Handpump maintenance, water use, and health in rural Kenya

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Abstract

This thesis examines the use and maintenance of handpumps that rural communities rely on to abstract groundwater for their daily water needs. It considers professionalization of services, changes in use in response to rainfall, and the health impact on households from reducing pump downtimes. This study took place in Kwale County in southern Kenya.

By combining data on handpump downtimes from pumps that were part of a data-driven professional repair service with health data from household surveys, this thesis analyses the relationship between pump downtimes and diarrhoea period prevalence. While the repair service reduced average pump downtime by an order of magnitude to less than three days, analysis against self-reported diarrhoea suggests that only an extremely rapid repair (within 24hrs) is associated with a reduction in diarrhoea morbidity: Households who collected water from pumps that had consistently repaired within 24hrs saw a 60% reduction in reported diarrhoea compared to those whose pumps had taken longer to repair, which showed no reduction. These results support previous modelling work which suggests that even short periods without safe water can have disproportionate adverse health effects. Using novel data generated from Smart Handpumps, hourly data from handpumps were examined and modelled against rainfall data from manual rain gauges. This showed that pump use in Kwale is highly correlated to weather patterns, with low rainfall conditions leading to an increased demand for groundwater and days of heavy rainfall leading to a transient, but large reduction is pump use.

This thesis then discusses the mechanisms behind these observed effects and their implications. The findings suggest that the community management of handpumps, which does not consistently result in rapid pump repairs, is unlikely to realise the hoped health benefits associated with drinking uncontaminated groundwater. Professional services are likely to perform better, especially when supported by improved monitoring of handpump use and functionality, but will still struggle to deliver consistent high levels of service. Handpumps may be a necessary interim solution for some time to come but are unlikely to be able to make any substantial contribution to meeting SDG 6.1.

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Chapter 1 – Introduction

For generations a key source of water for rural communities has been groundwater. MacDonald and Calow (2009) describe the advantages of groundwater as a source of drinking water:

> *Across large swathes of Africa, South America and Asia, groundwater provides the only realistic water supply option for meeting dispersed rural demand. Alternative water resources can be unreliable and expensive to develop: surface water (if available) is prone to contamination and often seasonal; rainwater harvesting can be expensive and requires good rainfall throughout the year. Groundwater, however, can be found in most environments. It generally requires no prior treatment since it is naturally protected from contamination; it does not vary significantly seasonally and is often drought resistant.* (MacDonald and Calow, 2009: 546)

In rural areas with no grid electricity or limited funds to run diesel generators, handpumps accessing shallow groundwater are still key to providing rural communities with their daily water needs. These small-scale water supply systems, often comprising a single village handpump, are more often than not community managed, in contrast to urban piped water systems which are run by directly by governments or sub-contracted to a water service provider. Community management became the sanctioned discourse for rural water supply from the late 1970s onwards. Investment in the sector increased following the UN's Mar del Plata conference in 1977 and the subsequent action plan (Falkenmark 1977) leading to the 'International Drinking Water Supply and Sanitation Decade' (1981 to 1990). This increased expenditure came with optimism, based on the assumption that an increase in community participation could solve the problems of poor sustainability associated with the previous model of centralised management (Narayan 1994; Kleemeier 2000; Prokopy 2005; Harvey and Reed 2006b; Whittington et al. 2009). The causes of this lack of sustainability, and the challenges of community management, began to be examined more critically in the 2000s (Prokopy 2005; Kleemeier 2000; Iyer, Davis, and Yavuz 2006; Isham and Kahkonen 2001; Mansuri 2004). The community-managed model for rural water services has not been a panacea, with an estimated one in four handpumps in Sub-Saharan Africa still non-functioning at any given moment (RWSN 2010; Foster 2013; Foster et al. 2019).

The situation has arguably been improving: Between 2000 and 2017, 328 million people in Sub-Saharan Africa gained access to basic water services (World Health Organization and UNICEF 2019). But population growth exacerbates the challenges of increasing coverage: over this same period the number of people lacking even a basic service increased by 50 million (World Health Organization and UNICEF 2019). Globally, rural coverage of safely managed services increased from 39% to 53%

during this time. This lagged urban coverage by 32%, which remained static over the same period in percentage terms with coverage just about keeping up with population growth (World Health Organization and UNICEF 2019).

