A, all of which would be within Block 2. Section 7.3.3 showed that influence of such heavy rainfall days is significant in Community A, not B, therefore Block 3 is not universally appropriate. Practically, this could either be a) based on forecasts if they are accurate in the community in question, or b) applied on the morning after observation by community stakeholders. While a lag effect is not measured for Community A, Block 3 could also extend +1 or +2 days depending on local water storage behaviours. Total days in Block 3 would be less predictable than Block 2.

Dynamic pricing *each* day, tied to precise weather forecasts, is inappropriate, as was shown by the weaknesses of the daily models in Section 7.3.3. It is also hypothesised that users would be unwilling or unable to plan routines around sub-daily dynamic pricing changes. Therefore the proposed blocks are a suitable balance between precision and practicality, and both are flexible depending on weather patterns and setting.

8.2.3 Selection of magnitude of pricing adjustments for Block 2

Next, selection of the *magnitude* of price changes for Block 2 and 3 is guided by considering water demand and user behaviour. The desired increase in demand (ΔQ)[6] during rainfall months (Block 2) in Community A = 26.0%, Community B = 28.5%, was established in Section 7.3.1 (Figure 7.3). Empirical data or representative demand curves demonstrating the exact changes in price (ΔP) needed for these desired ΔQ are not available, however ΔP can be estimated precisely using economic theory and findings from similar settings.

Price is not the sole determinant for choice of water source by users in this context; for instance time taken for collection can be a significant determinant (Mu et al., 1990). However, smart meters have significantly reduced time taken for collection (as shown in Section 5.5.1), and therefore price can more confidently be taken as the major factor for calculating magnitudes of price changes here. This is another reason why WDP is now possible with smart

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[6] In this chapter, Q refers to ‘demand’ (and not flow rate as in Chapter 4) because of economic convention

meters rather than conventional payment schemes. The importance of price is also seen elsewhere (e.g. Gross and Elshiewy, 2019; Wagner et al., 2019).

Baseline water prices (p_1) in this context are theoretically set according to national standards. This itself is not a simple task (Hope et al., 2020). A commonly cited rule of thumb is that water tariffs should account for 3-5% of total household expenditure, but this has no empirical basis. Pricing is a particularly challenging decision dependent on conflicting financial, environmental, economic efficiency, and social objectives (OECD, 2010). Fixed baseline price in Community A = 25 TSH[7] per 20 litre bucket (1.25 TSH per litre); in Community B = 0.5 GMD per 20 litre bucket (0.025 GMD per litre).

Price elasticity of demand (E_P) refers to the percentage change in quantity demanded that results from a percentage change in price:

$$E_P = \frac{\%\Delta Q}{\%\Delta P} \tag{8.1}$$

For instance, a percentage price decrease of 30% would result in a percentage demand increase of 15% if $E_P = -0.5$, of 21% if $E_P = -0.7$, or of 30% if $E_P = -1$. E_P for water demand is expected to be negative, with decreasing price resulting in increasing demand, and vice versa. Knowledge of price elasticity values therefore allows a calculation of a suitable price reduction (ΔP) that would theoretically result in a desired change in quantity demand of clean DP water (ΔQ). A simple price reduction by the same percentage increase as required of quantity demanded will not work (i.e. $\Delta P \neq \Delta Q$), because water does not exhibit a unitary elastic demand. In general, water tends to be a price inelastic good ($-1 < E_P < 0$) due to its lack of substitutes (which is therefore often used as a method to increase revenues). E_P is reported to be closer to zero for basic needs such as drinking, cooking and hygiene (Savenije and Van Der Zaag, 2002).

E_P values cannot be calculated for Communities A and B because only one point on the demand curve is known (i.e. Community A: 1.25 TSH per litre for

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[7] TSH = Tanzanian Shilling; GMD = Gambian Dalasi. Prices here are for the purposes of demonstrating WDP and may differ circumstantially.

an average total of 10,448 litres per day in the rainy season; Community B: 0.025 dalasi per litre for an average total of 30,725 litres per day in rainy season, as determined in Section 7.3.1). However, it is possible to glean E_P values reported elsewhere for settings in the developing world. These are shown in Table 8.1.

Table 8.1. E_P values reported in relevant studies in developing countries, focusing on household use of communal water points, representing either water demand, or access to a water source.

Study context	Reported price elasticity	Study
Summary of 1987-90 global investigation, focused mostly on water kiosk collection. E_P represents choice of using improved sources, with respect to monthly tariff.	-0.7 (rural Zimbabwe) -0.4 (rural Kenya)	World Bank Water Demand Research Team, 1993
Urban Indonesia, based on household monthly water use.	-0.48 (vended water) -0.60 (public hydrants)	Crane, 1994
Rural Nigeria, including households who purchase water and households that combined purchasing and free collection.	-0.07	Acharya and Barbier, 2002
Low revenue population in rural Tunisia.	-0.24	Zekri and Dinar, 2003
Based on 17 cities in Central America; household monthly water use for households without private connections.	-0.1	Strand and Walker, 2005
Three cities in El Salvador; water use per capita per month.	-0.4 to -0.7	Nauges and Strand, 2007
Rural Benin, small population; specifically focusing only on users who purchase water.	-0.15	Arouna and Dabbert, 2010
Rural Kenya, estimated from individual sources rather than aggregated source type.	-0.56	Wagner et al., 2019
Rural Benin, communities with low service coverage.	-0.26 (public tap)	Gross and Elshiewy, 2019

The average of -0.40 from Table 8.1 suggests that a slightly low price elasticity of water is generally the case in the developing world, and perhaps in rural settings, approximately aligning with those from the developed world where values of -0.3 to -0.6 are typically reported for urban private connections (Nauges and Whittington, 2010).

However, the limitations of relying on other divergent studies notwithstanding, there is some strong evidence to suggest that water demand in settings such as

Community A and B is less price inelastic (i.e. closer to -1) than conventional wisdom would suggest. These are as follows:

1) Demand for a good should become more price-elastic with increasing numbers of substitutes. Different water sources act as close economic substitutes, and therefore water is likely to be less price inelastic (i.e. closer to -1) in settings such as Community A and B where users turn to alternative sources because they cost no money. Low elasticities shown in Table 8.1 may be biased downwards (towards 0) from not incorporating alternative sources, which is in line with a general neglect of multiple water source use in previous research. This has been demonstrated for alternative purchased water sources in Jordan, which show greater elasticities at -1.33 (Coulibaly et al., 2014). Similarly, it has been shown in Vietnam (Cheeseman et al., 2008) and Sri Lanka (Nauges and Van Den Berg, 2009) that demand is more elastic for households that use more than one source of water, compared to those that only use municipal piped water. It has been specifically speculated that choice of water source made by households will be quite sensitive to changes in prices of water from different sources (Nauges and Whittington, 2010), and this particularly applies to rural contexts like Community A and B. Further, DP water is cleaner than alternatives and therefore a more desirable good.
2) Reported price elasticity values vary between different income groups, quantified in a three-block IBT in urban South Africa as high-income = -0.23; middle-income = -0.32; and low-income = -0.99 (Jansen and Schulz, 2006). Therefore, the low-income group, which matches Community A and B with low daily consumption, shows less inelasticity (-0.99).
3) Lower water scarcity is likely to correspond to higher price elasticities. The very low price elasticity reported in rural Benin (-0.15, Arouna and Dabbert, 2010) is partly explained by significant water scarcity because households are willing to pay more for improvements in water supply because of water scarcity in the area. This suggests that in areas without this pressure from water scarcity, for instance where there is a functioning PWS like in Communities A and B, water price would be more elastic. This is also seen on a global scale (Garrone et al., 2019).
4) General price inelasticity of water is largely a result of the necessity of water whatever the cost. However, a decreasing price as proposed with WDP may

act to lift an 'affordability cap' that previously limited volume collected, and may therefore have greater impact than inversely increasing price, and therefore have a correspondingly greater elasticity.

Considering these reasons, it is therefore predicted that elasticity in Communities A and B is greater than the average from Table 8.1. E_P values within the range -0.5 to -1 are considered more likely.

The demand curve is likely to be convex indicating that the marginal value of water does not decline at a uniform rate with increases of water use (Whittington and Swarna, 1994). This is especially the case when demand is disaggregated into different uses as discussed in Chapters 5 and 6, where reductions of price are more likely to result in water collection for uses beyond drinking and cooking. At higher levels of prices, users are likely to be more responsive to price reductions, with greater E_P values. This is therefore dependent on the baseline price for each community in question. Such changes along the demand curve are very unpredictable. Here, therefore, WDP is developed with the assumption that prices in communities are similarly low and that starting baseline (p_1) price values are not a significant factor, and E_P values are assumed to be constant along the demand curve.

Additionally, no clear picture of how price elasticity might change between dry and rainy seasons is available from the above literature. Elasticity can vary with changes of water demand (Harou et al., 2009). In Texas, USA, price elasticity has been show to vary seasonally (Griffin and Chang, 1991); summer months generally have higher price elasticities by approximately 30%. Here, seasonal changes in elasticity can be disregarded because Block 2 only applies in rainy seasons. Furthermore, rigid adherence to price elasticities based on volume is not totally appropriate here, where the objective is to both: 1) change the choice between alternative sources, and 2) increase volumetric demand from DPs. Volumetric demand is also determined by distance, household use, and availability of source as shown in Section 6.4.3.

Because an exact E_P cannot be known, $\%\Delta P$ values are presented in Table 8.2 for a range of potential E_P values, based on the desired $\%\Delta Q$ in each Community. Actual prices corresponding to each E_P value are presented based on current baseline (p_1) prices in Community A and B. %ΔP values for hypothetical %ΔQ values based on the range of E_P values are also illustrated.

Table 8.2. Proposed price changes for Block 2, based on range of price elasticities. Likely E_P range = -0.5 to -1.

	Community A desired %ΔQ = **26.0%** (average 10,448 litres per day in rainfall months to 13,167 in dry months) p_1 = 1.25 TSH		Community B desired %ΔQ = **28.5%** (average 30,725 litres per day in rainfall months to 39,488 in dry months) p_1 = 0.025 GMD		Hypothetical %ΔQ		
					%ΔQ = 20	%ΔQ = 40	%ΔQ = 60
E_p	%ΔP	p_2 (TSH)	%ΔP	p_2 (GMD)	%ΔP	%ΔP	%ΔP
-0.1	*-260%*	*-2.00*	*-285%*	*-0.046*	*-200%*	*-400%*	*-600%*
-0.2	*-130%*	*-0.38*	*-142%*	*-0.011*	*-100%*	*-200%*	*-300%*
-0.3	-86.7%	0.17	-95%	0.001	-66.7%	*-133%*	*-200%*
-0.4	-65.0%	0.44	-71.3%	0.007	-50%	-100%	*-150%*
-0.5	-52.0%	0.60	-57%	0.011	-40%	-80%	*-120%*
-0.6	-43.3%	0.71	-47.5%	0.013	-33.3%	-66.7%	-100%
-0.7	-37.1%	0.79	-40.7%	0.015	-28.6%	-57.1%	-85.7%
-0.8	-32.5%	0.84	-35.6%	0.016	-25%	-50%	-75%
-0.9	-28.9%	0.89	-31.7%	0.017	-22.2%	-44.4%	-66.7%
-1.0	-26.0%	0.93	-28.1%	0.018	-20%	-40%	-60%

It is clear that very low elasticity values (closer to 0) would require negative prices, which is not directly possible with pre-payment (subsidies are discussed below). As argued above, such low elasticities are not likely. The dispersion of required %ΔP decreases as E_P tends toward -1, i.e. the difference in p_2 between -0.9 and -0.8 is much less than between -0.4 and -0.3. This is seen in Figure 8.1. This would make decisions of precise E_P easier for implementers in different settings.

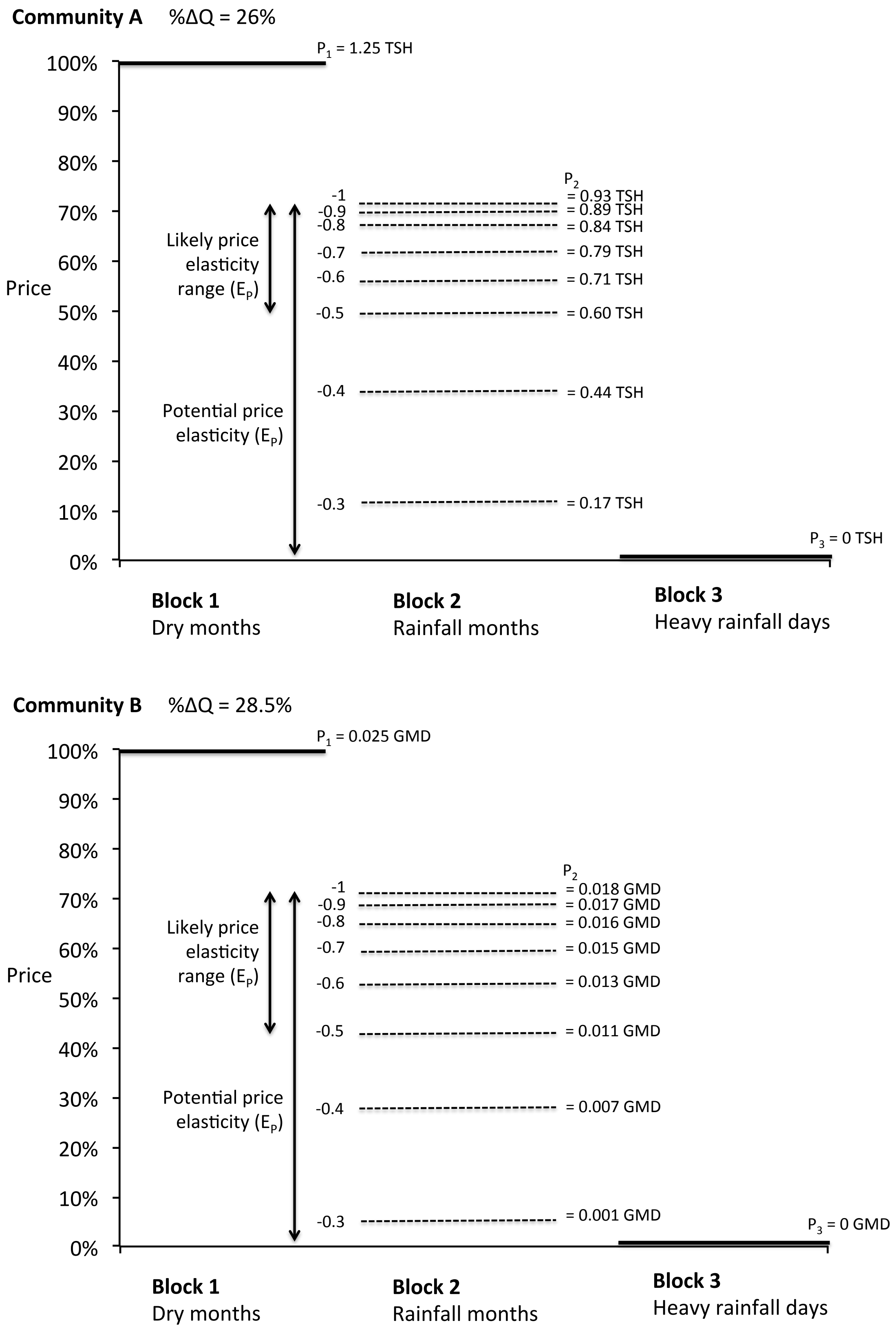

Figure 8.1 Price adjustments for proposed Block 2 and 3 for weather dependent pricing for Communities A and B

8.2.4 Selection of magnitude of pricing adjustments for Block 3

The magnitude of ΔQ required for Block 3 in Community A is shown to be significantly greater than for rainfall months (Block 2). Days of heavy rainfall can be generalised as having a high desired %ΔQ of 45% for Community A. Even assuming an E_P value between -0.5 and -1, this would constitute a major price drop from 1.25 TSH to between 0.625 – 0.125 TSH (E_P = -0.5 – -0.9). Two pricing options are therefore considered for Block 3: a) follow the %ΔP predicted by uncertain E_P values, or b) free water.

The free water dilemma is well rehearsed (Savenije and Van Der Zaag, 2002), and providing free water often results in unsustainable and inequitable service provision where full costs including economic and environmental externalities, opportunity costs, capital charges, and O&M are not met. Free water can also lead to unrestrained use and shortfalls of supply. However, free water is appropriate for Block 3, shown in Figure 8.1, for the following reasons:

1) The number of days Block 3 would apply is low (only 9% of days in Community A, 32 days), minimising lost revenue (demonstrated below).
2) While lower prices increase affordability, 'free' conveys a new social norm (i.e. 'this is something that we *should* do'), and communicates an 'affective influence' (i.e. excitement at having 'won' free water). Research has shown that the difference in price for certain health goods in developing countries between zero and just above zero has dramatic influences on uptake (WDR, 2015). It is hypothesised that associating this special free pricing with heavy rainfall will discourage collection of contaminated water. This effect may be more significant among poorer households, who are more at risk. One user explained that: "*I would use* [smart meters] *more if it was free, instead I go to the riverbed*" (C30). The risk that free water conveys a negative message on water quality should be negated by the existing community perception of PWS DP water cleanliness.

It is more critical to incentivise use of clean DP water during Block 3, when heavy rain makes effluent run off and contamination of alternative water sources more likely. Block 3 has similarities with schemes that provide free 'lifeline' water, which address social dimensions alongside economic ones. In the case that free water still does little to keep clean water collection high, ‘conditional cash transfers’, which have shown success in affecting behavioural change with vaccination and smoking in developing countries, could be considered. ‘Conditional credit transfers’ direct to individual users’ tags if they are used during rainfall events could be a straightforward upgrade. Usage caps can be set for each tag to limit users abusing free water.

8.3 Application and validation of weather dependent pricing

The details of WDP have been outlined and justified. Next, the cost of WDP is quantified, and value for money is analysed for Community A and B and hypothetical communities. A decision support tool is presented, and sensitivity and uncertainty analysis is undertaken.

8.3.1 Relative revenue loss from implementing WDP in Communities A and B

Price reductions from WDP will incur lost revenue to the service provider, proportional to both price and volume dispensed. Annual revenues for Community A and B across the range of elasticity values when Blocks 2 and/or 3 are applied are estimated and presented in Figure 8.2. Calculations are based on average volumes dispensed from the timeframe of 2017 to 2019 (non-leap years). Annual timescales are used because: 1) they are more representative of project cycle funding, 2) health impacts of clean water are in the shorter-term (unlike e.g. vaccinations, stopping smoking) which precludes the need for discounting adjustments, and 3) they negate missing days of data.

The following equations are used to calculate expected revenue for:

- Annual revenue without WDP
- Annual revenue with only Block 2
- Annual revenue with only Block 3
- Annual revenue with both Block 2 and 3

Numerical examples are also provided here with each equation for further clarification; these use characteristics of Community A with an assumed E_P value of -0.7 (the influence of different E_P values is seen in Figure 8.2).

p_1 = baseline or Block 1 price; p_2 = Block 2 price; p_3 = Block 3 price i.e. free.

- **Annual revenue without WDP** = (p_1 × mean daily litres dispensed across year × number of days in year) (8.2)

  = 1.25 TSH x 11,663 litres x 365 days
  = 5,321,243 TSH

  For clarity of Equation 8.2, this same equation can alternatively be split up into dry and rainy seasons and expressed as:

  Annual revenue without WDP = (p_1 × mean daily litres dispensed in dry months × days per year in dry months) + (p_1 × mean daily litres dispensed in rainfall months × number of days per year in rainfall months)

  = (1.25 TSH x 13,167 litres x 153 days) + (1.25 TSH x 10,448 litres x 212 days)
  = 2,518,189 + 2,768,720 = 5,286,909 TSH

  (The negligible difference is value from the first equation originates from the slightly uneven split between the length of dry and rainfall seasons).

- **Annual revenue with only Block 2** = (p_1 × mean daily litres dispensed in Block 1 × days per year in Block 1) + (p_2 × mean daily litres dispensed in Block 1* × number of days per year in Block 2) (8.3)

  (* using the value of mean daily litres dispensed in Block 1 here, rather than those of Block 2, is required to account for the desired increase in volume collected (ΔQ) that results from the p_2 pricing. This increased demand will increase revenue, however this is in turn limited by the reduced price, which depends on the E_P value as outlined in Section 8.2.3.)

= (1.25 TSH x 13,167 litres x 153 days) + (0.79 TSH x 13,167 litres x 212 days)
= 2,518,189 + 2,193,246 = 4,711,435 TSH

- **Annual revenue with only Block 3** = (p_1 × mean daily litres dispensed across year × [365 – number of days per year in Block 3])

(8.4)

= (1.25 TSH x 11,663 litres x [365 days – 32 days])
= 4,854,724 TSH

- **Annual revenue with both Block 2 and 3** = (p_1 × mean daily litres dispensed in Block 1 × days per year in Block 1) + (p_2 x mean daily litres dispensed in Block 1 × [number of days per year in Block 2 – number of days in Block 3])

= (1.25 TSH x 13,167 litres x 153 days) + (0.79 TSH x 13,167 litres x [212 days – 32 days])
= 2,518,189 + 1,862,190 = 4,380,378 TSH

(8.5)

Lost revenue is calculated as the difference from annual revenue without WDP for each option. This revenue relates only to purchased water, and so other costs relating to O&M or the committee are not included; it is assumed here that these will remain constant throughout the year. Further costs of WDP from management are discussed in Section 8.4.2. For very high price elasticities there is a chance that revenue could reach even higher than without WDP. However, such high elasticities are unlikely and the chance of this is low, and the revenues would not be significantly greater anyway. The overall objective is to incentivise collection, not increase revenue.

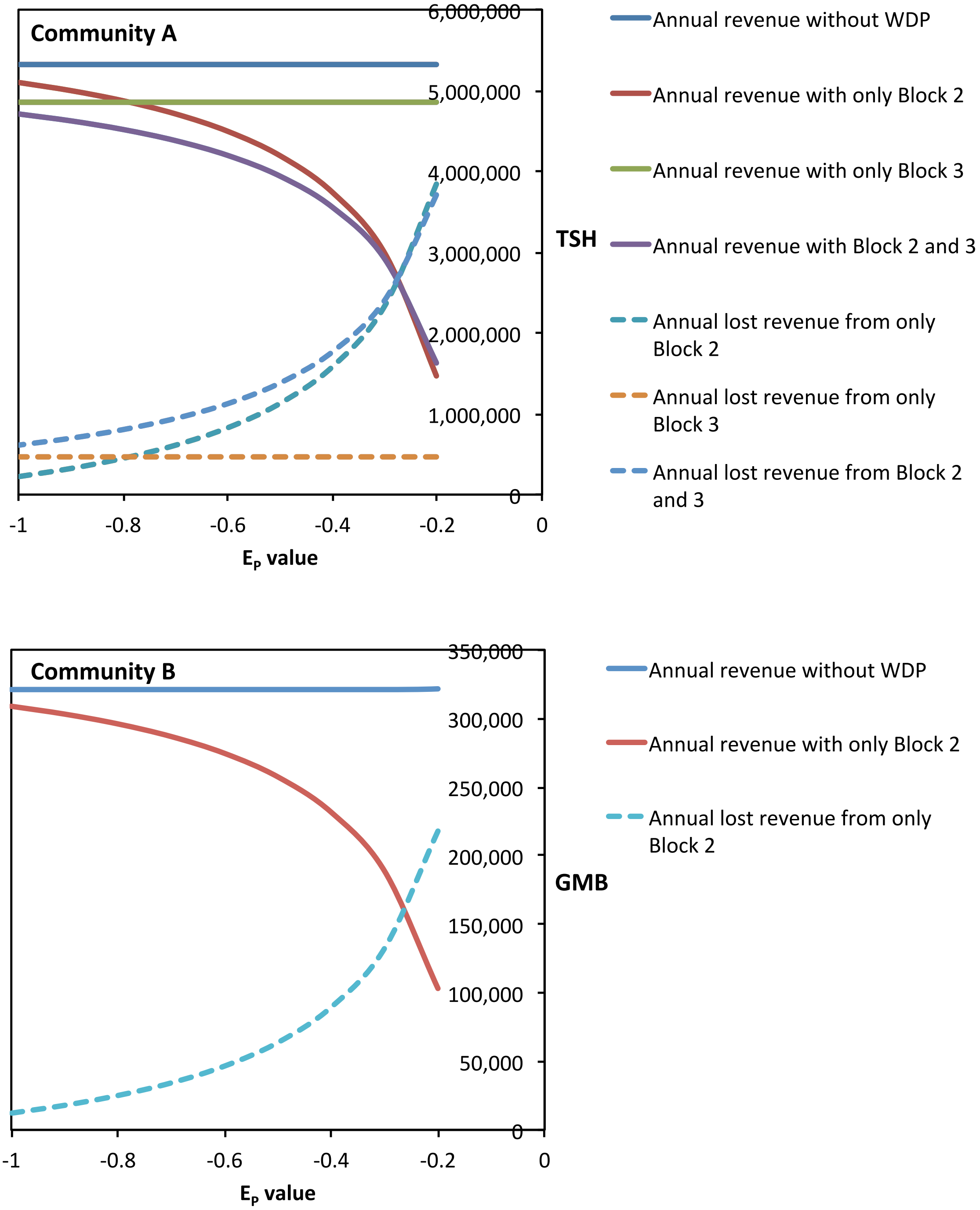

Figure 8.2. Annual revenues and lost annual revenues from WDP Blocks 2 and 3, across the range of price elasticities, for Communities A and B. 1,000,000 TSH ≈ 333 GBP; 100,000 GMB ≈ 1,490 GBP (in 2020).

In Community A, Block 2 would appear to result in more lost revenue than Block 3 (32 days) when elasticity is between -0.8 and -0.2, even though its price remains above zero, because it applies for significantly longer (212 days). Beyond E_P = -0.8, Block 3 incurs more lost revenue, however within this range amounts are comparable. Therefore, because price elasticity only applies to

Block 2, elasticities closer to zero significantly increase lost revenue, because greater price reductions would be needed. This also applies to Community B.

If demand is more elastic than the literature suggests, as proposed for the reasons given above, WDP will result in less lost revenue and be more economically efficient. Shortening Block 2 also reduces lost revenue by a proportional amount, as does changing the desired %ΔQ.

Block 3 would only result in 9% of annual revenue lost for Community A over 2017-2019, which is generally less than Block 2 (4%–44%). Yet, as suggested above, Block 3 is likely to dramatically incentivise the use of clean water on days of heavy rainfall and result in greater health benefits. The number of days in Block 3 is less predictable than Block 2 and dependent on increasing rainfall variability in sub-Saharan Africa (see below), but is assumed to remain relatively low. Block 3 is therefore more likely to be cost effective than Block 2. Overall, WDP is not likely to result in significant lost revenue. 'Value' of this lost revenue is assessed next.

8.3.2 Quantification of health and economic cost-benefit from WDP in Communities A and B

Calculating lost revenues in the previous section reveals the 'cost' of WDP. (Further costs from community engagement and management are discussed below, along with mechanisms for meeting costs with direct subsidy). This now allows an examination of the question: 'is WDP worth the cost?'

It is hypothesised that the overall health benefits from reduced use of potentially contaminated water will be relatively cheap and generally offset the costs with economic benefits. A rigorous 'cost-effectiveness' or 'social cost-benefit analysis' (Pond et al., 2011) here is limited without empirical data from implementing the WDP and controlling for the baseline availability of clean DP water, or without studies of similar interventions, which are not apparent. Accurately estimating expected impact of health is impossible. It is a challenge here to model causality.

Instead, at this stage the objective is to determine general economic feasibility. Useful estimations of this can be made using existing estimations of health and economic impacts of analogue metrics. To this end, the flow chart in Figure 8.3 shows how this is calculated for Communities A and B:

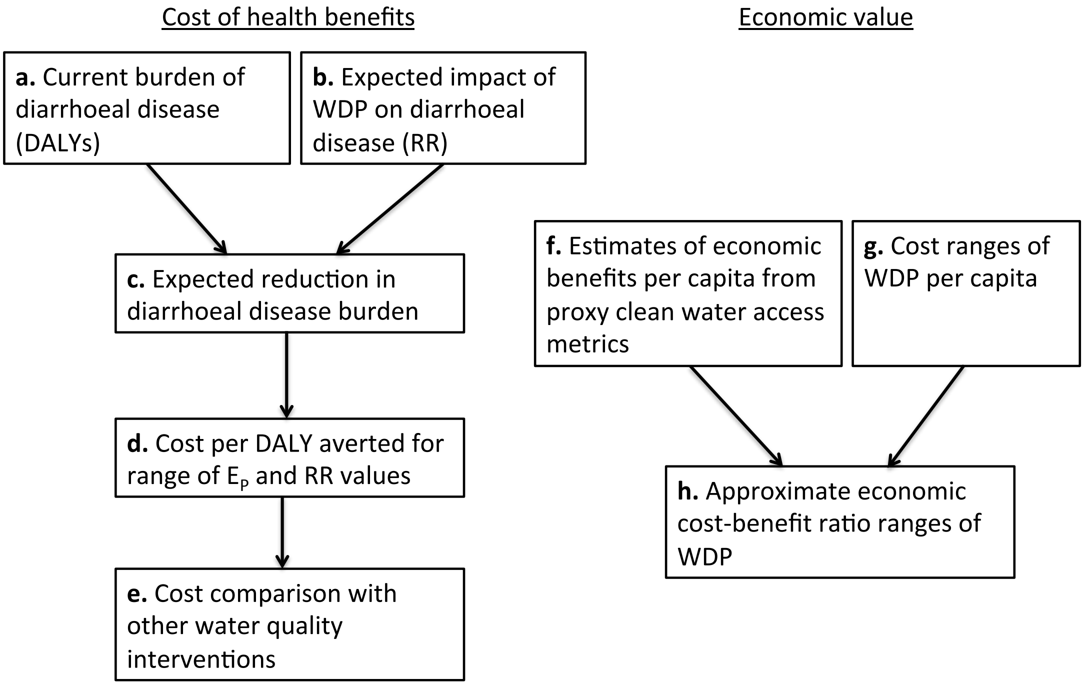

Figure 8.3. Steps of analysis for estimations of health and economic cost-benefit from WDP (DALY and RR outlined below)

The steps in Figure 8.3 and their adopted quantification approaches are summarised as below, first for the cost of health benefits (boxes a to e), then separately for the economic value (boxes f to h).

a. Diarrhoeal disease is the most appropriate indicator of health related to contaminated water to use here. An appropriate measure for comparison of the burden of disease is the ‘disability-adjusted life year’ (DALY). DALY is the major physical indicator for cost-benefit analyses and is equivalent to one lost year of healthy life (based on years lived with disability combined with years of life lost, weighted for individual illness and age) (WHO, n.d.). Global health programming therefore aims to avert DALYs. It is a more comprehensive indicator than simple diarrhoea incident-count as it incorporates mortality, morbidity, and time. DALYs that are attributable to diarrhoeal diseases are provided by the WHO. The latest data is from 2000-2016, available as total estimates for each WHO Member State (Global Health Estimates, 2016). There is some uncertainty of estimates, but they give good approximations for this purpose. In Tanzania, 61% of DALYs from diarrhoeal diseases are for children aged 0-14 years old, and in The Gambia 76%. As referred to, WDP therefore has greater impact potential for children[8]. The following equation is used to estimate total current DALYs from diarrhoeal diseases for all ages and genders in specific communities, i.e. Communities A and B.

- **Estimated total DALYs per community** = (Estimated total DALYs per country / total country population) × community population

(8.6)

Country populations from 2016 are used to match to the 2016 WHO DALY estimates. Therefore, carrying this national scale homogeneity for each country to the local level gives approximately 61 DALYs attributable for diarrhoeal disease for Community A (population ~1,770, see Section 5.3), and 54 in Community B (population ~1,840). This represents 0.035 DALYs per capita attributable for diarrhoeal disease for Community A, and 0.029 DALYs per capita attributable for diarrhoeal disease for Community B. These values are likely underestimations given the rural contexts where diarrhoeal disease is much more prevalent and lower average age. Furthermore, other diseases such as waterborne rotavirus, cholera, or schistosomiasis are not included.

b. Expected impact of WDP on diarrhoeal disease in rainfall months (i.e. the relative risk, RR, after implementation, where RR of 1.00 would indicate that risk of diarrhoeal disease is the same with the intervention as without) is impossible to estimate accurately because of scarcity of existing studies and the fact that diarrhoeal disease has complex causes beyond contaminated rainwater. RR is also dependent on the complex interplay with other socio-economic factors. However, estimates can be approximated from analysis of proxies.

The existing burden of diarrhoeal disease caused by the impact of rainfall in rural sub-Saharan Africa would indicate a baseline from which the intervention

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[8] Furthermore, some researchers suggest diarrhea DALYs in under-fives are potentially underestimated by 39% because of the long-term health impacts (Troeger et al., 2018).

can improve on. The general observation that rainfall increases incidence of diarrhoeal (and other) disease, as outlined above, is poorly quantified (Levy et al., 2018), particularly in rural Africa. One study measured childhood diarrhoeal incidence in Senegal to be higher in rainy seasons compared to dry seasons with an incident rate ratio (IRR) in rural areas of 1.70 (95% CI: 1.29-2.24) (Thiam et al., 2017). It follows that avoidance of this risk from rainfall months by successful WDP would lead to a relative risk of childhood diarrhoeal disease of RR = 0.58 down from this current peak (a 42% reduction). WDP would not contribute to all of this. Additionally, in Ethiopia rainfall was found to be a significant risk factor of childhood diarrhoea with a relative risk (RR) of 1.00167 (95% CI: 1.001306–1.001928) per 1 mm increase in average monthly rainfall (Alemayehu et al., 2020). For a monthly rainfall of 250 mm, reached in Community A, this would give an RR of 1.40, leading to a hypothetical reduction to RR = 0.71 (29% reduction). These studies are strongly limited by spatial variability and monthly time resolution.

A more useful source of evidence for the estimation here comes from the inverse of these studies, i.e. the RR seen with existing water quality interventions. A meta-analysis of water quality interventions gives the RR of diarrhoeal disease after a ‘new source, supply or connection’ is provided as RR = 0.75 (Risebro and Hunter, 2011), with a 95% confidence interval from 0.62 to 0.91 (~0.87 in Clasen et al. 2007b)[9]. These values are predicated on a binary distinction between potentially contaminated water on one hand, and a clean water source on the other, and can therefore be taken here roughly analogous to switching from potentially contaminated water to clean DP water. This is not to say the full benefit of a ‘new source’ is attributable to WDP; the objective is not to find how much WDP contributes on top of a ‘new source’, but rather to estimate the reduction of diarrhoeal disease that WDP could bring from its current levels in rainy seasons using the best available evidence. While an

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[9] Different RR values are also provided for various WASH *counterfactual* scenarios (Prüss-Ustün et al., 2019), pertinently: diarrhoea with household water filtering or boiling RR = 0.52; schistosomiasis with basic drinking water services RR = 0.53; malaria with safe water resource management RR = 0.31; soil-transmitted helminth infections with safely management WASH services RR = 0; and trachoma with safely managed WASH services RR = 0. These low values suggest a lower RR value is more representative to use in this step, and also suggest that WDP health gains would reach beyond just diarrhoea.

imperfect representation of WDP, these values provide better estimations and fit well with reports that water quality interventions at source can reduce diarrhoea among children by 20-70% (Waddington and Snilstveit, 2009). The fact that only a short relapse to contaminated water has significant health impacts suggests that avoiding this by maintaining clean water use should result in a lower overall RR value attributable to WDP. For example, a drop in adherence to water treatment from 100% to 90% can reduce predicted health gains by up to 96% (Brown and Clasen, 2012).

One factor that would limit WDP's reduction of risk is that effects are only in rainfall months, whereas diarrhoea and other waterborne disease is, despite tending to peak in rainfall months, still spread across the year. This is very dependent on local seasonality and context and is not possible to quantify here.

Taken together, this evidence suggests that a significant proportion of annual diarrhoeal disease could be averted by maintained use of clean water supply during periods of rainfall. This does not include other waterborne diseases, which would also be reduced by WDP. However, the reality is that the expected impact of WDP on diarrhoeal disease is impossible to predict. Use of the 95% confidence interval range provided by Risebro and Hunter (2011) of 0.62 to 0.91 is a reasonable way to accommodate the insurmountable uncertainties of this estimation. That is to say, the expected reduction in diarrhoeal disease from achieving the target ΔQ as a result of WDP is likely to range between 38% – 9% on 95% of occasions, with 25% as a middle estimate. This is a suitable first approximation.

c. Expected reduction in diarrhoeal diseases from an intervention is therefore given by:

- **Averted DALYs** = Current DALYs × (1.0 - Expected RR) (8.7)

Averted DALYs for Community A with WDP are therefore expected to be approximately between 23 and 5 (when RR = 0.75, 15 averted DALYs expected), and 20 and 5 (when RR = 0.75, 13 averted DALYs expected) for Community B. Put another way, WDP has the potential to avert the loss of 5 to 23 years of healthy life, across Community A. As per capita estimations, these represent between 0.013 and 0.003 (0.009) DALYs per capita averted in Community A, and between 0.011 and 0.002 (0.007) DALYs per capita averted in Community B.

d. The '*cost* per DALY averted' can be approximated for the expected ranges of E_P and RR values based on the lost revenues calculated above, using:

- **Cost per DALY averted** = Lost revenue / Averted DALYs (8.8)

The cost per DALY averted can be considered as how much it would cost to avert the loss of one year of healthy life in these communities. It is a stand-alone unit, and not per capita or per community. It is an annual cost here to fit with the annual lost revenues above, but could also be calculated across a project lifespan. Costs per DALY averted are shown for Communities A and B in Table 8.3 with the uncertainty ranges from E_P and RR values determined above.

Table 8.3. Approximated costs per DALY averted for different E_P and RR values, in GBP *(USD)* to the nearest whole pound *(dollar)*

	Community A			Community B		
	Relative risks					
E_P	**0.62**	**0.75**	**0.91**	**0.62**	**0.75**	**0.91**
-0.3	36 *(45)*	55 *(68)*	154 *(189)*	102 *(125)*	154 *(190)*	429 *(529)*
-0.7	14 *(18)*	22 *(27)*	60 *(74)*	26 *(32)*	40 *(49)*	111 *(137)*
-1.0	9 *(11)*	14 *(17)*	39 *(48)*	9 *(12)*	14 *(18)*	39 *(49)*

It is clear that the costs per DALY averted are sensitive to elasticity due to lost revenue as shown above, and to the relative risk of diarrhoeal disease from the intervention. Lower relative risks of the intervention and greater elasticities would result in cheaper cost per DALYs. Sensitivities and uncertainties are analysed below.

The cost per DALY averted is generally lower in Community A than Community B. These differences originate from population size, influence of rainfall on volume dispensed, and total DALYs from diarrhoeal disease in each country; but more significant is that Community B has higher lost revenue due to greater overall water consumption.

e. These approximations of costs per DALY averted can be compared with gross costs per DALY averted estimated for other water quality interventions, which have been reported in meta-analyses (Edwards, 2011). These estimates have their own wide ranges. Their averages are shown in Figure 8.4.

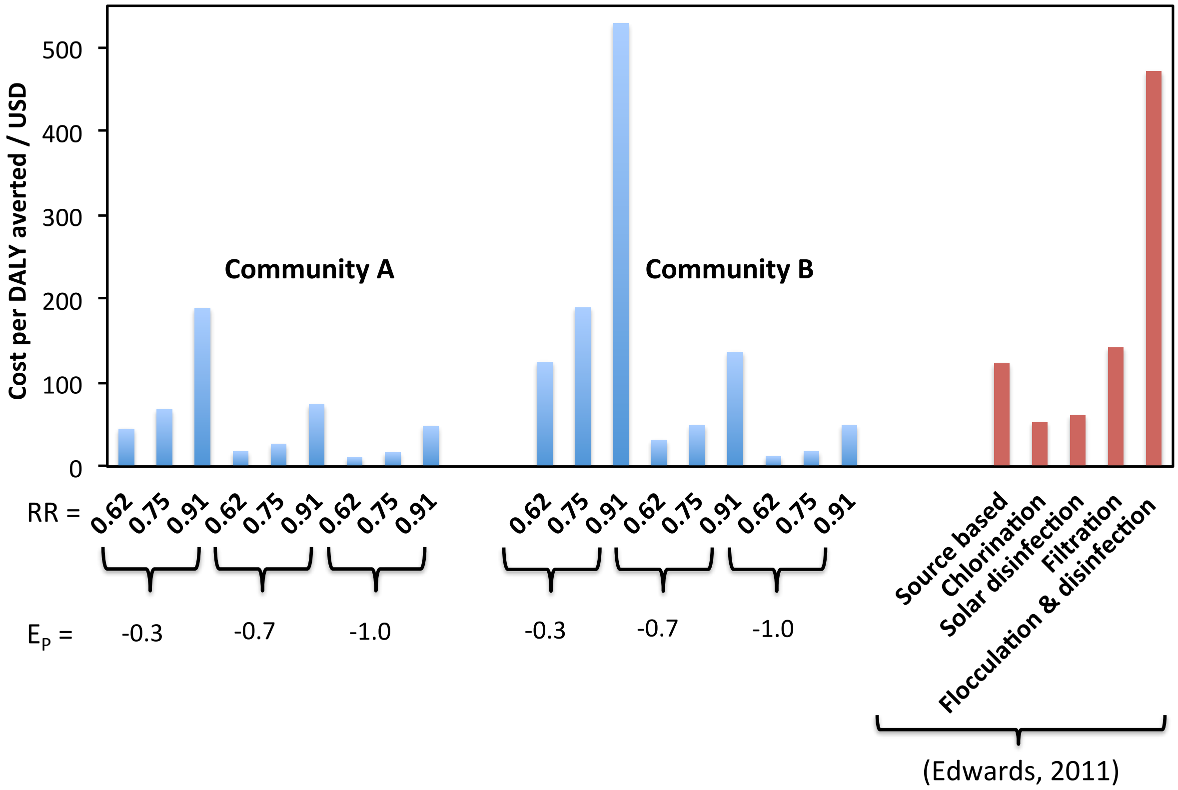


Figure 8.4 Comparison of cost per DALY averted ranges for WDP in Community A and B against other water quality intervention averages (using USD for comparison).

Wide ranges of costs of other interventions (and different frequencies of costs) limit this comparison. However, the cost per DALY averted from WDP in both communities compare favourably against other water quality interventions when there is higher elasticity and lower relative risk. With the assumption that elasticity will be between -0.5 and -1 as argued above, WDP compares favourably in both communities against even the lowest alternative cost per DALY averted (chlorination). If the elasticity is lower than expected, WDP compares less favourably against other interventions (apart from flocculation and disinfection). This comparison is one way to assess the worth of WDP and contextualise its costs. Different interventions can be applied in conjunction.

f. Separately, in addition to the previous steps, another way to assess the value of WDP is by comparing its expected economic benefits from health improvements against lost revenue. This is done here by comparing costs per capita of WDP with estimated economic benefit per capita. This is included to provide evidence that implementation of WDP is likely to bring broader economic benefits.

Economic benefits of clean water specifically include: 1) savings from less health care expenditure, 2) savings from more productive time, and 3) savings from reductions in premature mortality. These offset costs of WASH interventions. Mean cost offset per each averted case of diarrheal disease has been estimated at 2.77 USD, 88% of which is borne by the health sector (Clasen et al. 2007a). The average cost of childhood diarrhoeal illness in low and middle-income countries is estimated elsewhere to be about 37 USD per outpatient episode and 160 USD per inpatient episode (Baral et al., 2020), and avoiding these costs would be economically significant. On a regional scale in sub-Saharan Africa, the benefit-cost ratio of interventions towards universal access of improved drinking-water sources is purported to be 2.5:1 (Hutton, 2012b) (with other estimates ranging to 14:1), where the main contribution comes from increased productive time from reduced collection time as highlighted in Section 5.5.1, but with at least 35% from health improvements (10% from savings from health care).

Broad yet reasonable estimations of economic benefits of WDP per capita can be derived here using estimations of total economic benefit for achieving ‘universal clean water coverage’. Such values are reported at the country-level for seven countries in sub-Saharan Africa (Hutton, 2006). Here, ‘universal clean water coverage’ can be taken as a proxy for the maintained used of clean DP water throughout the year, as with estimations of the RR value. While not perfectly representative, this is a useful available proxy for avoiding switching to potentially contaminated sources. The fact that universal access results in higher economic benefits than simply halved-inaccess (i.e. the Millennium Development Goal) further suggests a significant economic benefit from reaching the most marginalised populations, which is more representative of Communities A and B.

Here, approximate *per capita* economic benefits of universal access for each country are derived from dividing these national-scale estimates by the 2006 country populations, and converted to GBP with 2006 exchange rates. Economic benefits therefore range between 1.58 GBP per capita (Ethiopia) and 6.15 GBP per capita (Dem. Rep. of Congo), with a mean of 2.84 GBP. In other words, it is reasonable to approximate that avoiding potentially contaminated water by implementing WDP can bring average economic benefits of between 1.58 and 6.15 GBP per capita. This presents a reasonable range for Tanzania and The Gambia.

g. The likely range of costs per capita of WDP with different E_P values are estimated using the above calculations of expected lost revenue (Figure 8.2). For Community A annual costs per capita range between 0.12 – 0.47 GBP (E_P range from -0.3 to -1), and for Community B as between 0.30 – 1.16 GBP.

h. Combining these two sets of ranges in the form of: 'estimated economic benefit per capita:cost of WDP per capita' gives a full range of approximate benefit-cost ratios for Community A of between 3.4:1 and 51.3:1, and for Community B of between 1.4:1 and 20.5:1. Even accounting for the uncertainties of community populations, national-to-community scale comparison, use of proxy economic benefits, and heterogeneity between communities, this strongly indicates an offsetting of the costs associated with lost revenue. Furthermore, the low per capita costs of WDP are miniscule in absolute terms compared with total per capita costs of PWS installation and smart meters, and the overall ~4.5 billion USD required for sustainable water management by 2030 (Strong et al. 2020).

In summary, the 'costs per DALY averted' are comparatively low, and these costs would be made up for by economic benefits. WDP is likely to be economically feasible, worth the lost revenue, and good value for money.

8.3.3 Decision support tool for application in different communities

WDP is designed for application in any community across rural sub-Saharan Africa that has smart meters in the future. Required pricing adjustments (ΔP), expected lost revenue, and expected cost per DALY averted will differ between different communities. WDP will not be suitable in every community and needs to be tailored to each setting. To this end, an Excel-based decision support tool has been developed to calculate these expected values for specific communities.

The tool is designed to assess whether WDP is appropriate for the community in question. Users are envisaged to be:

1. Local service providers, e.g. community water committee, district water engineer, local NGO, etc.
2. Funders; e.g. Ministry of Water, donor, external development partner, etc.

Specific questions the tool can answer are:

- What price should be set during Block 2 to achieve the desired ΔQ? This depends on the specific influence of rainfall on volume dispensed from DPs.
- How much annual revenue would be expected without WDP and when WDP is implemented? This assumes that the expected price elasticity achieves the desired ΔQ.
- What are the expected relative annual revenues between implementing Block 2, Block 3, or both?
- How much is the expected lost revenue per capita (i.e. subsidy required) and ‘cost per DALY averted’? (i.e. the value for money).

The tool’s required inputs and outputs are presented in Figure 8.5.