Common critiques of the community management paradigm are that communities are often unable to effect seemingly simple repairs, or that simple repairs are possible but more complex ones are not (Kleemeier 2000; Maluti 2010). It is also argued that as a result of designing pumps with low-cost spares that do not need frequent replacement, particularly in sparsely populated areas with low pump densities it is difficult to sustain the operation of a spare parts supply chain on a commercial basis (Harvey and Reed 2006a; Harvey 2007; Harvey and Reed 2006b). Moreover, purchasing decisions are often based on criteria of lowest capital cost, which favours importation rather than local production of parts. This reduces the availability of spares and local expertise (Arlosoroff et al. 1987; Rouse 2013; Harvey and Reed 2006a), leading to higher through-life costs and longer periods of non-functionality. These and other factors combine to make the sustainable operation of rural handpumps through community management more challenging and less effective that was envisioned some decades ago. In response to this, since the 2000s, there has been increasing interest in professional management models (Kleemeier 2010; Carter, Harvey, and Casey 2010; Harvey and Reed 2006b). This study is part of a wider project that is researching the role that information can play in enabling professional maintenance models.

The apparent lack of progress towards universal access to safe drinking water does not stand up favourably with the progressive realisation of the human right to water, a right which is gradually becoming an international norm through General Comment 15 (United Nations 2003, 1966) and is increasingly being explicitly written into national constitutions, policies and legislation. In addition, as the main burden of water collection falls disproportionately on women and girls the current situation is at odds with the UN Convention on the elimination of all forms of discrimination against women (United Nations 1979). The economic impacts of poor water service provision are also significant (Whittington, Mu, and Roche 1990; Stockholm International Water Institute 2005; Rosen, Vincent, and Rosen 1999; Jeuland et al. 2013; Fuente et al. 2020). While the economic aspect of poor Water Sanitation and Hygiene (WASH) may take second place to rights and health-related arguments as the primary motivation for action in the sector, modelling of health and non-health cost of poor WASH provision by Fuente et al. (2020) predicted that the non-health costs may now be higher than the health-related costs in countries in Sub-Saharan Africa with low mortality from water-related diseases.

In contrast to the disappointing progress towards better water services, the expansion of mobile phone networks across Africa has been an unambiguous success, and is now reaching rural areas that often lack any other type of infrastructure, e.g. sealed roads or electricity (Suri and Jack 2016; Sife, Kiondo, and Lyimo-Macha 2010; Furuholt and Matotay 2011). This is opening up new opportunities in numerous sectors, water supply being no exception. In West Africa operators have harnessed mobile coverage to provide monitoring of small scale urban water systems (Karim 2018). In East Africa and beyond applications on smart phones enable users to complete a survey, take pictures and GPS references of, for example, a gravity-fed stand-pipe, thus providing monitoring and evaluation data. However, these systems only provide snapshots, so while suitable for assessing the average performance of a large system or network over time, they are not suitable for immediate fault reporting and consequent rapid maintenance.

As part of the Smart Water Systems project, funded by UK Government Department for International Development (DFID), and subsequent grants from DFID and the Economic and Social Research Council ESRC, I started what became the Smart Handpumps project (University of Oxford 2014; Thomson, Hope, and Foster 2012a). This aim of this work was to address the specific issue of information being provided fast enough to trigger an effective professional maintenance response, as opposed to providing information that could only be used for M&E. To this end I developed a device designed to be attached to, or be fitted inside, a handpump to monitor the pump's use and transmits this information via the mobile phone network. Hourly data on each handpump is then displayed on a user interface and used to dispatch a mechanic to repair the pump[1]. This GSM-enabled maintenance service was successfully trialled over a year in Eastern Kenya with 66 WDTs deployed on Afridev handpumps. This trial was successful, reducing the average downtime of a handpump to less than three days, an order of magnitude improvement with respect to the baseline (Smith School Water Programme 2014).

[1] The kernel of this idea came to Tim Foster while in Lusaka in early 2011.