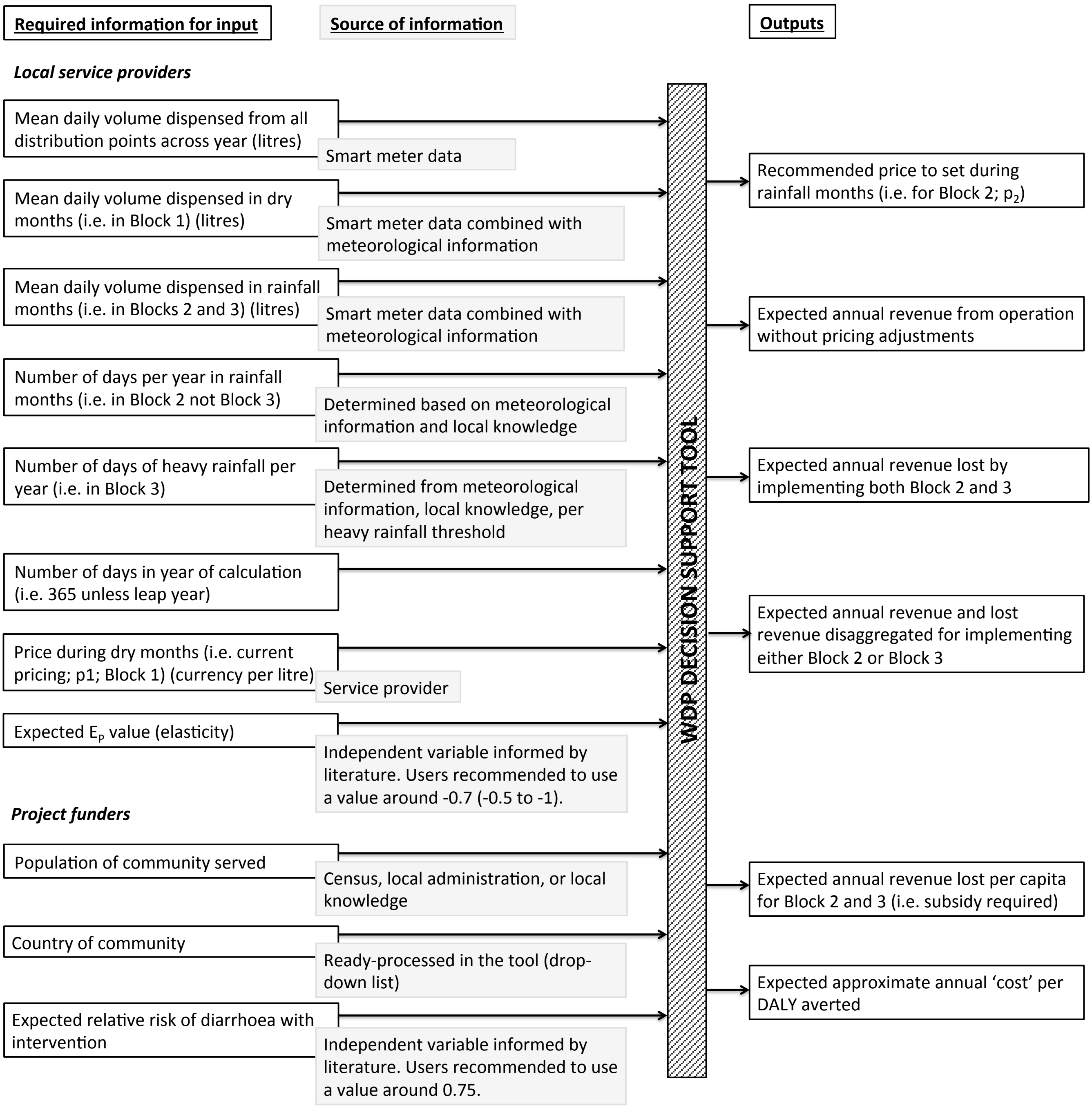
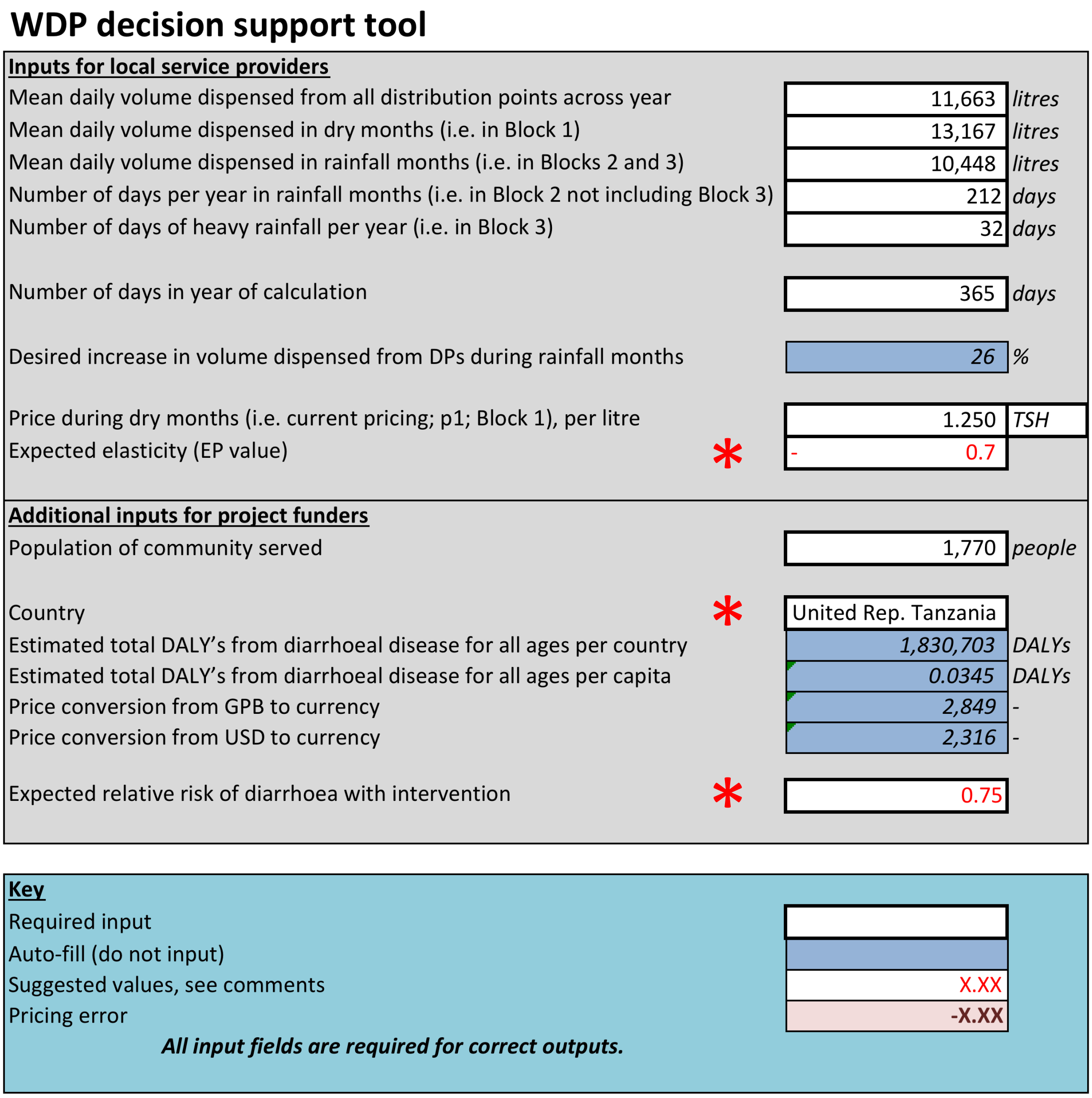


Figure 8.5. WDP decision support tool inputs, sources of information and outputs

The tool automatically calculates the estimated total DALY's from diarrhoeal disease per country selected and per capita. Available DALY data for diarrhoeal disease of all age groups from the WHO Global Burden of Disease (2016) are included in the tool for all sub-Saharan African countries, along with 2016 country population estimates (World Bank open data from https://data.worldbank.org). Conversion factors of currency to GBP and USD are also included. These data are processed in the tool using the equations as with Community A and B above, and users can simply select the country in question from a drop-down list, which automatically inputs the correct country DALY and currency information. Description for users based on the explanation here is provided in the tool. Figure 8.6 shows a screenshot of the tool.



WDP decision support tool

Inputs for local service providers			
Mean daily volume dispensed from all distribution points across year		11,663	*litres*
Mean daily volume dispensed in dry months (i.e. in Block 1)		13,167	*litres*
Mean daily volume dispensed in rainfall months (i.e. in Blocks 2 and 3)		10,448	*litres*
Number of days per year in rainfall months (i.e. in Block 2 not including Block 3)		212	*days*
Number of days of heavy rainfall per year (i.e. in Block 3)		32	*days*
Number of days in year of calculation		365	*days*
Desired increase in volume dispensed from DPs during rainfall months		*26*	*%*
Price during dry months (i.e. current pricing; p1; Block 1), per litre		1.250	*TSH*
Expected elasticity (EP value)	*	- 0.7	
Additional inputs for project funders			
Population of community served		1,770	*people*
Country	*	United Rep. Tanzania	
Estimated total DALY's from diarrhoeal disease for all ages per country		*1,830,703*	*DALYs*
Estimated total DALY's from diarrhoeal disease for all ages per capita		*0.0345*	*DALYs*
Price conversion from GPB to currency		*2,849*	-
Price conversion from USD to currency		*2,316*	-
Expected relative risk of diarrhoea with intervention	*	0.75	

Key	
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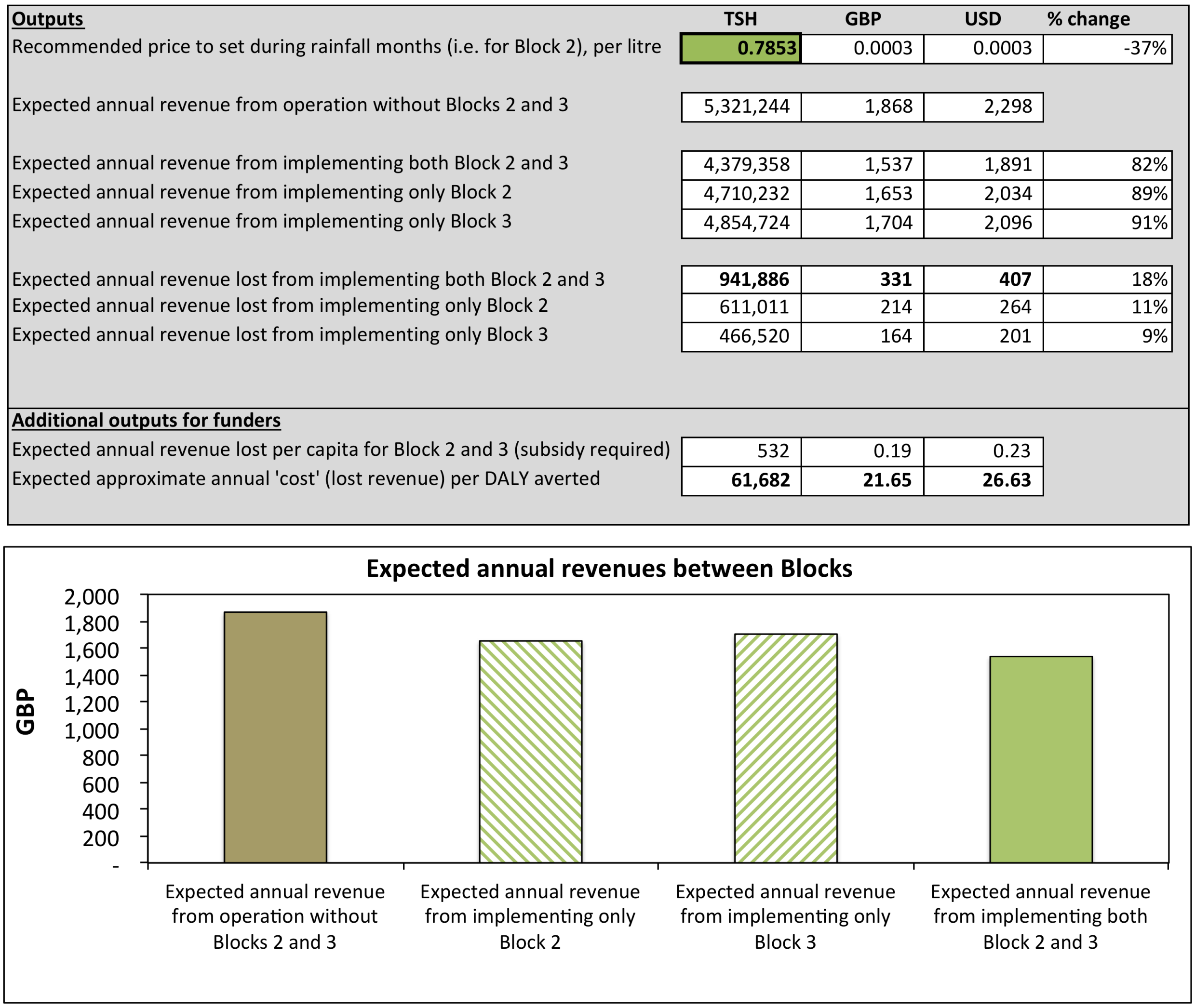
Suggested values, see comments	X.XX
Pricing error	**-X.XX**

All input fields are required for correct outputs.



Outputs	TSH	GBP	USD	% change
Recommended price to set during rainfall months (i.e. for Block 2), per litre	**0.7853**	0.0003	0.0003	-37%
Expected annual revenue from operation without Blocks 2 and 3	5,321,244	1,868	2,298	
Expected annual revenue from implementing both Block 2 and 3	4,379,358	1,537	1,891	82%
Expected annual revenue from implementing only Block 2	4,710,232	1,653	2,034	89%
Expected annual revenue from implementing only Block 3	4,854,724	1,704	2,096	91%
Expected annual revenue lost from implementing both Block 2 and 3	**941,886**	**331**	**407**	18%
Expected annual revenue lost from implementing only Block 2	611,011	214	264	11%
Expected annual revenue lost from implementing only Block 3	466,520	164	201	9%
Additional outputs for funders				
Expected annual revenue lost per capita for Block 2 and 3 (subsidy required)	532	0.19	0.23	
Expected approximate annual 'cost' (lost revenue) per DALY averted	**61,682**	**21.65**	**26.63**	

Figure 8.6 Screenshot of decision support tool with inputs for Community A; red asterisks are drop-down selections.

8.3.4 WDP scenario analysis in hypothetical communities

In order to extend initial testing of WDP beyond Community A and B, different hypothetical communities are tested. This is done using the decision support tool, and investigates the potential for WDP application in new settings. Additionally, it is also a first step to indicate which of the inputs the outputs are most sensitive to (conducted more formally below), and demonstrate the real-term impact of the uncertainty around both elasticity (E_P) and the expected impact on health (RR) (also examined more formally below).

12 hypothetical communities are tested using the decision support tool. Characteristics are varied to provide an appropriately broad range of realistic rural communities where WDP might be implemented. Variables are selected as

those most likely to reflect significant differences between communities. These are:

1) The influence of rainfall months on volume dispensed (i.e. desired %ΔQ). Influence of seasons will differ between communities in different climatic zones and with different water consumption.
2) Number of days of heavy rain (i.e. days in Block 3). This also incorporates different climatic zones, and the influence of climate change (see below).
3) Community population, which varies significantly across sub-Saharan Africa
4) Elasticity of water price (E_P). Two E_P values are tested against: -0.4 to reflect the average literature finding from Table 8.1, and -0.8 as adjusted towards a better guess of reality for the reasons outlined above (Section 8.2.3).
5) Relative risk of diarrhoeal disease is assumed to be 0.75, as above, but full ranges between 0.91 and 0.62 are also included in Table 8.5 below.

The scenarios here are based on the national characteristics for Tanzania shown in Figure 8.5 above. Consequently, the price is maintained as 1.25 TSH per litre, as in Community A. The per capita water collection is kept approximately equal between communities (based on Community A); therefore larger hypothetical populations have greater overall collection while %ΔQ remains the same. Days in Block 2 are taken as 212, the same as Community A, which is representative of a hypothetical binary climatic system. Providing a full range of each of these variables, which are considered less likely to differ between communities, would have made outputs unwieldy without any significant benefit. Table 8.4 shows the characteristics of each of these 12 scenarios, Table 8.5 shows the expected outputs.

Table 8.4. 12 hypothetical communities selected

Scenario label	**Community size**	**Influence of rainfall months**	**Days of heavy rainfall**	**Elasticity**
1.1	Small 800 people	Low %ΔQ = 10%	Low Block 3 = 10 days	High $E_P = -0.8$
1.2	Small 800 people	High %ΔQ = 39%	Low Block 3 = 10 days	High $E_P = -0.8$
1.3	Small 800 people	High %ΔQ = 39%	High Block 3 = 40 days	High $E_P = -0.8$
1.4	Large 2,500 people	Low %ΔQ = 10%	Low Block 3 = 10 days	High $E_P = -0.8$
1.5	Large 2,500 people	High %ΔQ = 39%	Low Block 3 = 10 days	High $E_P = -0.8$
1.6	Large 2,500 people	High %ΔQ = 39%	High Block 3 = 40 days	High $E_P = -0.8$
2.1	Small 800 people	Low %ΔQ = 10%	Low Block 3 = 10 days	Low $E_P = -0.4$
2.2	Small 800 people	High %ΔQ = 39%	Low Block 3 = 10 days	Low $E_P = -0.4$
2.3	Small 800 people	High %ΔQ = 39%	High Block 3 = 40 days	Low $E_P = -0.4$
2.4	Large 2,500 people	Low %ΔQ = 10%	Low Block 3 = 10 days	Low $E_P = -0.4$
2.5	Large 2,500 people	High %ΔQ = 39%	Low Block 3 = 10 days	Low $E_P = -0.4$
2.6	Large 2,500 people	High %ΔQ = 39%	High Block 3 = 40 days	Low $E_P = -0.4$

Table 8.5. Expected outputs calculated for WDP in each of the 12 hypothetical communities

Scenario *(From Table 8.4)*	Recommended price to set in Block 2 (TSH) *(p_1 = 1.25 TSH)*	Expected annual revenue lost per capita with Blocks 2 and 3, i.e. subsidy required (GBP) *(percentage decrease from total expected annual revenue without WDP)*	Expected approximate annual cost per DALY averted (GBP) *(RR range = 0.91 – 0.62)*
1.1	1.09	£0.05 *(-5.5%)*	£6.01 *(£16.69 - £3.95)*
1.2	0.26	£0.33 *(-33.6%)*	£36.53 *(£101.47 - £28.54)*
1.3	0.26	£0.35 *(-35.7%)*	£38.86 *(£107.97 - £25.57)*

1.4	1.09	£0.05 *(-5.5%)*	£5.77 *(£16.02 - £3.80)*
1.5	0.26	£0.32 *(-33.5%)*	£34.94 *(£97.06 - £22.99)*
1.6	0.26	£0.34 *(-33.6%)*	£35.60 *(£103.34 - £24.47)*
2.1	0.92	£0.13 *(-13.2%)*	£14.33 *(£39.80 - £9.43)*
2.2	*-0.72*	*n/a*	*n/a*
2.3	*-0.72*	*n/a*	*n/a*
2.4	0.92	£0.13 *(-35.6%)*	£13.75 *(£38.21 - £9.05)*
2.5	*-0.72*	*n/a*	*n/a*
2.6	*-0.72*	*n/a*	*n/a*

It is apparent that more revenue would be lost when the desired %ΔQ is higher. This is because the pricing 'financial lever' would need to be pulled further when the influence of rainfall months is greater. Lower elasticity with higher %ΔQ (Scenarios 2.2, 2.3, 2.5 and 2.6) results in an impossible negative price, suggesting that WDP with both Block 2 and 3 is not appropriate in these circumstances (just Block 3 would be more appropriate). The size of the community has low influence on the expected lost revenue per capita. This suggests that, with other favourable characteristics, WDP could be applied across the range of different sizes of communities seen in sub-Saharan Africa, which is significant considering population growth. However, this is contingent on roughly equal per capita water collection. The number of days in Block 3 also has insignificant influence, as seen above for Community A and B, even when free pricing is implemented for 40 days in the year. Changes in the relative risk of diarrhoeal disease also have significant influence on the expected approximate annual cost per DALY averted.

Overall, the best value for money from WDP, as indicated by cost per DALY averted, would come from communities where rainfall months have relatively low influence of volume collected from DPs and where users respond strongly to small price adjustments (i.e. high elasticity).

8.3.5 Sensitivity analysis

A further ‘sanity-check’ is required on WDP after testing hypothetical scenarios. Sensitivity analysis needs to be performed to understand the contribution from individual inputs towards the overall outputs (Cullen and Frey, 1999). Sensitivity analysis is generally used to assess how much trust to put in model results (Link et al., 2018). Here, it is used more to examine the question: ‘which input variables have the largest influence on the key outputs?’ The extent of change of the different outputs is measured over a realistic range of variation of the different inputs.

The appropriate method for sensitivity analysis in this instance is testing of one input at a time while all others are maintained. This ‘one-at-a-time’ (OAT) method is typically used to compare importance of inputs, and while this method does not accommodate for interactions between variables (it is “local”) this does not matter here as the inputs are known to be relatively independent from one another. More computationally heavy “global” sensitivity analysis (GSA) methods that can simultaneously account for interactions and huge numbers of inputs are therefore not required for the more conceptual purposes here (Link et al., 2018; Zhang et al., 2015). Such refined GSA methods are also not required to inform any model calibration, and the lack of empirical basis for development of WDP means that the OAT method’s broader simplicity is better suited.

The hypothetical scenarios above revealed that some input variables are clearly more significant than others. Therefore, only the following variables need to be tested as variable inputs:

1) Elasticity (E_P)
2) Desired increase in volume dispensed during rainfall months ($\%\Delta Q$)
3) Relative risk of diarrhoeal disease (RR)

In sensitivity analysis of other models based on empirical data the range of variation of inputs that is tested is typically based on a range of ±1 standard deviation from the average, with the sensitivity revealed by the maximum and minimum output values. This is not possible here because 1) there is no empirical data, and 2) input ranges are not normal distributions. However, use of all values between the most likely estimations of input ranges allows a presentation of the sensitivity as plots for easy comparison, shown in Figure 8.7. The E_P range used is -1 to -0.2, which accommodates for extremes. The RR range used is 0.91 to 0.62, based on the 95% confidence interval provided above (Risebro and Hunter, 2011). The %ΔQ range used is approximated widely at 0% to 50%. The constant values used while other inputs are varied are based on best estimates: E_P = -0.7, RR = 0.75, and %ΔQ = 26% (i.e. as seen in Community A). The outputs are 'expected annual revenue lost per capita', and the 'expected approximate cost per DALY averted'. All other variables are kept constant as in Community A, which is an appropriate real-life scenario for demonstrating sensitivity: price at 1.25 TSH; community size at 1,770 people; days in Block 3 = 32; mean daily volume dispensed in dry months = 13,167 litres; and DALY characteristics for Tanzania. The mean daily volume dispensed across the whole year (dry *and* rainfall months) used here is based on the same relationship between rainfall and dry months in Community A.

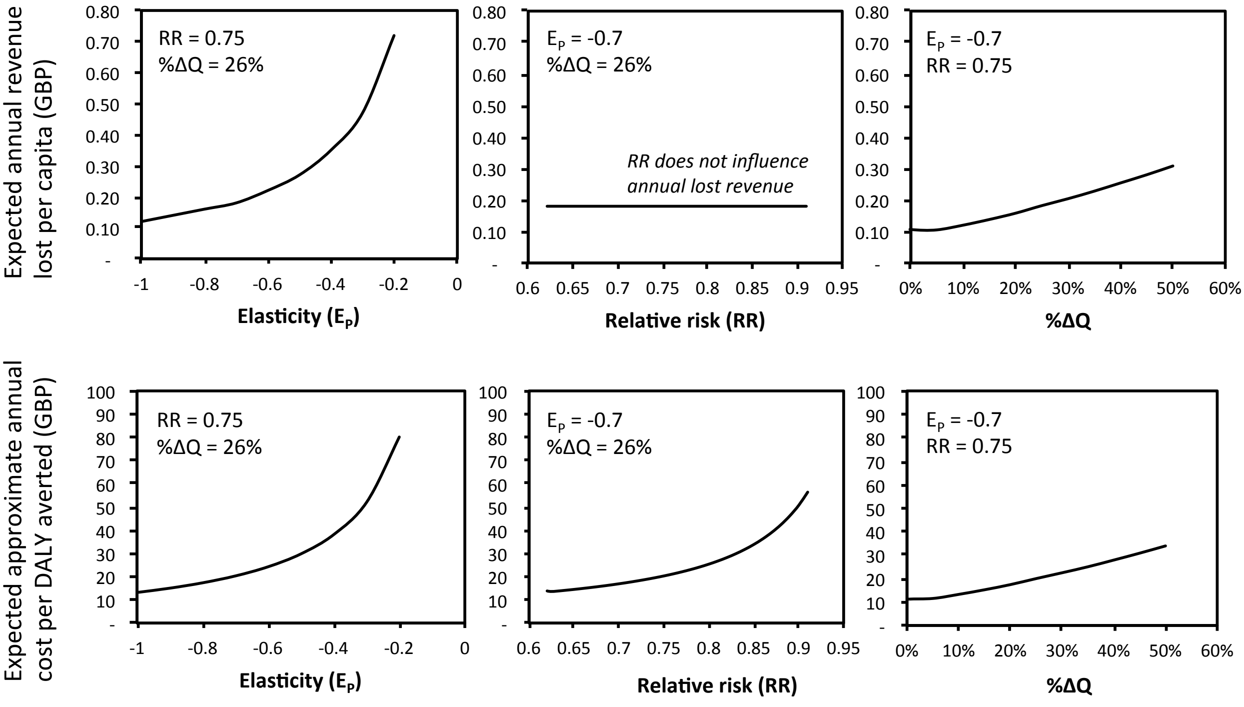


Figure 8.7 Sensitivity of WDP outputs to different inputs

It is clear that expected lost revenue and cost per DALY averted are sensitive to each input (with the exception of expected annual revenue lost to RR). This gives additional confidence in the proposed WDP modelling process. Slopes from each plot give a useful comparison.

The sensitivity of outputs to variables E_P, RR and %ΔQ are therefore relatively similar. Each input is important and is therefore included in the uncertainty analysis below. Sensitivity of expected lost revenue and cost per DALY averted increases as E_P tends to 0 and RR to 1. This follows the influence of pricing changes based on the elasticity equation as above (Equation 8.1). Therefore, if E_P is between -0.5 and -0.1, as predicted in this setting, and RR is approximately 0.75, expected lost revenue and cost per DALY averted are less sensitive to minor variations in these inputs (the slope is flatter), compared to less elastic and greater relative risk inputs.

8.3.6 Uncertainty analysis

Expected WDP outputs in terms of cost and value have so far been presented as point-values. However, WDP outputs have inherent uncertainty due to unknown inputs. Next, uncertainty analysis is required to quantify the range of potential outputs from the expected ranges of these inputs. Monte Carlo simulation (Khatri and Vairavamoorthy, 2009; Farrance and Frenkel, 2014) is a suitable method to provide an estimate of the overall uncertainty in the predictions from WDP. Here, the cumulative interactions between different variables is therefore accounted for, unlike in the OAT sensitivity analysis.

The variable inputs for Monte Carlo simulations are the same as for the sensitivity analysis, and the other characteristics remain the same as above (i.e. for Community A). Uncertainty analysis including all potential inputs with estimated ranges is not appropriate like with sensitivity analysis. Outputs are not significantly sensitive to these additional variable inputs.

The steps to derive uncertainty using the Monte Carlo method were conducted as follows:

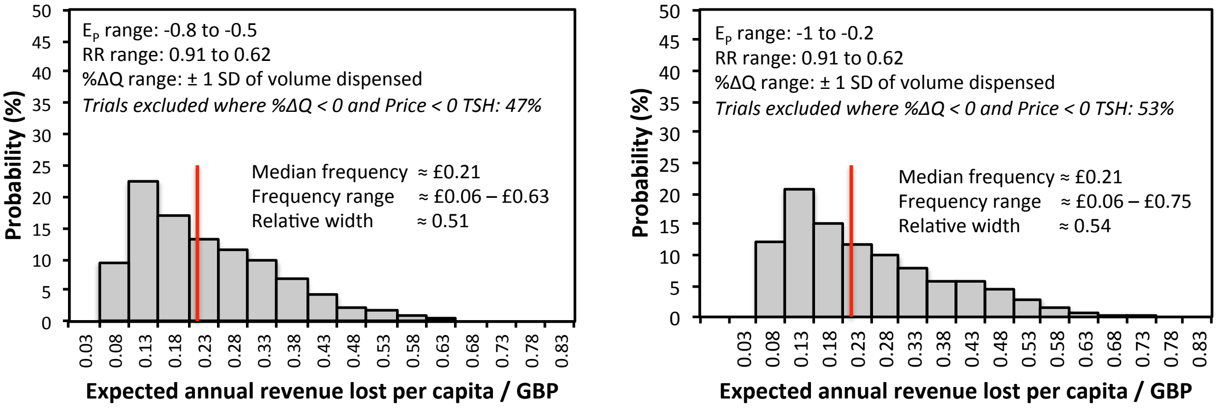
1) Realistic expected ranges of values were selected for each variable input.
    E_P: between -0.8 and -0.5, and between -1 and -0.2, to provide an extreme and less extreme range

RR: between 0.91 and 0.62 (Risebro and Hunter, 2011)

%ΔQ: calculated as ±1 standard deviation from the mean daily volume dispensed in dry months and rainfall months from Community A, with the mean daily volume average for the whole year calculated according to the relationship seen in Community A. ±1 standard deviation is wide enough for uncertainty analysis due to the influence of the other input variables, and because a wider range (e.g. ±2 standard deviations) would generate more results where WDP is inappropriate anyway.

2) Random values within each of these ranges were generated for each input variable and inputted into the WDP decision support tool, and outputs calculated.
3) This process is conducted with new random values for a number of trials with new output results generated for each. 2,000 trials per run was found to give adequately consistent results for the below step. Trials were excluded when the random %ΔQ or suggested price value was below 0% or 0 TSH.
4) Using the set of results from all the trials, the probability distribution of outputs was generated for each output variable. These are presented in Figure 8.8. Relative width is a method to quantify the uncertainty (Schaffner et al., 2009) calculated as standard deviation divided by the mean. A relative width close to zero indicates low uncertainty.

Expected annual revenue lost per capita:



Expected approximation annual cost per DALY averted:

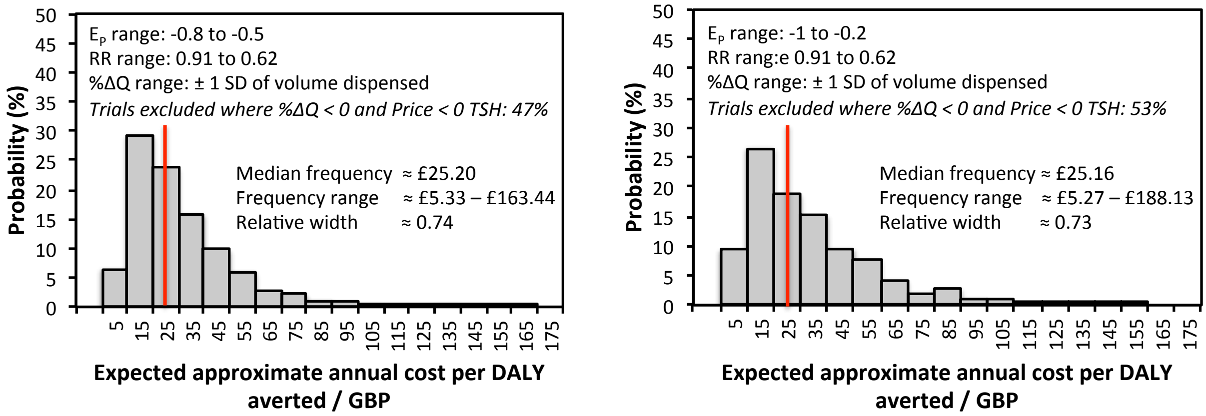


Figure 8.8. Uncertainty of WDP outputs as probability distributions for Monte Carlo simulations for variable inputs; median shown as red line

As expected, the combination of uncertainties of inputs manifests as relatively uncertain outputs. This is seen as high relative width values. The relative width of uncertainty of expected cost per DALY averted is higher then for expected lost revenue because this output incorporates the uncertainty from the likely range of RR values. A broadening of the range of E_P values from -0.8 - -0.5, to -1 to -0.2, does not result in a significant increase in uncertainty, showing this broadening is outweighed by the influence of the other variables on uncertainty. The probability distributions of the outputs are skewed towards lower values. Both the expected lost revenue and cost per DALY averted are therefore more likely to be less, i.e. equally likely to be below ~£0.21 and ~£25.20 respectively.

Practically, this means that despite the large uncertainty WDP is more likely to have less lost revenue and better value, and therefore be more favourable. Uncertainty is expected and does not invalidate WDP at this stage. Refinements from pilot testing would reduce uncertainty. When %ΔQ is a known value with data on volume dispensed from smart meters, (e.g. in Communities A and B) the uncertainty reduces significantly (relative widths ≈ 0.21 and 0.50 for expected lost revenue and cost per DALY averted, respectively).

In summary, annual revenue lost and cost per DALY averted are sensitive to E_P, RR and %ΔQ values, and have significant uncertainties at this stage, however these outputs are more likely to be lower and more favourable.

8.4 Discussion of weather dependant pricing

WDP has been presented and validated as a mechanism for mitigating the negative health impacts of use of potentially contaminated rainwater during rainfall months and periods of heavy rainfall. While there are uncertainties, WDP has potential as a flexible and remote intervention with good value for money. For instance, within the input ranges above the most probable expected annual revenue lost per capita is 0.13 GBP, and the most probable expected approximate annual cost per DALY averted is 15 GBP. The WDP decision support tool has been shown to be a relatively robust method to estimate the appropriateness of WDP in a given setting. It has been shown that WDP could be suitable in a range of settings. Because nothing new is needed once smart meters are installed, WDP is an 'off-the-shelf' intervention that could be most cost effective and easier than other water treatment solutions, and more likely to be culturally appropriate. Significantly, the improved access to water points from smart meters shown in Section 5.5.1 makes price a more significant determinant of collection. This means an unintended knock-on benefit is to make pricing more powerful. WDP directly combines SDG 6.1 with SDG 3.3 ('by 2030, end…water-borne diseases and other communicable diseases').

In order to substantiate this proposal, next are discussed how WDP can be underpinned by direct subsidies, other considerations for effective WDP, and broader impacts.

8.4.1 Novel potential for precise targeting of direct subsidy transfers

Subsidising annual lost revenues and costs per DALYs averted from WDP can allow service providers to maintain cost recovery.

The weigh-up between subsidised service provision on moral, economic, and financial grounds, versus the requirement for cost recovery, economic efficiency, and sense of ownership in service provision, has been well deliberated (Whittington et al., 2012). There is an understanding that subsidising water is not the best policy option to achieve economic or social goals in the long-run (Rogers et al., 2002). Subsidies are beset by implementation problems (Andrés et al., 2019), and moving away from subsidies can aid the move towards full-cost pricing. In rural sub-Saharan Africa, however, the Pigovian economic argument that positive externalities make public subsidies worth the cost can be better made. It has been recently shown that concessionary funding may be necessary for some rural water services (McNicholl et al., 2019). Across this debate, a key research challenge has been identifying service delivery models and technological innovations that make subsidies more feasible (Null et al., 2012). WDP with smart meters can partly answer this. New uses for funds from donors are needed in order to meet the ambition of the SDGs by 2030 (Hope et al., 2020).

With WDP, precisely known lost revenues in communities over precise timescales presents an opportunity to subsidise specific service providers with exact amounts, with 100% efficiency. Digital payment transfers from donors, government, or other development partners on an *ex-post* basis would maximise economic efficiency and cut through administrative and accountability limitations, circumventing long existing routes of financial flows. In this way, subsidies and cost-recovery can be decentralised (Cardone and Fonseca, 2003) while remaining accountable and efficient. Such efficient transfers would cut though the trade-offs between equity, economic efficiency and cost recovery that hinder IBTs (Nauges and Whittington, 2017). Subsidies must be predictable, transparent, targeted, and sufficient (Winpenny, 2011), and WDP with smart meter use can facilitate each of these. Common limitations of water subsidies would be avoided here such as exclusion of households in more remote settings. Similarly, the risk of falsely advantaging richer households with false price blocks (Nauges and Whittington, 2017) is lowered as this is more of a ‘connection subsidy’ (Banerjee and Morella, 2011) than it is a volumetric IBT-based subsidy. Such removals of pricing hurdles could influence poorer households more, who are more at susceptible to health risks. Transfers constitute one of the “3Ts” of revenue for WASH services: taxes, tariffs, and transfers. Blending these can allow for novel financing (OECD, 2009).

Practically, this format of subsidy could be appealing to donors because: 1) it is relatively cheap; 2) decentralised, digital transfers could reduce risks to donors that originate from credit and foreign exchange and therefore increase leverage (Winpenny, 2011); 3) could constitute a form of output-based aid to service providers (e.g. volumetric; ‘payment-by-results’ is of emerging relevance in the sector); 4) the duel benefits of health and financial sustainability are an opportunity to improve the benefit-cost ratio of money spent by donors; 5) it is very compatible with decentralised climate finance schemes (DCF Alliance, 2019) (see below); and 6) it allows direct combination of water and health budgets. It benefits from simplicity and minimal appraisal or M&E for the donor and could be offered as package by a service provider to donors, NGOs, or CSR budgets of companies based on precise projected benefits as above.

Overall, WDP can contribute to a vision of a sustainable local rural water supply system where tariffs are set with cost-recovery in mind but are subsidised in a smart way to maintain use of the DPs during rainfall and top-up reduced revenue collection. This can contribute to a move towards the service delivery approach outlined in Section 2.3.5. In addition, it is theoretically possible to account for any negative prices from very low E_P values (-0.1, -0.2) by paying users to collect clean DP water with credit.

8.4.2 Behavioural considerations, practicalities, and limitations of WDP

Pricing is not the sole mechanism of demand management (Savenije and Van Der Zaag, 2002). Behavioural responses are also significant, and understanding these is important for WDP (Hope and Ballon, 2019). Modern thinking around development interventions suggests that people often make decisions based on emotions and habit rather than rational thought, and impatience and temptation are economically significant (WDR, 2015). For instance, ‘present bias’ pushes harder, longer-term decisions into the future, such as the decision to travel to DPs when free rainfall water is available closer to home. ‘Nudging’ and habit changes from harnessing the power of people’s ‘automatic thinking’ have gained currency with recent WASH interventions, for instance with open defecation, by “strategically increasing friction for undesired behaviours and lessening it for desired ones” (Neal et al., 2016). Utilising this type of thinking is often a key business objective and needs to be considered for incentivising behaviour change with WDP.

A generic conceptual model for behaviour change interventions in the WASH sector at the household level has been developed (Mosler, 2012). This RANAS model is categorised into: Risk, Attitude, Normative, Ability, and Self-regulation. Within this model, WDP specifically targets the behavioural intervention of ‘facilitating resources’ (i.e. making water cheaper or free), which is a ‘self-efficacy’ factor of behaviour change, i.e. improving users’ ability to collect clean water. Pricing cannot comprehensively influence behaviour change.

A recent study in Bangladesh showed that in general there is little attachment to certain unsafe drinking water sources, specifically those contaminated with bacteria (ponds) or arsenic (shallow groundwater) (Naus et al., 2020), and incentivising collection from safer options represents a greater potential for behaviour change. In this instance communication around contamination is proposed as the most effective intervention. In Communities A and B, rainwater harvesting is assumed to have some attachment to users due to convenience but limited by other factors explained by users of temperature and taste. Surface water and wells are assumed to have less attachment than rainwater harvesting. On this basis, it is hypothesised that psychological hurdles to this behaviour change are not insurmountable and will not dramatically reduce elasticity of demand. A more challenging behavioural hurdle is hypothesised to be the process of reintroducing higher p_1 payments on the return of dry seasons because people feel losses more than gains. This could have negative health and revenue outcomes.

Practical application of behavioural considerations for WDP could be use of SMS text messages to users that combine information on pricing and timing with behavioural ‘nudging’ reminders of health impacts of using contaminated water. Other practical considerations of WDP are:

- How real-time price changes at smart meters can be made. Altering the currency-litre conversion factor for Block 2 is more practicable for service providers, however for Block 3 loading with ‘free’ credit for the day gives users the idea of having ‘won’ something that needs to be used[10].
- How a limit for water collection can be set during Block 3 days when water is free. Capping volume dispensed per tag would address this.
- These practicalities will both bear some additional cost, along with sending SMS text messages informing price changes, advertising, and community engagement. For example, SMS texts to 200 mobile phones across a community 10 times over a year could be costed at approximately 140 USD in Tanzania, and 20 USD in The Gambia, based on current average rates. While this may marginally increase net cost of the intervention, such engagement would help incentivise users to maintain use of clean DP water and therefore increase value for money. SMS would be the most efficient way to rapidly communicate, further leveraging the benefit of near comprehensive mobile phone penetration across Africa.
- Users may have less money during the rainy season (common in agricultural communities). This makes Block 2 pricing more significant as it can increase affordability.
- The responsiveness of users to price changes may be greater in communities where the distance to DPs is less of a hurdle, and price is elevated as a determinant of collection. The suitability of settings for smart meters is discussed in Section 9.4.
- Such an intervention requires full engagement with the target community and other stakeholders, along with regulatory oversight and transparency. The service provider should maintain sufficient autonomy to operate and maintain the system (Savenije and Van Der Zaag, 2002).

A further consideration is the extent to which households treat water before consumption at different times of the year, for example by boiling it. This was

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[10] E.g. ‘20 TSH free credit has been put on your tag that can only be used today’

beyond the scope of the research in Community A. However, a reasonable assumption would be that users in rural communities across sub-Saharan Africa are much more likely to want to treat water from alternative sources such as surface water than water from the PWS DPs that is perceived as clean (see Section 6.2). Water treatment incurs a further economic and time cost, particularly if done using a wood fire (which also brings significant indoor air pollution health risks, ecological damage, and wood collection labour for women), which is typical across this context. If this were the case then improved access to clean PWS water during rainfall months would limit the requirement for treatment, and this may be an additional benefit of WDP. Alternatively, if both PWS and alternative sources undergo the same level of treatment (or no treatment) then this further gain is not had. Treatment is not likely to significantly change the conclusions of this study. This would be an interesting area to include in further study of WDP.

Similarly, another consideration for successful WDP is the potential that greater overall volume of water (from whatever source) could be an equal or higher determinant of health gains than quality in these settings, particularly if households are treating water before use. Greater volume might facilitate improved hygiene behaviours. While there is a chance that smart meters might limit overall volume, WDP does not exclude collection from alternative sources, and therefore a comparison between ‘more lower quality’ and ‘less higher quality’ water is likely to be inappropriate here; an exclusive binary choice between the two is very unlikely. WDP aims to increase access and therefore overall volume and incentivise collection of higher quality water. The improved access to DPs from smart meters should only improve users’ ability to collect greater volumes. This would be a valuable area for further study, perhaps during WDP pilot testing.

Any risk of competition between smart meter service providers regarding water pricing for consumers (as opposed to the costs of smart meters themselves, see Section 2.5.6) is currently limited for two main reasons: rural consumers (i.e users) are not exposed to choice between different providers, and pricing remains determined by the existing service provider. Competing service providers with the same consumer base may optimise pricing based on profitability rather than user access or cost-recovery, however this will not be the case here. Pricing, as discussed in Section 5.4.3, is under the remit of the community management committee or national/district legislation; the factors behind tariff design have been discussed in Section 8.1.2.

A typical profit margin that results from smart meter projects in this context is not available, and would be incomparable to more traditional ‘smart metering’ done in water networks in the developed world. Considering that the aim of smart meter projects is to improve rural water service rather than fulfil private profit motives, and that projects are more *ad hoc* and decentralised, added revenue should be used for service improvement and sustainability. This is the ethical basis for profit margins in this context, and as discussed in Section 8.1.2 this is dependent on the management model in place and local pricing legislation.

As assumption might be that if adequate rainwater harvesting approaches are adopted in this context that improve quality, then the need for WDP is negated as the free alternative rainwater source becomes more appropriate. This assumption is limited for two reasons. Firstly, even improved harvesting infrastructure such as closed tanks, guttering, and proper roofing do not guarantee improved quality. More permanent and well-designed harvesting infrastructures in the developed world have still been shown to contain a diverse range of pathogens (Dobrowsky et al., 2014), and this risk is heightened in these rural settings. Secondly, such infrastructure and training has a high time and financial cost (let alone O&M costs), and, while some actors are promoting such interventions, the currently limited scale of roll-out shows that this cannot be an immediate solution. Furthermore, this cost would be more likely born by households themselves. Inversely, WDP is ready to implement in communities with smart meters, requires no additional hardware, and incurs no additional cost to consumers beyond normal water price.

WDP is only proposed as an additional tool for practitioners. There are limitations for its application and potential to create behaviour change:

- Effectiveness rests largely upon the existence of an elastic water demand. It is impossible to accurately estimate E_P and there is a possibility that elasticity will reduce at lower prices. Additionally, in Community A, some users reported using their tags until the credit runs out without knowing the exact price, which may reduce their responsiveness. Fundamentally, rainwater remains free. Similarly, costs of collection are not only monetary, and they include lost productive time and energy.

- Decision of the start and end dates of Blocks are subjective. Basing them on weather forecasts incorporates new inaccuracies. Furthermore, subsidies from funders need to be transferred *ex post*. However, recent work has shown the potential of forecasting seasonal rainfall magnitude for water management purposes using observed climatic conditions over the preceding months (Taye et al., 2020).
- Water is not only used for consumptive purposes, and low income households may only pay for clean water for drinking and cooking (as shown in Section 5.4.1; also Elliott et al. 2019), while continuing to use unimproved sources for washing and bathing purposes. The determinants of water collection behaviours vary between seasons (Arouna and Dabbert, 2010). This may therefore result in relative risk (RR) closer to 1.00. However, overlap and variability of uses means that even a small impact would still go some way to reduce health impacts.
- Household based interventions are often more effective for health impact than point of sources (Clasen et al., 2007b), however the comparison against other interventions appears favourable in terms of cost per DALY averted.
- Fundamentally, WDP requires fully functioning PWSs throughout the year, as concluded in Section 5.5.3. Additionally, smart meters are only currently deployed in a handful of communities across sub-Saharan Africa. However, these conditions are likely to be increasingly met.

Overall, the potential scale of knock-on benefits is large. While WDP may have some additional complexity regarding implementation, complexity in itself should not be a barrier. Instead, WDP is an additional sophistication that is now available with smart meters.

8.4.3 Broader potential impacts and contribution of WDP

There are some broader benefits to communities from WDP:

1. Reduced prices are likely to influence poorer households more who currently have affordability constraints. Therefore, this community-wide intervention could help poorer households more who tend to be more susceptible to health risks. This potentially makes WDP a bridge between the competing notions that a) water is a human right, and b) water is an economic good.
2. Combining transfers that directly subsidise WDP with emerging performance-based funding programmes (McNicholl et al., 2019), whereby greater annual clean water consumption could in-turn unlock more financial transfers, could bring local water supply into positive feedback loops.

Five key considerations for water tariff design in developing countries are: public acceptability, political acceptability, simplicity and transparency, net revenue stability, and ease of implementation (Boland and Whittington, 2000). For the reasons provided, WDP either strengthens these (e.g. stabilises annual revenue) or can be tailored to different community contexts.

In summary, the findings presented are relevant in guiding future deployment of smart meters in a sustainable and nuanced manner that is considerate of increasing variability of rainfall and the ‘use’ data from smart meters (the need for this was shown in Section 2.5.4). WDP can add to the toolbox of the move towards professionalised service delivery. It is envisaged that WDP will grow in relevance as more smart meters projects are deployed across sub-Saharan Africa.

8.5 Weather dependent pricing and climate change resilience

Maintaining clean water supply year-round in sub-Saharan Africa is crucial for resilience to climate change. WDP therefore has the potential to build resilience against the impact of climate change. There is a growing need for new solutions to climate change resilience, and the potential of WDP as a smart solution is outlined in this section.

There is an urgent need to improve climate change resilience in rural water supply, and new projects need to take climate risks into account (Howard and Bartram, 2010): this includes smart meters. The term ‘resilience’ has been variably used, but is essentially the degree to which a system minimises the level and duration of some failure (as outlined regarding water management by Butler et al., 2017). Climate change constitutes a ‘chronic-external’ threat to the rural water supply system (Butler et al., 2017). As the rural water supply system is based in a broad socio-economic context as outlined in Chapter 2, then resilience of this system to climate change must also be broad, incorporating community health, affordability of clean water, and ease of management.

Overall, WDP can be a significant component of climate change resilience in rural communities, alongside other physical engineering, socio-economic, and governance solutions. Currently, data collection especially for groundwater is missing, and there is a lack of usable instruments to support climate-water decision-making (GWP and ODI, 2019). WDP can be a mechanism for combining WASH system strengthening (discussed in Chapter 9) with climate change resilience, in alignment with the holistic objective of the SDGs, and can operate between the silos of water (SDG 6), health (SDG 3) and climate change (SDG 13) in a cost-effective way.

8.5.1 Predicted impacts of climate change on rural water supply in sub-Saharan Africa

The impacts of climate change in sub-Saharan Africa are: 1) increasing intensity of rainfall, 2) greater rainfall variability across time, duration and distribution, 3) longer-term decline in rainfall and run-off, and 4) sea-level rise (Oates et al., 2014). One of the more consistent and observed impacts of warming in tropical regions is an intensification of heavy rainfall (Fischer and Knutti, 2016). Climate change can increase the intensity of rain in storms over sub-Saharan Africa due to greater moisture content in a warmer atmosphere (Kendon et al., 2019). This predicted shift from lighter to heavier rainfall is pronounced in Africa-wide modelling (Jackson et al., 2020). This manifests as more frequent heavy rainfalls and fewer light rainfalls, and results in reduced soil moisture with more frequent and intense droughts and floods. Block 3 will increase in relevance as a form of climate resilience to more heavy rainfall events.

In Tanzania, application of 34 global climate models present widely different predictions for future rainfall, showing that variability makes generalisation inappropriate (FCFA, 2017). 11 models project lower rainfall and 23 project higher rainfall. Most show change of at least ±5% by the 2040s. Projections for temperature changes show less variability than rainfall in time and location. Climate change has been estimated to double the risk of extreme drought events in parts of east and southern Africa (Kolusu et al. 2019). In The Gambia, inter-annual variability also makes trend analysis difficult, however, mean annual rainfall across the country is predicted to decrease by around 8% by 2050, particularly in the rainy season (McSweeney et al., 2010), but with heavy rainfall events projected to make up more of the total annual rainfall. West Africa is already experiencing extreme rainfall variability (FCFA, 2020).

Rural water supply in sub-Saharan Africa is vulnerable to climate change on different levels (IPCC, 2014). Environmental impacts of increased rainfall variability centre on water resource availability, and include putting more pressure on infrastructure. This can lead to reduced access for users. Furthermore, floods and droughts can destroy infrastructure with inundation, or sedimentation and burnout of pumps. The impact of climate change on rural water supply is also predicted to exacerbate health risks that originate from contaminated water. More extreme rainfall events increase the likelihood of contamination from runoff, overflow, re-sedimentation and other mechanisms that mobilise pathogens (Levy et al., 2016). The costs of treating the predicted increase in diarrhoeal diseases, malnutrition, and malaria due to climate change by 2030 are estimated to be between 4 to 12 USD billion (Ebi, 2008).

It is less well understood how climate change will impact the broader rural water supply system. The ‘wicked problem’ nature of rural water supply outlined in Section 2.2.7 means that climate change exacerbates systemic risks and puts stress on the underpinning system. For instance, rainfall shocks have caused agricultural GDP to drop potentially 10% in Ethiopia (Borgomeo et al., 2017), and the agricultural sector in Tanzania suffers annual losses of approximately

200 million USD due to droughts and other weather-related incidents (World Bank, 2017c). Less available finance at a local level can decrease affordability for users and reduce revenue collection.