Picture 1: Rufus Mwaniki of repairing a handpump (credit: Tim Foster)

At the very least these shorter downtimes represent a significant benefit to the communities using these handpumps, purely by reducing the burden of collecting water from alternative sources further away. Reducing pump downtimes reduces reliance on other, often unimproved, sources and the increased time collecting water from that other source (Rosen, Vincent, and Rosen 1999; Fuente et al. 2020; Pickering and Davis 2012). Health benefit may also be generated from rapid repairs as the alternative sources used when the handpump is broken may be less safe to drink. The benefits of drinking high quality treated piped water are known, and at the other end the adverse effects of drinking poor quality contaminated water are similarly clear. The immediate effects of an intervention should manifest themselves relatively quickly in terms of reduced morbidity, even if the longer term benefits, such as improved physical and mental development of children, and economic benefits will take time to be realised and be difficult to unambiguously attribute to the intervention in question. Esrey et al. (1991) analysed 144 studies on the effects of improved water supply and sanitation on the morbidity and severity of a range of diseases, showing the unambiguous health benefits of having access to safe water, with subsequent studies having broadly similar findings.

Despite all the effort, study and investment in the intervening decades water related diseases remain a significant part of the global burden of disease, especially in LMICs and more needs to be done (Hunter, MacDonald, and Carter 2010; Bartram and Cairncross 2010; Cairncross et al. 2010) indicating that these issues are far from solved.

Efforts to improve water services have often been underpinned by the two inter-related assumptions. The first is that if a "better" form of water supply infrastructure is made available to households they will necessarily use it. The second assumption is that interventions and improvements will improve health outcomes by reducing the exposure of individuals and households to pathogens in poorer quality water. In the rural context in LMICs, the cost of water can be high relative to incomes, and it simply cannot be assumed that the proportion of household expenditure on water, and thus the price elasticity of demand for water, is low. This, coupled with the fact that there are often significant time or other cost considerations with respect to water collection, undermines the acceptability and uptake of single water source "solutions", leading to households switching between and/or mixing water sources (Elliott et al. 2017). WASH policies and interventions are often, to a greater or lesser extent, predicated on the assumption that the intervention will have a positive health impact, an assumption that may not be valid if people do not choose to drink water from the safest source available to them.

Table 1: PubMed.gov searches 2000 to 2019

Search terms	2000 to 2009	2010 to 2019	Increase	w.r.t. "water"
water AND supply AND intermittent	293	496	1.7x	0.9x (p<0.10)
water AND supply AND intermittent AND urban	16	53	3.3x	1.8x (p<0.05)
water AND supply AND intermittent AND rural	10	15	1.5x	0.8x
"drinking water"	13,507	27,802	2.1x	1.1x (p<0.01)
"water"	258,175	485,199	1.9x	reference

Source: https://pubmed.ncbi.nlm.nih.gov[2]

This table compares the number of articles from the PubMed database featuring specific terms in the title, over the periods 2000 to 2009 and 2010 to 2019. These are compared against the increase in articles with simply "water" in the title.

Related to source choice and whether interventions will in fact generate health benefits, is the role of supply intermittency and unreliability. To date most research on this has considered piped

[2] Interest in rural water supply reached its peak of 18% of "drinking water" papers in 1973, steadily declining to 5% in the last decade.

systems (Majuru et al. 2011; Majuru, Suhrcke, and Hunter 2016; Hunter, Zmirou-Navier, and Hartemann 2009; Hunter et al. 2005; Kumpel and Nelson 2016; Ercumen et al. 2015; Kumpel and Nelson 2013). Most of the research to date does not consider the impact of the actual variation in water use and consumption in rural areas, be that the use of multiple water sources through choice or necessity; there is little epidemiological data focusing on the transition from one state to the other, as opposed to comparing one state to another. Such a change cannot be artificially induced, in particular a transition from good to bad, and when such a change happens naturally, identifying and analysing it ex post is difficult.

In terms of managing maintenance operations so that they have the most benefit, the impact of intermittency and reliability must be understood. Knowing how quickly a pump must be repaired in order to avoid significant adverse health impacts is critical. A system that can guarantee to repair a pump (or any mechanical device, or piece of infrastructure, for that matter) within a day or two will be very different to, and more expensive to operate, than one only capable of effecting the repair within a week. Related to this is understanding how people actually use water supply sources, specifically, what triggers people to switch from the "best available" source. While the long-term goal may be to provide safely managed water for all, the effective management of the current sub-optimal situation remains a challenge. Given limited resources it is important to determine the benefit of providing a high level of service to a small number of communities, in comparison to providing a mediocre level of service to many. If we better understand actual handpump use, both by choice and due to breakdowns, we can optimise maintenance operations to maximise the health benefits of such services, and plan the investment in and deployment of resources more effectively.

Shared handpumps have brought water to many communities and households around the world. But they are an interim solution to providing universal, high quality water services. The limits of their technical performance are known. This PhD aims to explore the limits of their ability to deliver water *services*, by examining them within the context of a best-in-class maintenance system, and examining the limits of that system. My specific aims are to:

1. Discuss the role of professional maintenance in rural water service provision and how data can contribute to improving the performance and sustainability of these services.
2. Investigate the variability in handpump use in response to rainfall over both seasonal and short-term timescales.
3. Test the hypothesis that a reduction in pump downtimes leads to a reduction in water-related diseases in households receiving this repair service.

4. Discuss the interaction between this new knowledge about actual pump use patterns, and the health impacts of pump downtime, and the ability of professionally maintained handpumps to generate health benefits for the households that use them.

In answering these questions I will generate new knowledge on pump use variation and the impact of repair performance. I hope to increase the understanding of how rural communities use their water supply infrastructure, and to determine whether the service improvements generated from professional handpump maintenance generates actual improved outcomes for households.

I will situate this within the past and current debates on rural water provision and water-related health, building on this prior scholarship and adding to it. I will conceptualise, design and implement a number of study elements, and combine traditional and novel data gathering and analysis techniques in order to contribute something novel and substantive to this contested area of research. This new knowledge about rural water service provision and the epidemiology of water-related disease will be of interest to policy makers, public health officers, and those charged with the day-to-day running of rural water systems. The core of this work will be presented as four journal articles, three of which have been published during the course of this PhD, with the final one under review at time of writing. In support of these this thesis will have a review of the literature on water-related diseases, as pertinent to rural water provision, and background on the wider research in which this PhD sits. Following the presentation of the four journal articles, I will discuss the validity of these findings beyond the study itself, and their implications when considered together, covering additional elements that were beyond the scope of the individual articles. After reflecting on the process of conducting this research, I will conclude by suggesting what the implications of these findings may be for policy and practise in the rural water sector, in particular in regard to what role handpumps may have to play in achieving SDG 6.1.

Chapter 2 –Literature Review of Rural Water Supply and Health in LMICs

Introduction

While Safely Managed Water remains the goal for water services for all, the size of the task and difficulty in achieving it is acknowledged through the WHO/UNICEF Joint Monitoring Programme's (JMP's) Service Ladder, that includes—crucially—the interim service level of "Basic Water", the category into which most community managed rural handpumps fall. There are many reasons for aspiring to Safely Managed Water for all, but one of the main drivers, and that of much of the effort to improve water services more generally, has been the understanding that disease morbidity can be reduced through better water service provision. Piped chlorinated water to the home, the most usual conception of Safely Managed Water, is associated with lower disease morbidity, in particular diarrheal disease. But given that 29% percent of the world's population, and in the case of sub-Saharan Africa 76%, still lack Safely Managed Water (World Health Organization and UNICEF 2019), it is important to understand the health implications of having only Basic Water supply, and the variation that may exist even within that definition.

This literature review aims to do three things. The first is to examine the literature relevant to this study, in particular the emerging empirical literature on supply intermittency—as unreliable handpump services manifest themselves as an intermittent supply—and the modelling literature that predicts the health consequences of intermittent supplies. The second is to outline the Bradley Classifications, which are the lens through which this and many other studies examine water-related diseases within an operational context. Finally, noting the limitations of this study, it will consider Environmental Enteric Dysfunction (EED) and the health impacts of chemical contaminates, two issues that are highly relevant to water related disease in rural settings, but not examined in the empirical part of this PhD.