8.5.2 WDP contribution towards climate change resilience

In general, the smart meter benefits presented in Chapters 2 and 5, i.e. more effective revenue collection, access, and monitoring/service provision, will help build resilience of rural water supply systems to climate change at the local level. Furthermore, PWSs (which smart meters supplement) provide greater resilience than other ‘improved’ surface or shallow water sources.

Broadening adaptive measures beyond physical engineering in the rural water supply system is also critically important. New management models for service delivery are called for to further reduce risks (Howard et al., 2016). Behaviour change is as important as physical engineering solutions. WDP can be a mechanism to improve communities’ climate change resilience to impacts on water, health, and economics because it aims to improve the use of clean water, reduce health impacts, and improve access. WDP has potential to build systemic resilience to climate change on a local level in two further ways:

1) The flexibility of the Block start and end times can accommodate the predicted increase in extreme rainfall events and rainfall variability, and can be implemented by service providers in a flexible way, therefore facilitating adaptive management. As shown, Block 3 tends to result in less lost revenue than Block 2, and could therefore be a nimble and cost-effective direct method for adaptation to unpredicted heavy rainfall.
2) Lower prices during rainfall months over Block 2 could lower affordability hurdles to access, and therefore aid financial resilience of users.

The adaptability of both the degree of WDP implemented (i.e. price change) and the timing makes it well suited to address the duel challenges of increasing extremity and unpredictability of weather events. Furthermore, less predictable rainfall is postulated to reduce user’s reliance on domestic rainwater harvesting (Kisakye et al., 2018) which can act in tandem with WDP.

WDP can be extended in the inverse direction for droughts, which are of particular concern in regions such as the Horn of Africa. For instance, there is potential for integration of WDP with programmes like the Sweetsense-enabled drought monitoring in Ethiopia and Kenya outlined in Section 7.1.4 (Thomas et al., 2019).

Researchers have pointed out that access to multiple water sources can also be important for resilience (Elliott et al., 2017; 2019), because of the lower likelihood of all sources become unavailable at once during an extreme weather event. WDP does not block the use of alternative sources, and therefore would not diminish this component of resilience.

8.5.3 WDP and groundwater as a buffer to climate change

Clean PWS water, and therefore WDP, relies on groundwater supply. Groundwater is the major source of domestic water in rural sub-Saharan Africa. Its availability is subject to dynamic interplay between aquifer recharge and abstraction. Detailed knowledge of these resources at the local level across sub-Saharan Africa remains low and is subject to complex hydrogeology (MacDonald et al., 2012). In Tanzania, accurate information around groundwater availability is lacking (Nachmany, 2018). Individual communities are subject to local recharge rates and precipitation-infiltration relationships, e.g. aquifers of coastal communities are more at risk of saline penetration (Ferrer et al., 2020).

At a general scale, however, recent research shows groundwater availability to potentially be a buffer to the impacts of climate change on water resources in sub-Saharan Africa. This is contrary to the ‘high certainty’ of decreasing water resources in most dry sub-tropical regions that is prescribed by the IPCC (Jiménez Cisneros et al., 2014). Isotope analysis has shown that mean residence times of groundwater in sedimentary and basement aquifers in West Africa have great resilience across inter-annual precipitation variance, and that they have the potential to sustain abstraction (Lapworth et al., 2013). GRACE (Gravity Recovery and Climate Experiment) satellite data, which uses precision measurements of gravity, showed no evidence of decline in groundwater storage in any major sedimentary aquifer in Africa over the past 20 years, indicating that there is insignificant stress from current rates of abstraction (Bonsor et al, 2018a). Furthermore, multi-decadal hydrograph time series across the region show that recharge tends to be largest following *intense* rainfall (subject to local aridity and geology) providing more evidence for general groundwater resilience to increased variation in rainfall intensity (Cuthbert et al., 2019). Borehole sensors have demonstrated fast recovery and residence times in rural Ethiopia and the subsequent resilience to drought conditions (MacDonald et al., 2019). Some researchers claim that in most sub-Saharan African countries current groundwater abstraction remains less that 5% of a national sustainable yield (3.3% in Tanzania), which is actually far too low considering the developmental benefits (Cobbing and Hiller, 2019). Therefore groundwater abstraction should be encouraged.

This 'silver lining' of groundwater buffering the impacts of climate change means that, in a general sense, PWS reliance on groundwater can uphold WDP, and WDP can help turn or maintain demand towards groundwater rather than surface or harvested rainwater.

8.5.4 WDP and climate change finance

Local resilience to climate change is underpinned by access to finance, and WDP could strengthen the case for channelling dedicated climate finance to local rural water supply projects, particularly from multilateral climate funds. This is predicated on the efficiency of direct transfer subsidies outlined above. Currently, only about one fifth of overall climate finance is directed to adaptation, and a small proportion of this is used on WASH interventions (WaterAid, 2020). There is a noted lack of integration between water and wider climate-related finance (GWP and ODI, 2019). Innovative, blended finance solutions for water and climate can help to leverage investment. Devolved climate finance whereby finance is distributed more directly to local level partners benefits from local knowledge and increased value for money (DFC Alliance, 2019; Soanes et al., 2019). WDP represents an opportunity for very devolved climate finance, e.g. potentially to individual DPs or tags.

8.6 Conclusions and novelty of work

The conclusions from this chapter are as follows:

- Weather dependent pricing (WDP) has been conceptualised, developed, and validated. WDP is designed to incentivise users to maintain collection of clean DP groundwater over rainfall periods rather than turn to potentially contaminated alternative water sources such as rainwater harvesting. It is hypothesised that this could improve community health.
- WDP is premised on Block 1: baseline pricing in dry months; Block 2: discounted water prices over rainfall months; and Block 3: free water on days of heavy rainfall. This is based on findings from Chapter 7.
- Lost revenue (i.e. cost) in Community A of Block 3 is estimated at 9% of annual revenue, and Block 2 at 4 to 44% depending on price elasticity.
- Approximated ‘costs per DALY averted’ are comparatively low against other water quality interventions (e.g. 14 to 55 GPB, at RR = 0.75), dependent on price elasticity (E_P) and relative risk of disease (RR). Costs of WDP are likely far out-weighted by expected economic benefits.
- An accompanying WDP decision support tool for additional communities has been designed and presented. This tool provides recommended price changes and costs for inputted community characteristics.
- WDP was tested for 12 hypothetical scenarios showing that the best value for money from WDP would probably be had in communities where rainfall months have relatively low influence of volume collected from DPs ($\%\Delta Q$), and where users respond strongly to small price adjustments (i.e. high elasticity). Communities of different sizes would be suitable.
- Sensitivity analysis shows WDP outputs are sensitive to E_P, RR, and $\%\Delta Q$. Uncertainty analysis shows WDP outputs are relatively uncertain at this stage but probabilities tend towards to lower costs and better value.
- Precise targeting of direct subsidy transfers for specific costs per community would facilitate WDP. WDP has the potential for systemic change, to help realise gains of smart meter projects, to strengthen rural water supply systems, to contribute towards climate change resilience, and to be supported with 100% efficient finance transfers.

As far as evident, pricing is not recorded anywhere as being used as a direct tool to incentivise the use of clean water sources in this manner, nor as a dynamic response to weather. WDP has now been made possible by smart meters, specifically by their remote price changes and potential for direct subsidy. This is an additional benefit of smart meters. This work goes beyond the monitoring, which so far has highlighted problems in rural water supply, to provide a potential solution.

In the next chapter, this concept of smart meters as solutions is scrutinised.

8.7 Further work on WDP

While it has been possible to quantify the influence of rainfall on volume dispensed in Chapter 7, empirical understanding of elasticity and relative risk of disease are not possible. Therefore, expected lost revenues and costs per DALY averted are caveated by significant uncertainties, which have been presented. Further work that would refine WDP is as follows:

- More continuous data collection from smart meters into the future can add accuracy and granularity to the relationship between rainfall and volume dispensed.
- WDP should be tested in its operating context to properly investigate the effectiveness of the intervention. Randomised controlled trials (RCTs) are preferable to single pilots and WDP could be tested in a number of communities with smart meters with randomly assigned controls. Data collected should include volume dispensed from DPs and meteorological data, along with questionnaires on water use practices and health that are implemented before and after price changes in the communities. Health clinic records could also indicate impacts on diarrhoeal disease. The challenges of these requirements inhibit full testing now. This testing would also provide necessary understanding of the practical challenges outlined above. Discovering that WDP does not work would be an equally valuable finding.

- RCTs would allow for a more detailed economic investigation into precise elasticity values in specific communities.
- An economic analysis of how much users top up pre-payment tags during rainfall months could provide insight into seasonal payment.
- Understanding behaviour change in this context could better show how different WDP implementation could change collection of clean DP water. Harnessing 'automatic thinking', i.e. effortless/associative, and how decision-making is based on changes in values from other reference points (e.g. rainwater harvesting) can lead to more effective development interventions (WDR, 2015).
- Further analysis on the time of collection from DPs during days of heavy rainfall could provide insight into how SMS communication could be timed.
- For PWSs with solar pumping, WDP could be a method of combining the timings of supply side pumping with demand. Solar pumping may be affected more often in rainfall months due to reduced sunlight from cloudy days; even across successful solar pumping systems 53% of systems are reported to have experienced issues with seasonality (UNICEF, 2016).

Chapter 9. RESEARCH IMPLICATIONS AND FURTHER DISCUSSION

9.1 Introduction

Chapter 2 demonstrated the need for: further independent evaluation on smart meters, evaluation of technical robustness, use of smart meter data for insights into water collection, and for insights into, and management, of seasonality. Each of these research gaps has been systematically addressed in Chapters 4, 5, 6, 7, and 8. Overall, the approach of combining technical, socio-economic and environmental factors in the research has given a more comprehensive picture of how smart meters can improve rural water supply. The approach has provided greater insight into smart meter operation and allowed additional outputs such as weather dependent pricing, and has promoted the notion of systems thinking.

A counterbalance to these and to hype around the new technologies is needed. It is important that decision makers avoid simple assumptions around smart meters, such as uniform suitability or that they are interventions isolated from the rest of the system. Understanding suitable context for deployment and other fundamental challenges can help avoid the ‘valley of death’, i.e. failing to scale up from endless pilots, which is commonly seen with rural water supply innovations (Murthy et al. 2018).

The purpose of this chapter is to propose broader considerations for effective smart meter deployment. This builds on the previous chapters and pulls the different research strands together. This chapter is relevant for practitioners, funders, and decision makers, and the following are investigated:

- The implications of the findings for more general smart meter deployment and operation into the future
- Suitable settings for smart meter deployment
- Broader contextual considerations for successful smart meter operation
- How smart meters can strengthen rural water supply systems.

It is reasonable to assume that more smart meters will be deployed across sub-Saharan Africa, and this field of research will therefore grow in relevance. New smart meter providers and models are likely to emerge, and research is likely to move beyond evaluations towards development of new uses of data, remote management, and finance. It is challenging to predict growth and deployment of smart meters. This could follow the 'diffusion of innovation' S-shaped curve that has been the trend for similar technological innovations such as electricity smart meters (Spodniak et al., 2014). This model follows a bell-shaped product uptake pathway through 'innovators', 'early adopters', 'early majority', 'late majority', and 'laggards'. Less simply, soon after product 'take-off' a 'saddle' is possible due to unforeseen market forces (Peres et al., 2010). Rural sub-Saharan Africa tends to lag behind the developed world in the 'Ease of Doing Business' indexes (World Bank, 2020), and is strongly non-homogeneous, meaning that assumptions of the traditional S-shaped diffusion model may be inappropriate. Smart meter market penetration also relies on PWS construction, and is therefore tied into a complex ecosystem of NGO/agency support, local governance, receptivity to innovation, and available finance. This is in keeping with the complexity of rural water supply, outlined in Section 2.2.7. In any case, sector professionals have a growing interest in smart meters for rural water supply, and the research here will have growing relevance and potential for impact. Now is a key time to consider contextual challenges.

9.2 Potential applications of the research findings

Translating research into practice is important for progress towards SDG 6 (Sadoff et al. 2020).

In Chapter 2, the literature review revealed the need to develop new potential for 'analysis & reporting' and 'use' of data collected by IoT-enabled innovations in rural sub-Saharan Africa. This potential has been developed in Chapters 4 to 8 by:

- Using smart meter data to research technical questions around the smart meter itself, in turn ensuring quality of data collected
- Pattern analysis of water collection in communities, including novel combination of smart meter data with information from users
- Analysis of seasonality of water collection in communities, providing a basis for weather dependent pricing.

Furthermore, the research has demonstrated the value of smart meters as direct ‘research instruments’ in the field, which has also not be previously emphasised. This has great potential to unveil new understandings of rural water supply and ways to improve it; for instance, quantification of seasonality has allowed for precision-design of weather dependent pricing, and high precision data has showed precise time of water collection.

Table 9.1 presents potential ‘real-world’ applications of the research:

Table 9.1. Potential applications of the research

	Potential application
Technical findings (Chapter 4)	• Validation of accuracy of measurement. • Accuracy findings showed that remote calibration of individual smart meters, or all smart meters in a project, can be a done by smart meter providers or service providers. This means that software solutions can be used to overcome physical hardware limitations, which may be much more practicable. • The findings that flow rate is negligibly impacted by insertion of a y-strainer has application for smart meter design, and also opens up the possibility of addition of other useful components to smart meters (discussed in Future Work in Chapter 10). • Future choice of y-strainer gauze size can be tailored to specific debris in different PWSs, based on the findings presented. • Real-time measurement of flow rate reduction can be used by smart meters for predictive management for y-strainer

	cleaning or other maintenance requirements, and help eliminate non-functionality. Empirical findings here can provide a basis for predictive software or machine learning.
Socio-economic evaluation (Chapter 5)	• The findings strengthen the evidence that smart meters bring benefits to rural water supply and the community. Positive findings from demand from managerial stakeholders, user experience and demand, and accessibility can inform future project design and help support the case for smart meter installation. • The demonstration of the importance of the COWSO and the underpinning of the PWS presents new evidence that service still fundamentally depends on local service providers and a well-functioning PWS. Smart meter projects should therefore prioritise PWS functionality and background service provision (e.g. community committee). • The evidence that smart meters can improve access for marginalised populations is significant for decisions based on equity. It was shown that reduced collection times essentially elevate the overall service level from limited to basic which are significant metrics for decision makers.
Patterns of water collection (Chapter 6)	• The variability shown of volume collected can influence future design of PWSs of larger pumping and storage capacities as a buffer to variability and to ensure supply stays greater than demand. • The finding that number of households is a better indicator of volume dispensed per DP can influence better DP positioning than arbitrary siting at certain positions in the community. • Specific findings such as time of collection or volume collected will differ between communities, but variability itself can apply to future planning of DP positioning to reduce marginalisation. • Combination of survey data with smart meter data to reveal new insights and hone specific assumptions can be a

	method employed by managers to improve monitoring and service delivery. - These findings demonstrate that smart meters can be used as ‘research instruments’ in the field
Seasonality and weather dependent pricing (Chapters 7 and 8)	- Further detailed evidence of a general decrease in clean water collection from PWSs during rainfall periods can be applied to decision-making around seasonal management, O&M, installation, and funding. - This detailed finding informs the timing of PWS or smart meter installation to harness a natural uptick in water collection after rainy seasons. This could apply in communities near existing smart meter projects. - WDP as a pricing mechanism can be adapted and applied for any smart meter in many different settings as outlined in Chapter 8, and is an ‘off-the-shelf’ intervention for health, climate resilience and rural water supply with strong potential to cheaply reduce the community disease burden. - This is further evidence that smart meters can be ‘research instruments’, and also tools for remote management aimed at additional development objectives.

In total, this provides good evidence that smart meters can aid a shift towards a service delivery approach.

9.3 Summary of benefits of smart meters

Table 2.16 in the literature review (Section 2.5.6) summarised the three main benefits of smart meters that were found from current evaluations. Now, the research here has contributed further evidence to these existing points; and Points 4 and 5 can be further added. These benefits are interlinked, and presented in Table 9.2.

Table 9.2. Benefits of smart meters

Benefit	**Reason**
1. Improved revenue collection	Pre-payment improves efficiency, reduced non-revenue water. Better accesses increases volumes collected.
2. Improved access to water point/DP for users	Anytime access because removal of short availability window and queue time. Improved finance and management improves access.
3. Improved monitoring, management, and service delivery	Accurate, real-time, precision monitoring improves O&M and decision-making. Improved revenue collection means better financial decisions and capacity.
4. Additional functionality for research purposes	Newly available high-quality data from ‘research instruments’ in the field, useful for planning objectives. (Further explained in Sections 6.4.2, 7.1.4, and 7.4).
5. Additional remote management functionality	Newly available ability to remotely change price and other factors, in combination with new research findings, e.g. with weather dependent pricing, or using software solutions for hardware problems. (Further explained in Sections 4.5.1, 4.5.3, and Chapter 8).

Some of these benefits could potentially be achieved individually by other non-smart meter solutions. For instance, monitoring could be done using traditional data loggers, or user access could be improved using e.g. coin-operated water dispensers. The inappropriateness of these alternative approaches for the context under study has been highlighted in Section 2.5.6. It is the combination of all of these benefits listed within one technological innovation that is the unique, real added value of smart meters. It is this combination that makes smart meters feasible in this challenging context in the first place, and therefore has allowed the data collection used in this research, improved access, and improved revenue collection.

9.4 Suitable setting for smart meter deployment

Selecting forms of service delivery that best fit the community context is key for sustainable rural water service provision. This is in line with the systemic nature of rural water supply outlined in Section 2.2.7. The findings from Chapters 5 and 6, along with existing research outlined in the literature review, provides some early evidence of what community context smart meters would be most suitable for deployment in over upcoming years. This can inform programme design.

Figure 9.1 shows a proposed community setting range where smart meters are proposed to be beneficial. This is between very rural communities and peri-urban/urban settings. Baseline service levels tend to be higher in urban areas and lower in rural areas.

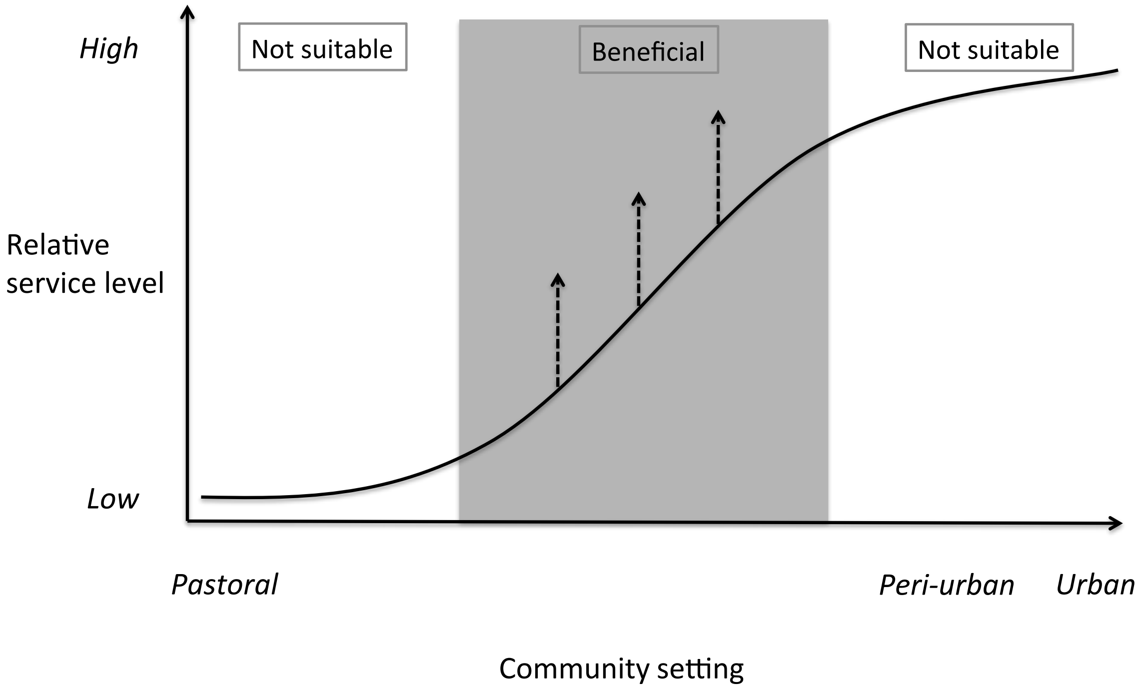

Figure 9.1 Representation of community context where smart meters are more and less likely to be suitable, against approximate service level

In very rural or pastoral communities on the left side of the curve smart meters are less likely to be suitable for the following reasons:

- Smart meters require connection to DPs of a PWS. PWSs are less likely to be constructed in very rural settings because of constraints of logistics, finance, local government, and power dynamics. The relative numbers of PWSs, handpumps and other sources have been discussed, but one survey of primary sources of water in central Tanzania gives standpipe (i.e. PWS) as only 48.6% (Young et al., 2019). This is a current engineering limitation and a future limitation to upscaling.

- As demonstrated in Section 5.5.3, the PWS must be well functioning or benefits from smart meters are lost. O&M tends to be more limited in very rural areas far from urban centres (Foster et al., 2018) because of transport logistics and access to spare parts and expertise.
- Along with well functioning PWSs, a fully functioning community water organisation (dependent on local governance) is essential, however such capacity is not uniform: in (mainland) Tanzania there are only about 3,000 COWSOs serving about one quarter of the ~12,300 villages (Kwezi, 2020). In Tanzania, water point functionality decreases in more remote areas where the District Water Department has responsibility for greater numbers of people (Impact Tanzania, 2017b).
- Adequate revenue collection is important as shown in Section 5.4.2 and Section 5.5.4 and very rural communities are less likely to be able to overcome affordability barriers.
- Smaller, more dispersed and isolated communities are less likely to be commercially viable and therefore of less ‘interest’ for utilities and the private sector (AguaConsult and WaterAid, 2018).
- Programmes in very rural communities are likely to have had a pre-existing emphasis on handpump provision, which (if still operational) could act to undermine smart meter revenue collection. Additionally, government mandated self-supply models (World Bank, 2017) would similarly undermine smart meter effectiveness.
- Specialist technical staff are likely to be needed along with programmes of community engagement. This could include the predictive maintenance outlined in Section 4.6.3, for example. Long distances of travel are a practical limitation (Foster et al., 2018).

These limitations mirror longstanding reasons why very rural communities are often left behind.

In more urban contexts on the right side of the curve smart meters are less likely to be suitable for the following reasons:

- Smart meters in more built-up settings would be part of a larger-scale municipal supply system. This does not exclude consideration of smart meters by themselves; (non-IoT) pre-payment meters have shown some potential in urban sub-Saharan Africa (Heymans et al. 2014) especially when compared to standard metering (Hanjahanja and Omuto, 2018). However, all of the existing complexities of management, governance, community engagement, and other systemic necessities are magnified, making the addition of smart meters more complex, which is therefore more likely to outweigh benefits. Greater population density, variation in wealth and water use, variable migration, and growth make this a more complex system. Service provision must fit within the operating system, and greater complexity makes this less likely.
- Management of water supply at the municipal level is complicated by a larger variety of service provision, i.e. DPs are not the sole water source in towns and cities. Household connections, tanker deliveries, and kiosks, all with different pricing, undermine sustainable revenue collection from smart meters. This is already being seen for a smart meter project in an urban setting in Tanzania, where additional household connections increased from 122 to 300 between February 2019 and August 2019, which could mean that the service provider “will soon limit their efforts in maintaining the [non-household] prepaid kiosks or even abandon them altogether” (Komakech et al., 2020). In another large Tanzanian town, only 37% of households use pre-payment kiosks compared to approximately 92% in rural Community A (Section 5.4.1). Further evidence in Dar es Salaam shows a downward trend of smart meter use compared to a comparative rural setting, most likely because of increasing household connections (Check et al., 2017). Such pressures severely limit sustainability.
- Municipal piped networks and management are extending outwards due to increasing urbanisation of rural areas, government pressure, and growing demand for piped services (Moriarty, 2020). While this is a positive step for peri-urban communities, it puts these same pressures on smart meter effectiveness in these zones. Rapid urbanisation in sub-Saharan Africa increases this pressure.
- One extreme but significant negative outcome of pre-payment meter operation (let alone smart meters) in urban contexts in instances where

broader systems were not fully considered has been civil strife and unrest. Major civil unrest because of pre-payment meters has been documented in Ghana (Shang-Quartey, 2017) and South Africa (Von Schnitzler, 2008) triggered by pricing problems, poor accountability and implementation, curtailment of services, restrictions to rights to water, cut-offs on non-payment, and constant metrological scrutiny of users. This challenge interfaces with other complex socio-political and economic concerns such as external imposition of economic ‘structural adjustment’ and local democracy, and is therefore another manifestation of the wicked problem outlined in Section 2.2.7.

While urban areas have more households and users, and therefore a potential for some ‘economies of scale’ regarding the number of smart meters possible, socio-economic benefits, and revenue for the service provider, the reasons listed above are likely to negate this potential. Specifically the greater complexity and competition from household connections and other sources are likely to undercut these impacts, or result in unsustainability as postulated in Tanzania (Komakech et al., 2020). Smart meters will therefore be most effective in settings where only one PWS serves a community without other competing sources; the larger such a community then the greater the potential for successful ‘economies of scale’. This is an important consideration for policy makers and planners. (Some smart meters, e.g. CityTaps, are specifically designed for household connection in urban settings, and have different challenges and research questions.)

Between these two settings smart meters can be suitable and also best allow the benefits of smart meters expounded above. The central section of the service level curve in Figure 9.1 can be raised by the positive feedbacks established from revenue collection, monitoring, accessibility, and data use. This is contingent on a well-functioning PWS and management, adequate water resources, and the other systemic attributes required. For example: a suitable community for smart meter installation would be located away from encroachment of municipal utilities but close enough to urban centres for O&M, banking services and community engagement, and be served by one PWS with a well-designed borehole, pump, tank, pipework and DP siting, adequate groundwater resources, and a well-trained management committee or external service provider.

Understanding which settings smart meters would be beneficial can help programme designers select if and where smart meter deployment is appropriate, and can also provide focus for smart meter providers. Saliently, deployment in non-suitable contexts is likely to reduce service levels for the reasons listed above. Innovations that ignore rural areas, which is common with new technologies (Ali et al., 2018), will remain unable to scale. Urban settings are often more financially viable for water service providers because of higher economic activity, populations, and willingness to pay for services. This provides greater incentives for smart meter providers to follow projects in towns and cities. It would be easy, therefore, for decision makers to overlook the challenges of smart meter operation in urban settings compared to rural ones. The potential amplification of marginalisation of some communities over others due to non-uniform suitability of smart meters is discussed further below.

9.5 Broader considerations for smart meter success

In addition to the suitable community setting and specifics of implementation and management, there are broader factors that can influence smart meter success over upcoming years. Researchers have recognised the need to overtly consider contextual factors in WASH research (Setty et al., 2019). Smart meters can be considered successful when they have scaled up and provide benefits to service provision over a long time.

9.5.1 Contextual considerations

Such broader questions have begun to be examined and recent work has developed critique of smart meter deployment, specifically in Tanzania (Komakech et al., 2020). It is argued that smart pre-payment meters are not panaceas for sustainable and equitable water services. The relatively high price (at the time of research) and the fact that this capital expenditure (CapEx) has come from non-recoverable donor funding were highlighted as limitations, alongside case-specific financial flow transparency issues. While these criticisms are valid (indeed it is unreasonable to expect any single technology to be a panacea) they are largely based on limitations of implementation and finance. A more fundamental consideration of factors for smart meter success is required that goes beyond criticisms of individual business models and CapEx, which can have relatively tractable solutions. Assuming that smart meters will continue to penetrate the rural water supply system over upcoming years, a deeper understanding is needed to inform perceptions of the technology, and this is developed here.

Smart meter providers understandably focus on their technology and product development. Like technologically minded stakeholders elsewhere, they are more likely to consider the product as an isolated intervention. It is argued that these actors are more likely to see smart meters as a uniformly positive opportunity, disregard red flags, and not understand underlying challenges (Mushamba, 2019; Whittington et al., 2012). This has been described as "techno-deterministic process that attempts to construct a new reality for rural water service provision" (Komakech et al., 2020).

In fact, smart meters are only at best supplementary, and no substitute for strong rural water supply systems (this is discussed more in Section 9.5.2 and 9.6). Indeed, smart meters are adding more complexity to an already complex system, which brings additional risks. The benefits of smart meters will come to nothing without a strong rural water supply system already in place. Even when the smart meter technology is perfect, no individual components of the system can act to strengthen the system alone. Further, when rural water supply is considered as a wicked problem, explained in Section 2.2.6, isolated smart meter deployment that doesn't account for the rest of the system cannot be seen as making any progress at all.

Many development projects based on a technology fail because of single-minded focus on the product itself and a failure to take the context fully into account (Sharpe et al., 2019). The fact that technology can never be a silver bullet in this system is evident with the stagnation of service levels in rural areas despite technological innovations elsewhere in the rural water supply system over previous decades such as acclaimed new handpump designs. There some is recognition from professionals in the sector that smart meter or pre-payment technologies cannot be quick fixes or silver bullets (Heymans et al., 2014; Kwezi, 2019). This is in tune with the emergence of systems thinking in rural water supply outlined in Section 2.2.7.

Table 2.4 in Section 2.2.6 showed that 'every wicked problem can be considered to be symptom of another problem', and in this sense there is a nesting of contextual challenges to smart meter operation (such as COWSO capacity) within broader contextual challenges (such as local governance and budgetary allocation). One practical manifestation of this is that the retail-consumers of smart meters are actually service providers, authorities, or NGOs (Sharpe et al., 2019), not the users themselves. This is different to other technologies such as household water filters. The incentives of such 'customers' and other local government stakeholders must be included in plans for deployment and scaling.

Because systems thinking grows in importance as smart meters progress from prototyping to field testing to piloting and then to upscaling, each stage should anticipate contextual challenges before the complexity of the environment increases (Sharpe et al., 2019). Two specific illustrative examples of contextual challenges are presented here: 1) use of monitoring data, and 2) the service delivery management system in place.

1) In the case of the monitoring capabilities of smart meters, the collection of data is useless without a management system where such data is valued and put into use for planning and O&M. This need for 'use' of data was illustrated in Section 2.5.4. However, there are contextual reasons why 'use' of data may be challenging, and these include:

i. Limited capacity at the community or district level to react to such real-time data, despite best intentions of using the data. Lack of resources, training, time, and clear institutional arrangements all limit capacity, and this is particularly the case in rural areas, which are often allocated fewer staff and less finance (Impact Tanzania, 2017b).

ii. Incompatible format of the data and information with the local decision-making process, in terms of timescale or pertinent management foci.

iii. Political dynamics influencing data use. For instance, appointed officials are often more accountable to those above who appointed them and therefore report upwards. Data could be used for different purposes than O&M or local planning, e.g. with an emphasis on revenue collected rather than service levels.

Ways to improve data-based decision making in WASH have been much deliberated elsewhere (WaterAid, 2019a) and it is recommended to look “beyond direct, instrumental uses [of data] and understand data as an input to wider decision-making chains that may involve multiple stakeholders at multiple levels”.

2) Another contextual challenge is fitting smart meter operation within the service delivery management system in place, which itself fits within a broader enabling environment. There is a large range of different models for rural water service delivery across different settings, and these are well and continuously reviewed (World Bank, 2017b; Aguaconsult and WaterAid, 2018; McNicholl et al., 2019; RWSN, 2019; Lockwood, 2019). The Rural Water Supply Network alone catalogues 14 models submitted to them (RWSN, 2019). Regardless of the model (assuming basic suitability) it is important for smart meters not to aggravate key vulnerabilities of the model. Such vulnerabilities might be an imbalance between CapEx and recurrent expenditure, which may be affected by price of smart meter installation, which has been raised as a limitation of smart meters (Komakech et al., 2020). Another vulnerability might lie in complications of financial chains and accountability. Technology providers should strive to integrate into national rural water supply systems rather than set up as new utilities. Smart meters are theoretically adaptable to diverse service delivery models.

9.5.2 Systemic considerations

Beyond these contextual considerations of smart meters, more general thinking on the place of technology in international development can inform fundamental considerations of smart meter success. Here, some themes from the expansive 'ICT4D'[11] literature are drawn upon.

Macroscopically, the history of technology is one of intended and unintended effects. These are often intended benefits and unintended harms. Technology developed today to address harms from, for instance, lack of clean water, has the hidden potential to cause unintended harm in the future. Implications of technology shift in time (and location). This is in keeping with the nature of wicked problems. With this in mind, one argument proposed is that the known risks of current water supply management models, specifically community management, are actually preferable to unknown risks of new management models (Brown and van den Broek, 2017). This argument extends to smart meters. Limitations of this argument are: 1) change from a status quo is evidently very much needed, as shown by the current service levels of rural water supply in Section 2.2.1, and 2) the fact that risks are context specific. Aversion to unknown risks is not a strong argument against technological innovation, specially considering that innovation in the water sector traditionally lags behind other sectors. Solutions to wicked problems are neither true or false, but good or bad.

There is a risk that technology such as smart meters is a 'solution that is looking for a problem', or 'procrustean' by inappropriately enforcing uniformity. This is common in technology for development, seen for example with needless smartphone apps created for challenges that are better addressed with more 'basic' interventions. This further emphasises the need for case-by-case consideration of smart meter deployment. In ICT4D research in general, a 'critical' approach is not common (De et al., 2018) and an ideology exists that technologies for development have a general additive effect. Some general challenges of ICT and IoT in development have been introduced in Section

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[11] 'Information and Communication Technology for Development'

2.5.1. Here, some specific challenges that are pertinent for broader considerations of smart meter success are investigated.

One criticism of imposition of technologies is that they limit community engagement. For example, sensor-based monitoring of cook-stove use in poor households have been shown to provide good quality monitoring data but results may not be understandable for the participants, who have no way to feedback their own experiences (MIT D-Lab, 2018). While smart meters are more then simple monitoring devices, and users do have feedback channels through community management organisations, full engagement with users is still essential to overcome this (the choice to combine survey methods with remote data collection in Chapters 5 and 6 was based on this understanding). Many years can be needed for feedback to filter up from users. Service or technology providers can have different viewpoints on the usefulness of technologies than users themselves. Users in Community A explained in Section 5.4.3 that a key benefit to their lives from smart meters is the extra time made available by quicker access, however this tends to feature only tangentially in marketing of smart meters, which initially conceptualises monitoring and revenue benefits. The importance of community engagement with smart meter projects is self-evident, and has been raised by implementers elsewhere (e.g. WaterAid, 2019b), in particular regarding changes to payment.

Understanding community acceptance of a new technology partly addresses this. This consideration formed part of the evaluation outlined in Chapter 5 where 94% of users believe smart meters are an improvement, mostly from the improved anytime access and the extra time available. 81% of users are ‘happy’ or ‘very happy’ with availability. However, the evaluation raised minor dissatisfactions around poor supply from the PWS and occasional inaccuracy of tag credit removal.

Another concern is around the ownership of the data collected, what is it used for, and whom is it shared with. The ‘Principles for Digital Development’ outlined in Section 2.5.1 suggest open source data should underpin digital development. Integration of water collection data into the Water Point Data Exchange (www.waterpointdata.org) and national level data services would be an effective way of doing this. Contrarily, private incentives for data use may be a driver for smart meter deployment as seen in other technologies, for instance in digital agriculture.

A more systemic concern is how access to services can be transformed by technology across a population in an uneven way. Technology enables or fulfils relationships with its context in different ways (Smith et al., 2018) and unevenness of these relationships has been well deliberated for digital technologies such as mobile phones and the Internet, which have had decades of use in development projects (Hernandez and Roberts, 2018; Chambers, 2017). Unevenness of use is also pertinent for asking contextual questions about access to the benefits of smart meters and marginalisation.

Pursuant to this, a technology does not solve wicked problems or address root causes of development issues. Rather, actors do. Technology is never to blame or credit. The technology is not the goal itself, it is a tool in service of another goal, and is less important than the way in which it is implemented (Murthy et al., 2018). This is in accordance with the first of 'Kranzberg's laws of technology' that 'technology is neither good nor bad, nor is it neutral' (Kranzberg, 1986). This means that the foundations of transformative change lie in social, political, and economic trends and actors, which in the case of rural water supply manifest in the complex operating system. Building on this, 'amplification theory' suggests that technology is only a tool that 'multiplies human capacity in the direction of human intent' (Toyama, 2011), which is distinct from the idea of technology having an additive impact in itself. Introducing a new technology such as smart meters in a system characterised by high levels of inequality of service between different communities is therefore likely to amplify these existing inequalities. The research in Chapter 5 (Section 5.5.2) revealed that smart meters in fact work against intra-community marginalisation by making it easier for households further from DPs to collect clean water due to improved access. However, as established above, it is not possible to deploy smart meters in very rural communities (i.e. communities more marginalised than Community A) that do not have adequate infrastructure or management capacity. This fundamental limitation of smart meters is regardless of the 'direction of human intent'. Communities with well-functioning water supply benefit twice with smart meters while communities without PWSs lose out. A weighting of benefits of rural water supply programs towards less marginalised, higher wealth communities and households is longstanding, even with older handpump projects (Katuva et al., 2019). Technology research and projects in rural communities are considered to be far behind urban settings (Chambers, 2017).

This manifestation of amplification theory of the most marginalised communities missing out from benefits of smart meters echoes the notion of the 'poverty trap' (Banerjee and Duflo, 2011), which suggests that poorer households, individuals, and communities are unable to build wealth and escape from poverty because of systemic economic hindrances. This is represented in Figure 9.2. The fact that smart meters cannot be deployed in more marginalised communities could form another hindrance to escape from the poverty trap in these places.

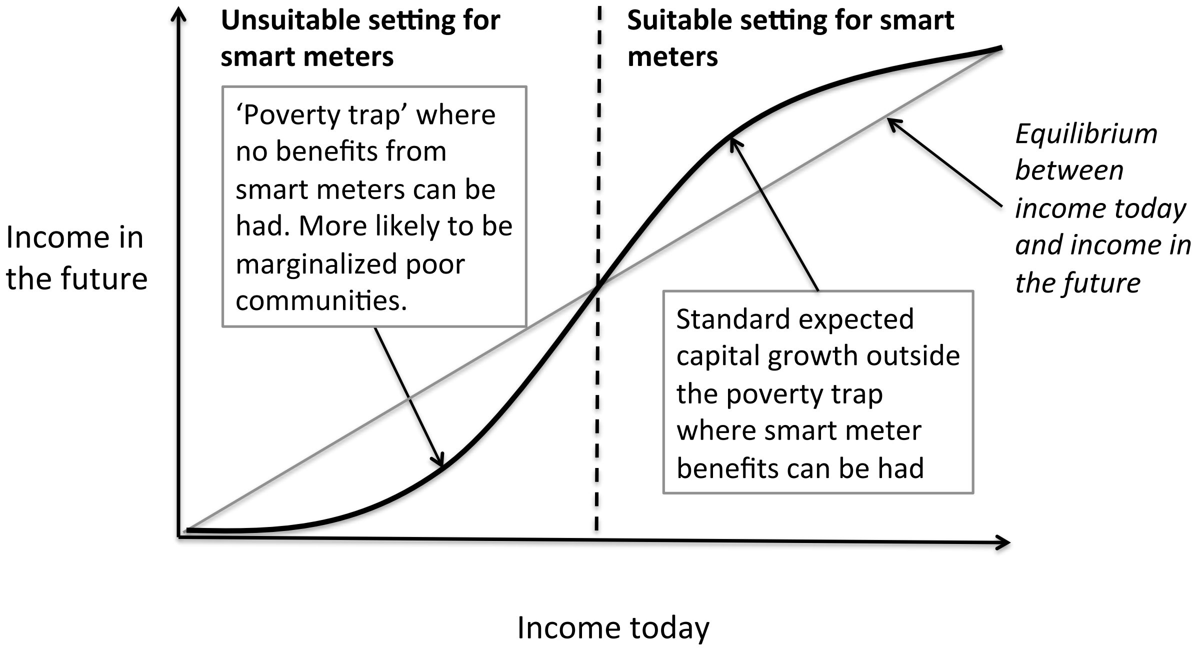

Figure 9.2. Representation of the S-shaped curve of the 'poverty trap', adapted from Banerjee and Duflo (2011), showing potential division between communities where smart meters are suitable and not suitable.

The nature of smart meters therefore simultaneously satisfies and is antithetical to the 'leave no one behind' agenda. Smart meters can further this aim within a community but can work against it at a district or national level. This fundamental limitation of smart meters may be at odds with the viewpoints of technocrats hunting for innovation to disrupt the status quo. IoT-based innovations for handpumps like those reviewed in Section 2.5.5 present a more even method of programme design because of the ubiquity of handpump deployment.

Practically, this opens up new questions for funders around allocation of finance for rural water supply projects in order to avoid merely reaching the low-hanging fruit, which was a key failing of the MDGs (Hernandez and Roberts, 2018). Additionally, it emphasises the importance of project reporting relaying all of the systemic factors of project success (or failures) rather than just the ‘impact’ of smart meters.

9.5.3 Potential barriers to general smart meter deployment

There are some factors that could act as barriers to general smart meter deployment or uptake for rural water supply projects over the upcoming years. Public health literature adopts a framework (Greenhalgh et al., 2017) to understand barriers to health technology success, and this is applicable for smart meters:

- Non-adoption of technology
- Abandonment of technology
- Failure of local scale-up
- Lack of distance spread, i.e. across a district or region
- Lack of long-term sustainability

Non-adoption of technology does not apply for smart meters once they are installed, where users have been using PWSs already. Chapter 5 and elsewhere showed that the community and managerial stakeholders have readily adopted smart meters. Abandonment is not evident, however is not possible to exclude at this stage. Managerial stakeholders in Community A expressed that it would be hard to stop wanting to use smart meters because of the benefits they bring. Mass community rejection resulting from perception of smart meters as the cause of a problem with rural water supply could increase the likelihood of abandonment by users. Poor implementation of tariff design using pre-payment meters was shown to result in civil unrest in cities above.

Potential causes of non-adoption, abandonment, failure to scale up, or unsustainability in a more general sense can lie in a number of potential barriers:

1) Smart meters can only be effective in a relatively narrow setting between very rural and peri-urban settings as shown above, and this non-uniform deployment can amplify existing inequalities between communities. Planners may find that this limits the potential for spread or sustainability.
2) The number of PWSs in rural communities in sub-Saharan Africa is limited. PWSs are necessary for smart meters. Furthermore, PWSs need to be well functioning for smart meter benefits to be realised. This incompleteness of PWS installation across rural sub-Saharan Africa is a key factor of the timing of the technology. Timing is the most critical factor of business success and is more important than the execution, business model, funding, or the idea itself. This raises the potential that smart meters are an innovation that is too early for this context, at least in areas with slower PWS installation rates. On the other hand, timing is favourable for other factors, specifically regarding the almost universal mobile network connectivity, the growing need for climate resilience, and reliance on groundwater resources.
3) If universal household connections becomes cheaper through scaling there is a risk that household connections become more cost effective than DP smart meter installation. DP-based PWSs are only a stopgap to household service, and in this sense smart meters are not final manifestations of perfect rural water supply anyway. This step could be ‘leap-frogged’.
4) Considering the turnover of new ideas in the development sector, interest of funders and NGOs may shift away from smart meters and IoT innovations. This could limit the ability of smart meter providers to reach service providers. Similarly, unfavourable market forces or macroeconomic trends (e.g. recession, manufacturing restrictions, import taxes) could limit demand, putting smart meter provider sustainability in jeopardy.
5) ‘Scope creep’ by smart meter providers or service providers, i.e. adding features and functionality to the project’s or technology’s scope without

addressing the effects on time, cost, and resources (Larson and Larson, 2009), could dilute the key impacts of smart meters. For instance, diverting resources and energy in new research and development directions may limit the ability to delivery of the basics of smart meter projects.

6) A new innovation may supplant smart meters.

Regardless, these barriers are not insurmountable. Not even the most successful technological innovations in history had limitless potential, and Africa is increasingly a crucible for disruptive technological innovation. The existence of these potential barriers only further emphasises the importance of broader consideration of smart meter deployment. Researchers of innovation processes have recently focused on smart meter development in Kenya and concluded that in order to successfully develop in this resource-constrained environment, smart meter providers must: 1) utilise versatile research and development approaches, 2) build internal acceptability, trust and legitimacy, and 3) leverage partnerships and networks to access resources and capabilities (Hyvärinen et al., 2020). These actions would also help overcome some of these barriers to general deployment.

It is important to point out (as in Section 5.5.5) that smart meters on DPs are not the ‘end-goal’ of rural water supply. They are only the next step towards the safely managed household connections. This vision can be easy to forget.

9.5.4 Transferability and scalability of smart meters

The smart meter innovation investigated in this research has been designed for rural sub-Saharan African communities. However, they have a degree of transferability to other rural contexts that experience some of the same challenges, such as unsustainability and poor access. For instance, some pre-payment ‘smart meter’ ATMs are already operating in rural India (Schmidt, 2020), and rural communities in parts of Latin America, Central Asia, and South Asia could also potential benefit. The challenges of urban areas were discussed in Section 9.4. As discussed, the contextual and systemic factors underpin whether smart meters can improve service levels in a given setting. For instance, mobile connectivity, management models, capacity for use of monitoring data, and individual community water collection behaviours are all key factors of success, and would require specific understanding before any transfer of smart meters into new contexts. Additionally, the specific challenge must exist in the first instance, rather than assuming that this ‘solution’ will automatically help; thus ensuring it is not a ‘solution looking for a problem’.

The assumption that the smart meter model is likely to continue to scale has been discussed in Section 9.1. However, similarly to assumptions around transferability, scaling is contingent on the potential barriers to deployment outlined in Section 9.5.3. The fundamental limit to scale is the setting of where smart meters are no longer an appropriate solution, such as in urban or very pastoral settings; and until better services are provided through expanded PWSs and household connections. Smart meters are not the end goal of rural water supply in this context. Consequently smart meters can only scale across a finite number of communities and only be part of the solution to the challenges outlined in Section 2.1.

9.6 Smart meters and rural water supply system strengthening

As established, smart meters cannot be a substitute for strong rural water supply systems. However, they can play a part in strengthening them. Strong systems need to be in place to deliver universal, resilient services and achieve SDG 6.1. Supporting and strengthening this system is an entry point to improving services.

Here, understanding of how smart meters can strengthen individual components of the rural water supply systems is developed. As far as evident, this has not been done for such technologies, and is useful to help visualise smart meter impacts. To do this, the nine IRC[12] ‘building blocks’ of WASH systems are used as a framework (Huston and Moriarty, 2018). These building blocks are useful ‘sub-systems’ that help visualise the larger complex system

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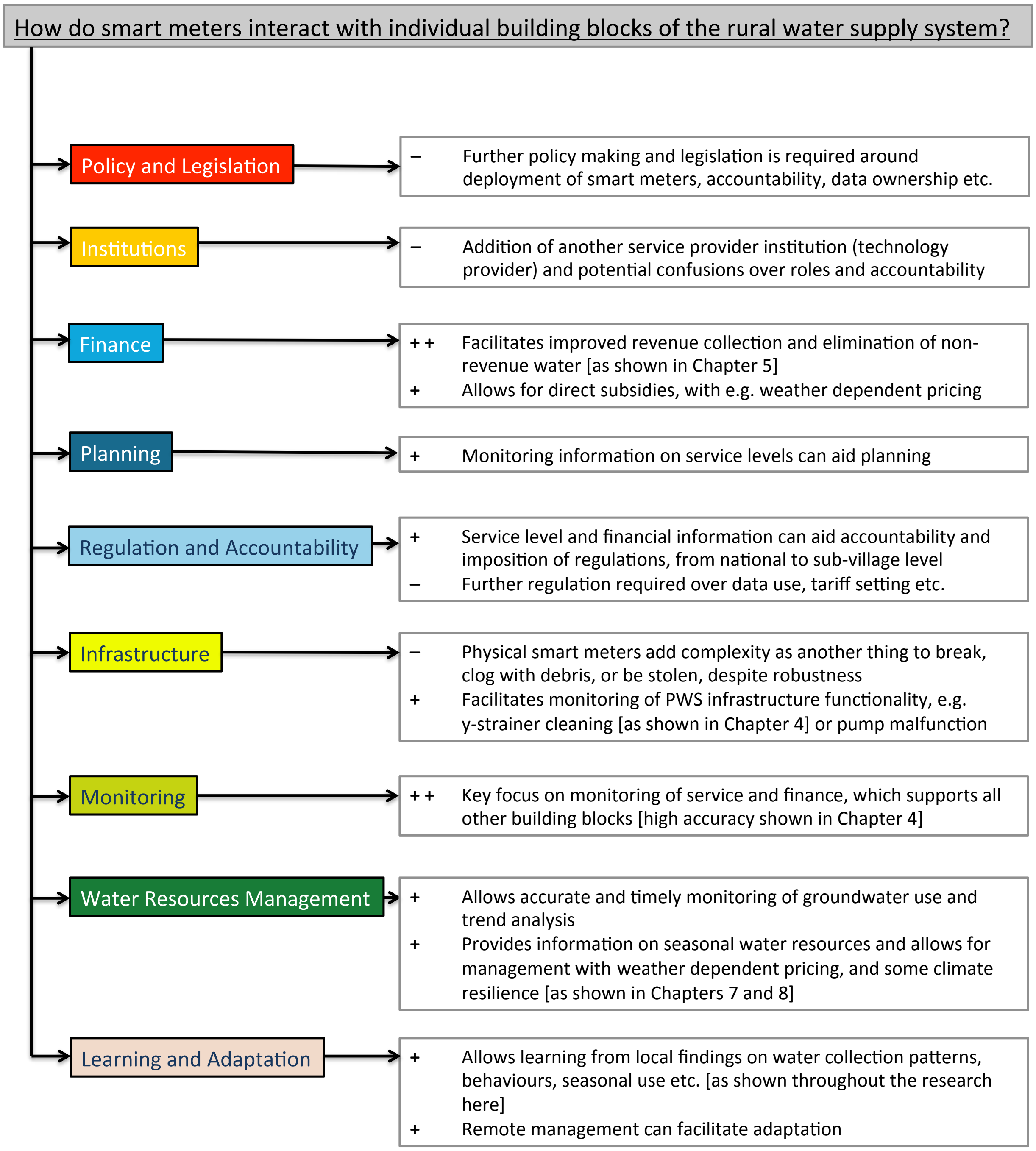
[12] IRC is an international ‘think-and-do-tank’ focused on building strong WASH (water, sanitation and hygiene) systems: ircwash.org.

and are presented in Figure 9.3. WASH (water, sanitation and hygiene) systems represent rural water supply systems. By addressing the condition of each building block, practitioners and researchers can identify weak points to target. These building blocks of the WASH system lie within health, education, political, and economic systems. There are other interpretations of WASH system building blocks used by other sector professionals that are almost the same (e.g. the nine blocks defined by Aguaconsult and WaterAid (2018) include 'Gender and Social inclusion', and 'Coordination'; and the World Bank (2017b) has used the five building blocks of sustainability: 'Institutional Capacity', 'Financing', 'Asset Management', 'Water Resources Management', and 'Monitoring and Regulatory Oversight'). The basic principle of defined building blocks is common and IRC is selected here because of its breadth and ubiquity.

Figure 9.3. Nine WASH system building blocks defined by IRC (from Huston and Moriarty, 2018, pg. 17)

An analysis of how smart meters can directly strengthen or weaken each individual building block of the rural water supply system is presented in Figure 9.4. This is based on the findings in Chapters 5 and 6 and findings and opinions from other studies and sector professionals. Plus (**+**) and minus (**–**) signs are used to represent when smart meters are more likely to have positive effects (reinforce) or negative effects (impede or complicate) on each building block. **++** denotes strongly positive. The degree of each positive or negative effect will vary depending on context. Therefore precise or quantifiable attribution is not possible. Instead, this provides a useful disaggregated overview.



How do smart meters interact with individual building blocks of the rural water supply system?

Policy and Legislation	–	Further policy making and legislation is required around deployment of smart meters, accountability, data ownership etc.
Institutions	–	Addition of another service provider institution (technology provider) and potential confusions over roles and accountability
Finance	+ + +	Facilitates improved revenue collection and elimination of non-revenue water [as shown in Chapter 5] Allows for direct subsidies, with e.g. weather dependent pricing
Planning	+	Monitoring information on service levels can aid planning
Regulation and Accountability	+ –	Service level and financial information can aid accountability and imposition of regulations, from national to sub-village level Further regulation required over data use, tariff setting etc.
Infrastructure	– +	Physical smart meters add complexity as another thing to break, clog with debris, or be stolen, despite robustness Facilitates monitoring of PWS infrastructure functionality, e.g. y-strainer cleaning [as shown in Chapter 4] or pump malfunction
Monitoring	+ +	Key focus on monitoring of service and finance, which supports all other building blocks [high accuracy shown in Chapter 4]
Water Resources Management	+ +	Allows accurate and timely monitoring of groundwater use and trend analysis Provides information on seasonal water resources and allows for management with weather dependent pricing, and some climate resilience [as shown in Chapters 7 and 8]
Learning and Adaptation	+ +	Allows learning from local findings on water collection patterns, behaviours, seasonal use etc. [as shown throughout the research here] Remote management can facilitate adaptation

Figure 9.4 Smart meter interaction with each individual IRC building block of the rural water supply system

Evidently, smart meters can strengthen some building blocks of rural water supply systems but can also potentially weaken or add complexity to others. Notably, monitoring and finance can be strengthened, while policy, institutions, and regulation can have added complications. Smart meters present both opportunities and risks, even in well-suited contexts. Generally smart meters strengthen (or have the potential to strengthen) more building blocks than weaken them. However, each interaction remains subject to local context, as building blocks are not inert objects and each overlaps with others. Practically, decision makers and programme designers must be especially careful with policy and legislation, institutions, regulation and accountability, and infrastructure. Most of these interactions are likely to be on longer timeframes, or extend beyond community-scale or district-scale system boundaries. The research and development in Chapter 4 on smart meter robustness is further justified by this vulnerability of infrastructure.

Furthermore, it is wrong to think of each interaction as a linear, mechanistic process. Because of the complexity of the system final outcomes cannot be predicted, and there are many second and third degree interactions and feedbacks. Strengthening one building block can lead to positive changes in others, for instance strengthening monitoring can improve planning. On the other hand, improvement across many blocks does not necessarily result in systemic change without other key improvements.

With this caveat, smart meters can be a 'leverage point' within the system that can accelerate system strengthening and trigger major change if deployed in a manner considerate of broader contextual challenges. Some caution must accompany this, as identifying leverage points in WASH systems across different contexts is known to be a very difficult task (Tillett et al., 2020; Valcourt et al., 2020). Donella Meadows' influentially identified an order of effectiveness of twelve leverage points of change in a system (Meadows, 1999). The least effective places to intervene are by changing constants, parameters, and amounts. Most effective are changing the mind-set out of which the system arises, and providing the power to transcend paradigms. Here, smart meters can be considered to create leverage points at the middle of this order (6th–7th respectively), with the facility to 'gain from positive feedback loops' (i.e. via increased revenue, better service provision, more willingness to pay, etc.), and by changing ‘the structure of information flows’ (via enhanced monitoring). Therefore, while smart meters can be leverage points in the rural water supply system, it would be overly ambitious to consider them as the most powerful way to leverage system change. This is in comparison to, for instance, a mind-set change from community management towards a professionalised service delivery approach as outlined in Section 2.3.5. System strengthening cannot be limited to one intervention such as smart meters.

Practically, this suggests that programmes, tenders, and development projects ought not to be devised as ‘smart meter projects’. Instead, smart meters should form only a supplementary component of more holistic rural water supply projects and funding, where they may form the cherry on the top but not the whole cake.

9.7 Conclusions and novelty of work

By examining the implications of findings and broader smart meter considerations, this chapter presents a number of novel points that go beyond current thinking.

- Smart meters are argued to be more suitable in a ‘sweet-spot’ between urban areas and very rural areas, and where strong rural water supply systems are already in place.
- It is shown that smart meters cannot be silver bullets, and that their deployment requires full consideration of contextual factors and relationships such as how they could amplify existing inequalities between communities and reinforce poverty traps.
- Some barriers to future smart meter deployment across sub-Saharan Africa are presented, including the current paucity of PWSs and competition from household connections, but these are not insurmountable.

In the right context, smart meters can strengthen rural water supply systems by initiating feedbacks and leverage with certain system ‘building blocks’.

Chapter 10. CONCLUSIONS AND FURTHER WORK

10.1 Conclusions

The aim of this research has been to investigate how smart meters can improve rural water supply service in sub-Saharan Africa. This has been achieved with the six main components of work presented in Section 1.6 and in the analytical framework in Chapter 3. These have been:

i. Identification of smart meter potential and research gaps (Chapter 2)
ii. Technical evaluation of robustness of smart meter (Chapter 4)
iii. Evaluation of effectiveness of smart meter in socio-economic context (Chapter 5)
iv. Investigation of water collection patterns using smart meters (Chapter 6)
v. Investigation of seasonality using smart meters and development of weather dependent pricing (Chapters 7 and 8)
vi. Examination of the implications of findings and broader smart meter considerations (Chapter 9)

The key conclusions from each element are presented below.

i) Identification of smart meter potential and research gaps

- IoT-enabled technologies like smart meters for rural water supply in sub-Saharan Africa can support the move from ‘community management’ towards a more professionalised ‘service delivery approach’. Benefits reported in current evaluations of smart meters include improved revenue collection, improved access to water, and improved management and service provision, which result from quality data collection and pre-payment.
- Research on such IoT innovations must go beyond current evaluations of innovation effectiveness and short-term management, and combine effective ‘collection’ of data with longer-term ‘analysis and reporting’ and appropriate ‘use’ of data.

- Full consideration of the complex rural water supply system that smart meters operate within is essential. Rural water supply is a ‘wicked problem’. Analytical framework must be constructed around technical, socio-economic, and environmental areas.

ii) Technical evaluation of robustness of smart meter

- Laboratory studies showed the smart meters studied (eWater taps) to have low average relative measurement error (+3.63%), unaffected by varying baseline flow rate. This in an insignificant error compared to broader benefits to rural water supply. A general calibration would fine-tune accuracy.
- y-strainer addition to the smart meter to address flow meter blockages from debris results in insignificant flow rate reductions across all gauze pore sizes. Reductions become significant beyond ~13 g of debris, more so with smaller gauze and larger debris sizes. Results can inform decisions of gauze size or identification of debris. Flow rate reductions relative to debris build-up for known gauze sizes provide a basis for accurate predictive maintenance with threshold-based alerts, which benefit from the high accuracy measured.
- Both of these findings reveal an original benefit for service providers to use software solutions to remotely overcome physical problems and improve service delivery.

iii) Evaluation of effectiveness of smart meter in socio-economic context

- Surveys and interviews in rural Tanzania showed that smart meters provide net benefits to user experience and access, largely from elimination of queuing at distribution points (DPs) and freeing of time for other economic or educational activities, among other benefits. 97% of users use smart meter DPs as their main source of drinking water.
- The proportion of users who have ‘basic’ service has been increased from 30% to 92%, which is much greater than the rural Tanzanian average (43%).
- Net benefits to service delivery were also shown, which are largely from better revenue collection and improved monitoring. Demand for smart meters from managerial stakeholders was shown to be high.

- Distance from households to DPs, and the limits of piped water system (PWS) and community management organisation remain as underpinning constraints to service delivery.

iv) Investigation of water collection patterns using smart meters

- Smart meter data was ‘used’ to investigate water collection patterns in rural Tanzania and The Gambia, and its combination with survey and interview data provides a new level of detail of patterns of water collection.
- Users collect water at different times of the day, depending on the community, when water is available at the DPs, and other social factors such as when children return from school.
- There is variability of volumes collected amongst households. Different DPs across communities distribute irregular and variable volumes over time, and those located in community centres or higher household densities do not consistently distribute more water. Instead, a higher number of households that use each DP is a better indicator of greater volumes dispensed, and this finding can contribute to better DP location planning.
- Fundamentally, while collection patterns result from socio-economic factors and behaviours, service delivery and collection patterns from smart meters are underpinned by PWS functionality and operation.

v) Investigation of seasonality using smart meters and development of weather dependent pricing

- Combination of multi-year meteorological data with smart meter data from rural Tanzania and The Gambia showed that water volume dispensed from DPs reduces by about 20% over rainfall months, and dramatically (up to 80%) on days of heavy rainfall, due to increased rainwater collection by users. Seasons or days of heavy rainfall are far better at explaining variation in volume dispensed than rainfall on a daily resolution. Reduced collection of clean DP water has potential for very negative health outcomes.
- Weather dependent pricing is developed and presented as an off-the-shelf intervention to incentivise clean water collection over rainfall months with discounted water, and over days of heavy rainfall with free water. This intervention is shown to be cost-effective, improve health, extend

developmental benefits of smart meter projects, and enhance climate resilience of rural water supply systems.

‘Costs per DALY averted’ in Community A (Tanzania) and Community B (The Gambia) are estimated as 14-55 GBP and 14-154 GBP respectively, and more cost-effective when the desired change in volume dispensed between seasons is low, price elasticity is high, and the relative risk of disease with WDP is low. Uncertainty analysis suggests that costs are more likely to be at the lower ranges of these estimates. Hypothetical scenario testing shows ‘cost per DALY averted’ to be generally favourable to other water quality interventions, therefore WDP could be better value for money.

vi) Examination of the implications of findings and broader smart meter considerations

- Smart meters are argued to be more suitable in a ‘sweet-spot’ between urban areas and very rural areas.
- Smart meters cannot be silver bullets, and require full consideration of contextual factors and relationships such as how they could amplify existing inequalities between communities.
- Some barriers to future smart meter deployment across sub-Saharan Africa exist, but are not insurmountable.
- In the right context smart meters can strengthen rural water supply systems by initiating feedbacks and leverage with certain system ‘building blocks’.

10.2 Further research required on smart meters

Specific further work has already been outlined in the chapters where relevant, specifically on predictive maintenance, pattern analysis, and WDP testing. With the expected smart meter deployment over upcoming years, the importance of research on smart meters will grow. Consequently, outlined below are:

- Proposed technical research and development for smart meters
- Further evaluation required of smart meter effectiveness
- Research required to improve implementation and new ideas for smart meter use

10.2.1 Further technical research and development

There is now new monitoring infrastructure on DPs ‘in the field’ in different settings across sub-Saharan Africa. This can be used for novel purposes. The findings in Chapter 4 showed that the smart meters studied measure flow relatively accurately, and addition of y-strainer gauzes insignificantly limits flow rate even with some debris loading. This means that: 1) monitoring data collected can be used for precise investigation of new questions (as begun in this research), and 2) new hardware can potentially be incorporated within flow channels of smart meters without disrupting user experience.

Firstly, this new source of high quality data on water collection can help address the general lack of data in development and earth systems science. For example, volumes dispensed can ‘ground truth’ hydrogeological estimates or remote sensing of water resources. Such research was begun with the development of weather dependent pricing, but could extend to groundwater, flooding and drought, solar activity, surface water resource management, and social measures such as migration, agricultural behaviour, and household expenditure. The SDGs call for interdisciplinary research of this nature.

Secondly, the robustness of flow rate to the insertion of new components means that additional sensors could be added. An interior pressure sensor would generate useful insights into PWS functionality. Modern pressure sensors can fit within ¾” pipework without disrupting flow, and could be incorporated into the y-strainer screw-cap on a trailing lead. Any sensor could connect to the smart meter control boards and therefore send data with the same time resolution as flow rate. Such sensor meters are relatively inexpensive, depending on size, precision and accuracy. A key benefit of pressure detection at individual DPs would be real time measurement of tank water level. Low pressures also risk infiltration of contamination to the pipework. Real time detection of decreasing pressure, e.g. throughout the afternoon, could generate threshold-based alerts for tank level. First steps to achieve this would be empirical measurement of tank level and corresponding pressure measurements at each DP at a selected PWS, over variable conditions. This would provide proof-of-concept and calibration. These measurements could be incorporated into an EPAnet mapping of PWSs. Physical tank-level sensors or regular checks from committee members bring their own expense, O&M, and human error. High time-resolution water quality sensors would also be suitable additions.

Insertion of water quality sensors (single or multi-parameter) within the smart meter would provide very useful information that could allow service providers to monitor and manage water quality. Real-time, remotely collected, high-resolution data on water quality from specific boreholes would also generate very useful information on groundwater quality for management or research purposes. For instance, understanding seasonal changes in water quality parameters is an important research question regarding increased intensity of rainfall with climate change. Such sensors currently appear to remain either too large for insertion within smart meters, uneconomical, or inaccurate. However, as such sensors develop this is a ripe area for further research.

A further area of research that would benefit from smart meter instalment in rural communities is ‘piggy backing’ on the IoT capacity of each smart meter for installation of other types of sensors. Weather stations (e.g. thermometer, barometer, hygrometer, anemometer, pyranometer, etc) could be installed onto DPs, connected to the smart meter IoT communication board. This would provide local hydro-meteorological information (useful for local agricultural decisions, flood/drought warnings etc). Joint communication of water service and weather information could be if integrated by the service provider. This data would also be very useful for calibrating satellite-based meteorological measurements (discussed in Section 7.2). Such weather stations are relatively inexpensive and commonplace, for example the Trans-African HydroMeteorological Observatory (TAHMO) project. Similarly, long-range wifi installation at DPs for community use could help low Internet connectivity. Mobile phone charging could also be incorporated into smart meters. Depending on the service delivery model, these things may potentially bring feedbacks from greater footfall. Additional technology on smart meters may bring additional challenges of energy use, theft or vandalism, increased O&M, increased complication, and ‘amplification’ of existing divides in access.

Lastly, there is potential for research in the area of energy harvesting from water flow within the smart meter from the PWS. Some water meters have been designed for municipal systems that are powered directly from a transducer that is coupled to a secondary water-driven turbine downstream of the meter (Becker et al., 2013). Other experiments show that a flow rate of 20 $\mathrm{l\ min^{-1}}$, which is relatively standard in the PWSs studied here, can provide 720 mW of power (7.1 V) (Hoffman et al., 2013). As PWSs are gravity-fed from elevated tanks, this is relying on the same energy harvesting principle as hydroelectric dams. No pumping energy is provided to the PWS distribution that would be lost through further energy harvesting at DPs as tank elevation is designed for appropriate distribution to all DPs at an appropriate flow rate. Higher elevation could increase this energy harvesting potential, however this would require more borehole pumping energy (unless it is a spring-fed hillside system) and potentially cause too high flow rates at DPs for users. Additional forms of power generation could charge the smart meter battery alongside a solar panel.

It is assumed that development firmware and software that underpins control, power and communication will be on-going for individual smart meter providers. Digital security of smart meters data will require attention into the future. This is likely to be a full-stack concern accountable to the data management service (e.g. Amazon Web Services), but could also include contingency re-routing of smart meter control.

10.2.2 Further evaluation of smart meter operation

The evaluation of smart meters conducted in Chapters 4 and 5 was constrained by time and resources, despite being able to address the research questions well. It focused on one smart meter, and covered one timeframe. This is a limitation of scale rather than methodology. Randomised control trials (RCTs) over a multi-year timeframe, which include a range of communities that are randomly selected to have smart meters or act as controls, would give comparative data. The same (or similar) methods as in Chapter 5 could be employed. Such larger scale studies would require joining projects just as they begin. As smart meter deployment increases, there will be a natural continual evaluation by stakeholders. Future failings will be equally useful to communicate, particularly if they open potential solutions to weakening of rural water supply building blocks. Longer-term indicators of success could be incorporated, specifically health (e.g. clinical records) and education (e.g. school attendance records).

Another valuable area for further evaluation would focus on the domestic wastewater from water used but not consumed. In this setting, household wastewater removal is typically small scale into the immediate surroundings and evaporates or drains quickly (or is used to water plants), but it could introduce additional health risks if from sanitary uses or if it contributes to stagnant pools that could harbour mosquito larvae or other parasites; these risks may be heightened if combined with rainfall runoff. Potential approaches to study whether additional water collected from smart meters contributes to changes in domestic wastewater removal could include using ‘water diaries’ (e.g. Hoque and Hope, 2019), where users record individual behaviours themselves, or more direct anthropological methods. Privacy and burden on users are potential ethical hurdles to such research.

10.2.3 Further ideas for implementation of smart meters

Rural water supply ‘building blocks’ that are more likely to be weakened were shown to be: ‘Policy and Legislation’, ‘Institutions’, ‘Regulations and

Accountability' and 'Infrastructure'. Greater understanding of smart meter interaction with these building blocks could be had with political economy research on how smart meter data would feed into different nations' governance systems (for example: Pichon, 2019), and how management approaches can incorporate smart meters. Generating a set of guiding principles for smart meter integration would be useful.

Development of a decision support tool would be very useful in ensuring the community and management model is suitable for smart meter deployment before installation. This could take decision makers through a set of considerations that are based on contextual factors (addressed in Chapter 9), which could include:

- PWS functionality
- Daily volume collected
- Population
- Distance from urban centre
- Capacity of committee or service provider
- Information exchange and communication with other stakeholders
- Competing water sources
- Seasonality
- Projected impacts of climate change
- Willingness to pay
- Accessibility of DPs for households
- Mobile phone ownership and mobile money use

Percentage scores could provide a ranking of overall suitability. Gathering input from experts (e.g. Delphi method based on successive rounds of questionnaires) could hone weightings for each factor. Even if such a tool could never provide perfectly accurate predictions due to the wicked problem nature of rural water supply it would help users thoroughly think through implementation and add weight to funding applications.

Another area suitable for development would be decentralised subsidisation of water for individuals, schools, or clinics by remotely loading pre-payment tags with credit. This idea was introduced in Chapter 8 for weather dependent pricing. Subsidies could come from government, donors, NGOs, or CSR budgets of companies anywhere in the world. They could leverage effective management if based on a payment-by-results mechanism. This would also be simple way to build in state participation to decentralised projects.

Lastly, a useful line of research would be detailed microeconomic analysis of tag-loading payments and revenue collection. Understanding who pays, what are the specific payment constraints, what would make users pay more (amount or frequency), and where the income originates from, would help understand a bigger picture of affordability, smart meter access, and sustainability of revenue collection. This could also reveal more information on price elasticity to help refine weather dependent pricing.

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Appendix A: Development of evaluation framework

A.1. Existing frameworks for evaluation of technology for development

The Comprehensive Initiative on Technology Evaluation (CITE) has generated a guide for practitioners who undertake technology evaluation in global development (CITE, 2017). This is a versatile, stepwise approach designed to help organisations select the best technology for a particular development objective. It is designed to inform practitioners who are designing technological development interventions, and incorporates desk and fieldwork. The approach has been applied to a range of technologies in development across energy, food and agriculture, health and mobility, education, and water. Water technologies evaluated include household water filtration kits and solar powered pumps.

The Technology Applicability Framework (TAF) is a decision support tool used to assess the applicability, scalability and sustainability of water, sanitation or hygiene (WASH) technologies (Olschewski, 2013). The TAF was designed to link assessment, technology, and sustainability.
It is designed to:

- evaluate WASH technologies
- start discussions about a new technology or upscaling approaches
- assess the potential of specific technologies regarding applicability, scalability, sustainability and uptake in context
- assess readiness of a sector to scale up the technology, including identification of potential measures for improving uptake
- monitor performance of technology and its introduction process.

Technologies that have applied the TAF cover wastewater, household water treatment, rainwater harvesting, solar pumping, and handpump designs. It was developed from an EU-funded and consortium-led action research project

(Olschewski and Casey, 2015), and has since been incorporated into government project implementation manuals, for instance in Tanzania (RWSN, 2015). Previous evaluations of new technologies using the TAF have had demonstrable policy relevance due to greater stakeholder engagement (Foster and McSorley, 2016). The TAF is based on participation of relevant stakeholders in data collection and discussion, including users, service authorities, and governments. This is based on lengthy engagements via workshops, fieldwork, questionnaires and focus group discussions, requiring a study team, a field visit team, at least three days of coordinated work and workshops, and formal inclusion of all stakeholders, with an estimated cost of 3,000 USD and approximately 18 people involved. It combines the perspectives of these stakeholders across six dimensions: 'social', 'economic', 'environmental', 'institutional', 'skills and know-how', and 'technological' in a matrix, using traffic light scoring. It is designed more for isolated evaluations of pilot WASH technologies, whereas eWater taps are more an 'upgrade' to existing technologies (i.e. borehole-fed PWSs) and is therefore less susceptible to pressures that see failures in other novel technologies. It was not appropriate to apply the full TAF process for the evaluation here.

Both the CITE and TAF have an emphasis on sustainability of a technology. There are also a number of global decision support tools available to practitioners regarding the sustainability of rural water supply services (Horecha, 2018). These include:

- Sustainability Assessment Tool (SAT) developed by AGUASAN. Uses 22 indicators with sub-questions to assess economic, environmental, institutional, knowledge, social, and technological aspects of a WASH program intervention.
- WaterAid Sustainability Snapshot tool. Scores the general technical, financial and equipment spare parts aspect of a rural water supply service.
- WASH Life-Cycle Assessment tool. Assesses the effectiveness and viability of WASH projects using five sustainability factors and five project life stages.
- Tool for Planning, Predicting & Evaluating Sustainability (TOPPES). Predicts service delivery sustainability from socio-economic, service

delivery, water resources and environmental needs, technical, financial, O&M and institutional indicators.

- Sustainability Index Tool (SIT), developed by USAID and Rotary International. Assesses sustainability of WASH services from institutional, management, financial, technical and environmental point of view.

These are not used directly in the framework outlined in Chapter 3. The ‘sustainability’ elements are implicit in the use of the TAF and CITE approaches that this evaluation here is drawn from.

A.2. eWater taps evaluation screening and scoping

Both CITE and TAF include a screening or scoping stage, which focuses on the background, context, need for the innovations, and the applicability of the innovation. This has largely been done already for smart meters in Chapter 2. Here, a more detailed outline of the screening and scoping stage is presented, with questions adapted from CITE and TAF existing questions used on other innovations. Answers are based on the literature review and information from fieldwork (Chapters 5 and 6). This is focused on rural Tanzania.

Table A.1. Screening and scoping of eWater taps in rural Tanzania

Background to the rural water supply challenge without eWater taps	
What are the key issues regarding rural water supply?	• Outlined in Chapter 2
Who are the key stakeholders, including users and service providers?	• All community members - users • COWSO (Community Owned Water Supply Organisation) • Village council, *Mwenye kiti* (chairman), *Mtendaji* (executive officer) • District Water Engineer (local government official) • Partner NGO, who part-constructed the PWS
How does the challenge affect them?	• Community members suffer from poor access to water • COWSO not having adequate finance or capacity to provide service • Village council affected as community members
What makes the challenge difficult to solve?	• Outlined in Chapter 2
Why is the challenge important to	• Improving access to non-contaminated water for

solve?	domestic uses will aid progress towards SDG 6.1
How will the Evaluation help decision makers?	• Objective evaluation against the evaluation framework criteria • Useful for present and future project planning • Will uncover new information about impact
Context for the Innovation	
Where is the project area and community for which eWater tap is being assessed?	• Rural Tanzanian communities
What is the socio-economic and political context for the community?	• Community of low-income or subsistence farmers
What is the rural water supply status in the area?	• Variable, with mostly good groundwater resources
What are the community demographics?	• Very rapid growth rate and young population
What are the community behaviours?	• Collection of water by women and children
What are the community aspirations?	• Improved development in line with the SDGs
Why is the context significant for the challenge?	• Distance from urban centres makes O&M more challenging
The Innovation	
How was the technology introduced?	• By eWater in partnership with NGOs
How long has eWater been used here?	• Since February 2017
Where and how are eWater taps installed?	• Onto existing DPs of PWS
What purpose and service level should it serve?	• Continual access to DPs throughout 24 hours, and generate enough revenue for O&M, providing suitable monitoring information
Why is this particular technology adopted here?	• Through an existing relationship with NGO
What is the per unit cost of an eWater tap?	• Variable
Is bulk ordering offered?	• Yes
Is training offered on the innovation to stakeholders?	• Yes
Is warranty on the product offered?	• Yes
Need for the Innovation	
What are the different types of water source from which people collect water in this community?	• DPs of the piped water distribution network, riverbed, lined wells, handpumps, rainwater harvesting
What purposes are water from these sources used for?	• Domestic uses (drinking, cooking, bathing, clothes washing, etc; varying depending on household and water quality) • Some small-scale irrigation and livestock watering
What issues exist regarding these water sources without eWater taps?	• On DPs of the water distribution network, vendors are only available in certain time windows causing queuing. Poor revenue collection. Poor monitoring. • Riverbed is far from households and seasonally

	dangerous riverbanks - Lined wells have contamination and poor taste - Handpumps are far from households, delays from vendors, regular breakdowns
What are the opportunities for overcoming these issues with eWater tap?	- Allows enhanced revenue collection for the COWSO - Makes access to improved water sources anytime without the need for vendors - Allows real-time monitoring of distribution point (DP) functionality
Why are eWater taps important for solving it?	- The innovation is designed to improve these things
Which user group are eWater tap intended for?	- Users and service providers
Does this technology provide the level of service needed in terms of technical capacity?	- Yes (see Chapter 4)
Has a clear need been expressed to improve rural water supply for this community?	- Yes through resource allocation from the DWE and NGO
Is water supply a top priority in this community?	- Yes, along with the other SDGs
Which are the main water uses that would benefit from this solution?	- Domestic water use
Who are the stakeholders in rural water supply now?	- Same as before, with eWater staff and credit resellers
In summary, can this technology contribute substantially to satisfying the need?	- Yes (see Chapter 6)
Applicability of the Innovation	
Are eWater taps reliant on water resources?	- Yes
Is there sufficient water availability throughout the year to deliver sufficient water for the technology to function properly?	- There are sufficient groundwater resources (see Chapters 5 and 7)
In general, is this proposed technology part of a system made of various components?	- Yes; in line with the complex system outlined in the literature review
How important is eWater tap reliability compared with reliability of other components in the system?	- Both are limiting factors to water availability (see discussion in Chapter 5)
At what depth is the groundwater usually found in the region during the dry season?	- Sufficient shallow groundwater with approximately 80% of unlined wells < 30 m deep (in nearby town; Pantaleo et al. 2018).
Are there issues within the target user group regarding acceptance, equity and inclusion to use the technology?	- Not significant (see findings in Chapter 5)

How well do eWater taps provide water from standpipes?	• No reduction of flow, good ease-of-use (see Chapter 4)
How efficiently is revenue collected by eWater taps?	• 100% efficiently, credit resellers pay on mobile money
How accurate is the eWater tap flow measurement?	• Adequate accuracy per international standards (ISO 17025) (see Chapter 4)
Can users afford to use eWater taps?	• Yes (see findings in Chapter 5)
Do users want eWater taps?	• Yes (see findings in Chapter 5)
In summary, is this innovation applicable in the context?	• Yes

A.3. Selection of evaluation criteria

CITE and TAF suggest a range of different criteria for evaluation. Here (Table A.2) the relevant ones for the evaluation criteria for this research are listed. CITE recommends between 7 and 12 criteria for a full evaluation, and ten were selected. These evaluation criteria best address the research gap need for further evaluation in alignment with the analytical framework.

Table A.2. Relevant evaluation criteria from TAF and CITE

TAF	**CITE**	**Evaluation criteria**
Demand	Demand from users, retailers, and stakeholders	**EF 1. Technical performance**
Affordability	Affordability; the cost, purchasers, and willingness to pay.	Accuracy of flow measurement
Skill set of user	Ease of use. Is there training?	Restriction of flow
Reliability and user satisfaction	Technical performance How well does it perform its primary functions?	**EF 2. Demand from service providers**
	Sustainability: How satisfied are users? What advantages does it bring? What is the likelihood of continued use over time?	Impacts
	Availability of the product in the study area	Satisfaction
	Accessibility. Is it at a reasonable distance for the consumer?	**EF 3. User experience and**

		demand
		Impacts
		Affordability
		User satisfaction
		Likelihood of continued use over time
		EF 4. Accessibility
		Ease-of-use of eWater tap and tag
		Equity of use

There are further criteria from CITE and TAF that are not included in the evaluation framework that are considered not relevant for this research (for instance ‘availability of the product in the study area’), or are dependent on the smart meter producer (for instance ‘after sales service’; ‘viable supply chains’), or are beyond the research scope of the socio-economic context and time limits here. These are assumed to be satisfactory for the purposes of this research (for instance, smart meters are available, and there are unlikely to be negative environmental impacts of smart meter use). The 18 criteria from the TAF are provided here:

Table A.3. Evaluation criteria from TAF

	Users	Producer/provider	Regulator
Social	Demand	Promotion	Behaviour change
Economic	Affordability	Profitability	Supportive finance mechanisms
Environmental	Negative environmental impacts	Local production of product or spares	Negative impacts of scaling up
Institutional and legal	Legal structures for management and accountability	Legal regulation and registration	Alignment with national strategies
Skills and knowhow	Skill set of user	Level of technological and business skills	Sector capacity
Technical dimension	Reliability and user satisfaction	Viable supply chains	Support mechanisms for upscaling

Eight criteria from CITE are provided here:

- Demand from users, retailers, and stakeholders.
- Sustainability: How satisfied are users? What advantages does it bring? What is the likelihood of continued use over time?
- Affordability: the cost, purchasers, and willingness to pay.
- Availability of the product in the study area
- Ease of use: Is there training?
- After-sales service.
- Technical performance: How well does it perform its primary functions?
- Accessibility: Is it at a reasonable distance for the consumer?

Further evaluations when smart meters have up-scaled in future years could be directed towards the producer/provider and regulator stakeholders.

Appendix B: Survey and interview protocols (A, C, E and B)

Protocol A

The purpose of the interview is to get information on eWater taps in rural Tanzania. This is independent from eWater. I will be asking a few questions about your organisation, demand from users for the eWater taps, accessibility and demand from your organisation. It should take about XX minutes. Your name and details will be anonymised and kept confidential, and destroyed after the work is completed. Your responses will be incorporated with other respondents.

- Are you happy to be interviewed on this topic?
- Are you happy for the interview to be recorded?
- Are you happy for your anonymised responses to be included in publications of this work?
- Do you have any questions?

Your participation in voluntary. If you want, you can withdraw at any time from the interview or not answer questions.

Signature/Mark: **Date:** **Time start:**

Coded name for anonymisation:
Name: *[on separate sheet with code]*
Gender:
Organisation:

Background information:

1. What does your organisation do?
2. What is your position in your organisation?
3. How long have you worked for the organisation?
4. How much do you interact with eWater tap users in your role?
5. What is the most difficult responsibility your organisation has to deal with regarding rural water supply?
6. Did you work with the water distribution system before eWater came?

   Where?
7. How often do you check the eWater dashboard?
   a: once a day or more; b: once every three days or more; c: once every week or more; d: once every month or more; e: less than once a month; f: never

Demand from users:

8. How robust are the eWater taps?
9. How satisfied are users with service levels from eWater taps?
10. Overall, do users have better or worse service from eWater than the previous system?
11. What feedback do you get from users on affordability of credits?

12. What will make users stop using the eWater taps in the future?
13. How does demand change during the rainy season? (precipitation and temperature)
14. How does demand change during one very rainy day? (precipitation and temperature)

Accessibility:

15. What other water sources do users collect water from, than eWater taps?
16. What groups in the community are unable to use the eWater taps?

Demand from service providers and service authorities:

17. Compared to the previous method, how is the eWater method of reporting breakdowns of water points or the water system?
    a: better; b: the same; c: worse
    Why is that?
18. How did the COWSO/Service Provider track revenue collection before eWater? Was this
    a: easy; b: medium; c: hard
19. Compared to the previous method, how is the eWater method of reporting revenue collection?
    a: better; b: the same; c: worse
    Why is that?
20. Name three things that could be improved with the eWater system?

    Please rank these in importance?
21. Was spending on operation and maintenance transparent in the previous system?
22. What will make your organisation want to stop using eWater in future?
23. What other information does your organisation get and use from eWater's technology?

Water system:

24. When was the system installed?
25. How frequently does either the borehole, pump, tank or pipes break?
    Which component breaks most frequently?
26. What is the biggest expenditure on O&M?
    How much is that?
27. Do you have enough money to spend on this when it breaks?

Any questions?

Debrief.
Time finish:
Interview Length:

Protocol C

The purpose of the interview is to get information eWater taps in rural Tanzania. This is independent from eWater. I will be asking a few questions about accessibility and demand for eWater taps. It should take about XX minutes. Your name and details will be anonymised and kept confidential, and destroyed after the work is completed. Your responses will be incorporated with other respondents.

- Are you happy to be interviewed on this topic?
- Are you happy for the interview to be recorded?
- Are you happy for your anonymised responses to be included in publications of this work?
- Do you have any questions?

Your participation in voluntary. If you want, you can withdraw at any time from the interview or not answer questions.

Signature/Mark: **Date:** **Time start:**
[or interpreter by verbal proxy consent]

Coded name for anonymisation:
Name: *[on separate sheet with code]*
Sub-village: **GPS:**

Background information:

1. Gender? m/f
2. How old are you? a: 18-25 b: 26-35 c: 35-45 d: 45-65 e: >66
3. What is your main livelihood occupation?
   CODE IN ANALYSIS
4. How many people live in your household?
   a: 1-3 b: 4-6 c: 7-9 d: 10-12 e: >12
5. How much water does your household collect every day?
   a: 1-2 buckets; b: 3 – 5; c: 6-10; d: 11-15; e: 15+
6. What is your households main water source for drinking?
7. What is your households main water source for cooking?
8. What is your households main water source for bathing and clothes washing?
9. What is your households main water source for your crops?
10. What is your households main water source for your animals?

Demand from users:

11. Do you use eWater taps to collect water? *y/n*
12. How many eWater taps do you use to collect water? #
13. How is it using the eWater taps?
14. How long is queuing time now at eWater water points, most of the time?
    a: no queue ever; b: < 2 minutes, c: 2-10 minutes; d: 11-30 minutes; e: > 30 minutes
15. How long was queuing time before eWater came?
    a: no queue ever; b: < 2 minutes, c: 2-10 minutes; d: 11-30 minutes; e: > 30 minutes
16. How many hours per day is the eWater water point that you use functional?
    a: 24 hrs; b: 24-16; c: 16-8; d: 8-0; e: 0 hrs.
17. How many times has the eWater tap that you most often use broken?
    a: >15; b: 14-8; c: 7-3; d: 2-1; e: 0
18. Why has the eWater tap broken?
19. When it has broken, how long has it taken to be repaired?

a: <1 day b: 1-3 days c: 3-10 days d: 10-30 days e: >30 days

20. Is repair of broken water points quicker now than before eWater?
21. Where do you collect water when the eWater tap is unavailable?
22. How happy are you with the availability of the water point with the eWater tap?
    1: very happy; 2; 3; 4; 5: very unhappy.
23. How does the eWater system compare to the previous system?
    1: much better; 2; 3; 4; 5: much worse.

    Why?
24. Does the eWater tap charge the right amount?
    y/n
25. Where is the data on your water collection use being recorded and sent to?
    1: good understanding; 2; 3; 4; 5: no understanding.
26. How do you feel about this?
27. What happens to the money that you buy credit with?
    1: good understanding; 2; 3; 4; 5: no understanding.
28. Have the eWater taps benefited the health of the community?
    1: very much; 2; 3; 4; 5: not at all.

    How?
29. How much does a 20 litre bucket cost in credit?
    1: good understanding; 2; 3; 4; 5: no understanding.
30. How is this price for your household?
    1: much too high; 2: a little too high; 3: roughly correct; 4: a little too low; 5: much too low
31. Would you pay more for credit if it made water service better?
    y/n
32. Do you pay more or less now with eWater, compared to before eWater?
    more/less
33. Will you be willing to keep paying for credit in the future?
    y/n

    Why?

Accessibility

34. Which eWater tap do you use the most?
    # *Note rough distance from home:*
35. How long does the travel and the collection take from this water point, including queuing?
    a: on compound; b: <10 minutes; c: 10-30 mins; d: 30 mins-1 hr; e: 1-2 hr; f: >2 hr
36. Who collects water in your household most often?
    a: male adult; b: female adult; c: male child; d: female child
37. What times does your household collect water?
    a: 00:00 – 04:00; b: 04:00 – 08:00; c: 08:00 – 12:00; d: 12:00 – 16:00; e: 16:00 – 20:00; d: 20:00 – 24:00.

    Why then?
38. How easy was it to get a tag when the eWater taps were installed?
    1: very easy; 2; 3; 4; 5: very difficult.
39. Did you register when you got your tag?
    y/n
40. How many tags do you have?
    #
41. Who in the community is not able to use the eWater taps?
42. How many mobile phones are in your household?

y/n

43. How do you get eWater credits most often? (cash, others, mobile)
    a: buy with cash; b: buy with mobile money; c: given from others
44. Is it easy paying for credits this way?
    y/n
45. How important is a good flow rate from the tap?
    1: very Important; 2; 3; 4; 5: very unimportant.
46. How many times have you lost your tag?
    #
47. How often do you lend your tag to other people in the community?
    a: never; b: occasionally to close friends and family; c: regularly to close friends and family; d: regularly to anyone

Pattern and Seasonality

48. When it rains heavily, where do you collect water?
49. Do you collect more water when it is very hot weather?

    y/n

Any questions?

Debrief.
Time finish:
Interview Length:

Protocol E

The purpose of the interview is to get information on the performance and sustainable implementation of eWater taps in rural Tanzania. This is independent from eWater. I will be asking a few questions about accessibility and demand for eWater taps. It should take about XX minutes. Your name and details will be anonymised and kept confidential, and destroyed after the work is completed. Your responses will be incorporated with other respondents.

- Are you happy to be interviewed on this topic?
- Are you happy for the interview to be recorded?
- Are you happy for your anonymised responses to be included in publications of this work?
- Do you have any questions?

Your participation in voluntary. If you want, you can withdraw at any time from the interview or not answer questions.

Signature/Mark: **Date:** **Time start:**
[or interpreter by verbal proxy consent]

Sub-village: **GPS:**

Background information:

1. Gender? *m/f*
2. How old are you? # *a: 18-25 b: 26-35 c: 35-45 d: 45-65 e: >66*
3. What is your main livelihood occupation?
    a. CODE IN ANALYSIS
4. How many people live in your household?
    a: 1-3 b: 4-6 c: 7-9 d: 10-12 e: >12
5. How much water does your household collect every day?
    a: 1-2 buckets; b: 3 – 5; c: 6-10; d: 11-15; e: 15+
6. What is your households main water source for drinking?
7. What is your households main water source for cooking?
8. What is your households main water source for bathing and clothes washing?
9. What is your households main water source for your crops?
10. What is your households main water source for your animals?

Demand from users/user experience:

11. Do you use eWater taps to collect water? *y/n*
12. How many eWater taps do you use to collect water? #

13. How long is queuing time now at eWater taps water points, most of the time?
    a: no queue ever; b: < 2 minutes, c: 2-10 minutes; d: 11-30 minutes; e: > 30 minutes

14. How long was queuing time before eWater came?
    a: no queue ever; b: < 2 minutes, c: 2-10 minutes; d: 11-30 minutes; e: > 30 minutes
15. How many hours per day is the eWater tap water point that you use functional?
    a: 24 hrs; b: 24-16; c: 16-8; d: 8-0; e: 0 hrs.
16. How many times has the eWater tap that you most often use broken?
    a: >15; b: 14-8; c: 7-3; d: 2-1; e: 0
17. When it has broken, how long has it taken to be repaired?

a: <1 day b: 1-3 days c: 3-10 days d: 10-30 days e: >30 days

18. How happy are you with the availability of the water point with eWater tap?
    1: very happy; 2; 3; 4; 5: very unhappy.
19. How does the eWater system compare to the previous system?
    1: much better; 2; 3; 4; 5: much worse.
20. Does the eWater tap charge the right amount?
    y/n
21. What happens to the money that you buy credit with?
    1: good understanding; 2; 3; 4; 5: no understanding.
22. Have the eWater taps benefited the health of the community?
    1: very much; 2; 3; 4; 5: not at all.
23. How much does a 20 litre bucket cost in credit?
    1: good understanding; 2; 3; 4; 5: no understanding.
24. How is this price for your household?
    1: much too high; 2: a little too high; 3: roughly correct; 4: a little too low; 5: much too low
25. Would you pay more for credit if it made water service better?
    y/n
26. Will you be willing to keep paying for credit in the future?
    y/n

Accessibility

27. Which eWater tap do you use the most?

    \#　　　　*Note the distance from home:*

28. How long does the travel and the collection take from this water point, including queuing?
    a: on compound; b: <10 minutes; c: 10-30 mins; d: 30 mins-1 hr; e: 1-2 hr; f: >2 hr
29. Who collects water in your household most often?
    a: male adult; b: female adult; c: male child; d: female child
30. How many mobile phones does your household have?
    \#
31. How do you get eWater credits most often?
    a: buy with cash; b: buy with mobile money; c: given from others
32. Is it easy paying for credits this way?
    y/n
33. How many times have you lost your tag?
    \#
34. Did you register when you first got your tag?
    y/n
35. How many tags do you have?
    \#
36. How often do you lend your tag to other people in the community?
    a: never; b: occasionally to close friends and family; c: regularly to close friends and family; d: regularly to anyone

Any questions?

Debrief.
Time finish:
Interview Length:

Protocol D

The purpose of the interview is to get information on community taps in rural Tanzania. This is related to eWater. I will be asking a few questions about accessibility and demand for community water points. It should take about XX minutes. Your name and details will be anonymised and kept confidential, and destroyed after the work is completed. Your responses will be incorporated with other respondents.

- Are you happy to be interviewed on this topic?
- Are you happy for your anonymised responses to be included in publications of this work?
- Do you have any questions?

Your participation in voluntary. If you want, you can withdraw at any time from the interview or not answer questions.

Signature/Mark: **Date:** **Time start:**
[or interpreter by verbal proxy consent]

Coded name for anonymisation:
Name: *[on separate sheet with code]*

Background information:

1. Gender? m/f
2. How old are you? a: 18-25 b: 26-35 c: 35-45 d: 45-65 e: >66
3. What is your main livelihood occupation?
4. How many people live in your household? *a: 1-3 b: 4-6 c: 7-9 d: 10-12 e: >12*
5. How much water does your household collect every day?
   a: 1-2 buckets; b: 3 – 5; c: 6-10; d: 11-15; e: 15+
6. What is your households main water source for drinking?
7. What is your households main water source for cooking?
8. What is your households main water source for bathing and clothes washing?
9. What is your households main water source for your crops?
10. What is your households main water source for your animals?

Demand from users:

11. How many hours per day is the water point that you use functional?
    a: 24 hrs; b: 24-16; c: 16-8; d: 8-0; e: 0 hrs.
12. How many times has it broken?
    a: >15; b: 14-8; c: 7-3; d: 2-1; e: 0
13. When it has broken, how long has it taken to be repaired?
    a: <1 day b: 1-3 days c: 3-10 days d: 10-30 days e: >30 days
14. How happy are you with the availability of the water point?
    1: very happy; 2; 3; 4; 5: very unhappy.
15. How much does a 20 litre bucket cost?
    # *1: good understanding; 2; 3; 4; 5: no understanding.*
16. How is this price for your household?
    1: much too high; 2: a little too high; 3: roughly correct; 4: a little too low; 5: much too low
17. How much does your household spend on water per day/per month?
    #
18. Would you pay more for a better water service?
    y/n

Accessibility

19. How far is the water source you use most from your home?
    #
20. How long does the travel and the collection take from this water point, including queuing?
    a: on compound; b: <10 minutes; c: 10-30 mins; d: 30 mins-1 hr; e: 1-2 hr; f: >2 hr
21. Does everybody in the community use the same water point?
    y/n
22. How many mobile phones are in your household?
    #

eWater

23. Do you know eWater?
    y/n
24. How does the eWater system work?
    1: good understanding; 2; 3; 4; 5: no understanding.
25. How did you hear about eWater?
26. Would you like your community to use eWater?
    y/n

Any questions?

Debrief.
Time finish:
Interview Length:

Appendix C: Model results of daily relationships between volume collected and weather

The results for the multivariate regression models outlined in Section 7.3.2 are provided in Table C.1, for Community A and B.

Table C.1: Multivariate regressions of daily volume dispensed against rainfall and temperature

	Community A			**Community B**		
	≥0.0 mm	**>0.0 mm**	**>1.0 mm**	**≥0.0 mm**	**>0.0 mm**	**>1.0 mm**
Daily GPM *n =*	*(299)*	*(157)*	*(100)*	*(297)*	*(202)*	*(97)*
Intercept	1519	-5594	-12590**	-55838**	-90680**	-81037*
Rainfall	-179***	-119***	-95***	-61	-127	-66
Temperature	392***	640***	916***	2929***	4206***	3810**
R^2	***0.16****	***0.20****	***0.29****	***0.06****	***0.12****	***0.08***
Daily TAMSAT *n =*	*(299)*	*(101*	*(96)*	*(297)*	*(128)*	*(110)*
Intercept	-1558	-25371***	-24371***	-54641**	-76771*	-69378*
Rainfall	-129**	81	77	-119	-452*	-445
Temperature	508***	1388***	1348	2896***	3842***	3583**
R^2	***0.08****	***0.24****	***0.22****	***0.06****	***0.14****	***0.13****
Daily CHIRPS *n =*	*(299)*	*(67)*	*(66)*	*(297)*	*(87)*	*(85)*
Intercept	-849	3185	3116	-53456*	-54927	-48842
Rainfall	-97**	-33	-32	-114	-394*	-380*
Temperature	476***	239	240	2857***	3153*	2929*
R^2	***0.08****	***-0.02***	***-0.02***	***0.06****	***0.14****	***0.13**
14-day GPM *n =*	*(424)*	*(418)*	*(299)*	*(460)*	*(325)*	*(158)*
Intercept	11024***	12591***	-5951*	-155198***	-134582***	-114448*
Rainfall	-487***	-478***	-186***	340	-194	-534
Temperature	42	-26	664***	6179***	5663	5110
R^2	***0.28****	***0.27****	***0.27****	***0.14****	***0.16****	***0.14****
14-day TAMSAT *n =*	*(424)*	*(362)*	*(283)*	*(460)*	*(209)*	*(182)*
Intercept	1190	-24876***	-23154***	-170112***	-139239**	-134480**
Rainfall	-285***	0.37	114**	723*	49	-58
Temperature	409***	1407***	1313***	6623***	5792**	5652***
R^2	***0.11****	***0.29****	***0.29****	***0.14****	***0.11****	***0.11****
14-day CHIRPS *n =*	*(424)*	*(365)*	*(284)*	*(460)*	*(144)*	*(139)*
Intercept	4816	13328***	9261*	-152319***	-97723*	-84259
Rainfall	-306***	-325***	-278***	285	-458	-513
Temperature	264*	-87	72	6088***	4539**	4096*
R^2	***0.10****	***0.07****	***0.05****	***0.14****	***0.13****	***0.11****

**Significant at 1%, **Significant at 0.1%, ***Significant at 0.01%. 'Adjusted R^2' values account for multiple variables.*

Appendix D: Publications

The publications associated with this thesis are attached, as follows:

- Ingram, W. & Memon, F. A. (2019). Internet of things innovation in rural water supply in sub-Saharan Africa: a critical assessment of emerging ICT. *Waterlines*, *38*(2), 71-93.
- Ingram, W., & Memon, F. A. (2020). Robustness of IoT-connected e-Taps for sustainable service delivery of rural water supply. *Water Supply*, *20*(6), 2251-2260.
- Ingram, W., & Memon, F. A. (2020). Rural Water Collection Patterns: Combining Smart Meter Data with User Experiences in Tanzania. *Water*, *12*(4), 1164.