The literature on the relationship between water and human health is extensive and has a long history. In the opening of On Airs, Waters and Places (Hippocrates 400BC), "The Father of Medicine" stated: "Whoever wishes to pursue properly the science of medicine must… consider the properties of the waters". He continues, suggesting among other things that in areas where "[waters] are marshy, standing and stagnant" there will be in summer potentially fatal epidemics of dysentery, diarrhoea and malaria. While not all of Hippocrates' assertions would stand up to rigorous epidemiological scrutiny—and those related to how wind direction affects disease, any epidemiological scrutiny—these statements show that the association between water and health has been recognised for as long as the discipline of medicine as we know it has existed. Water was also a key concern of ancient engineering with respect to the public health of cities, most famously of the Romans. Aqueducts brought water into cities, with public latrines and sewerage piping wastewater away into the Tiber and public baths facilitating hygiene for all strata of society. In Natural History Pliny the Elder (77AD) describes the use of a double cistern to settle out impurities, indicating an acknowledgement of the need to undertake some form of water treatment. In more recent history poor public health in cities, and the role that water plays in this, continued to pose a challenge to city planners. Contemporaries Joseph Bazalgette (1819 to 1891) and John Snow (1813 to 1858) were key figures in London's struggles with this problem in the 19th century. The former engineered London's sewer system, one which remains in operation today over a century and a half later, and the latter gave birth to the field of epidemiology by way of his famous investigation of the Broad Street cholera outbreak of 1854 (Johnson 2006; Stanwell-Smith 2015).

As science advanced the understanding of disease, the medical profession was able to distinguish between different pathogens, the symptoms they caused, and how they could be medically treated. For example, Giardia and Rotavirus, both associated with poor quality water, have very different symptoms and treatments, the former being a protozoan that can be treated with chemotherapy, the latter being a virus and not treatable in the same way. WASH interventions, this thesis and the work behind it, are primarily interested in actionable information that can abate disease rather than determining strict causality (Renwick 1973). Those tasked with prevention would often be from an engineering, urban planning background and may not have necessarily been fluent in medical language and terminology. This more detailed understanding of pathogens, be that of the pathogen itself or its effect on the infected patient, may have had a downside. Any distance between medical professionals, primarily concerned with treatment, and those primarily concerned with prevention, is likely to have been to the detriment of efforts to reduce water-related disease.

The Bradley Classifications

White, Bradley, and White (1972) proposed a way of classifying water-related diseases that considered the mechanisms of transmission of these diseases, rather than the biology of the pathogen in question. The rationale behind this was that such a classification would aid the district engineers and public health officers charged with devising and implementing methods for their control. While never intended to represent a perfectly orthogonal set, or be the final word on water-related diseases, or their transmission, Bradley proposed classifying water-related diseases into four categories: waterborne, water-washed, water-based, and diseases with water-related insect vectors.

Table 2: The Bradley Classification for water-related diseases*

A CLASSIFICATION OF INFECTIVE DISEASES RELATED TO WATER*

Category		Example
I.	Waterborne a) Classical b) Nonclassical	 Typhoid Infectious hepatitis
II.	Water-washed a) Superficial b) Intestinal	 Trachoma, Scabies *Shigella* dysentery
III.	Water-based a) Water-multiplied percutaneous b) Ingested	 Bilharziasis Guinea worm
IV.	Water-related insect vectors a) Water-biting b) Water-breeding	 Gambian sleeping sickness Onchocerciasis

*Exactly as originally presented in White, Bradley, and White (1972)

WATERBORNE

Waterborne diseases are those that exist in water and are transmitted through water, and are what one might first think of when considering water-related diseases. Classical examples include typhoid (Marchello, Hong, and Crump 2019; Radhakrishnan et al. 2018), cholera (Davies, Bowman, and Luby 2017; Clemens et al. 2017) and other diarrhoeal diseases, such as those caused by pathogenic *Escherichia coli*. Waterborne diseases can be due to bacteria, viruses, helminths or protozoa, and can be of varying severity in terms of their symptoms. They are often transmitted by the faecal-oral pathway (Wagner and Lanoix 1958), and thus can overlap with water-washed diseases, now commonly illustrated with the "F-diagram" (Figure 1).

WATER-WASHED

Water-washed diseases are those which increase(reduce) in the absence(availability) of water for personal washing. As such, other than in cases of extreme contamination, they are not affected by the quality of the water used, so having sufficient access to water that is not suitable for consumption (e.g. river or pond water) will reduce the prevalence of water-washed disease. Example of this are skin and eye infections, such as scabies (Romani et al. 2015; May et al. 2019) or trachoma (Stocks et al. 2014; Mabey, Solomon, and Foster 2003), where the disease-causing agents are not themselves related to water but prevention and treatment is effected through washing. There is overlap between water-washed diseases and waterborne diseases, in that inadequate availability of water for washing hands after preparing food or for personal hygiene can lead to the ingestion of these pathogens.

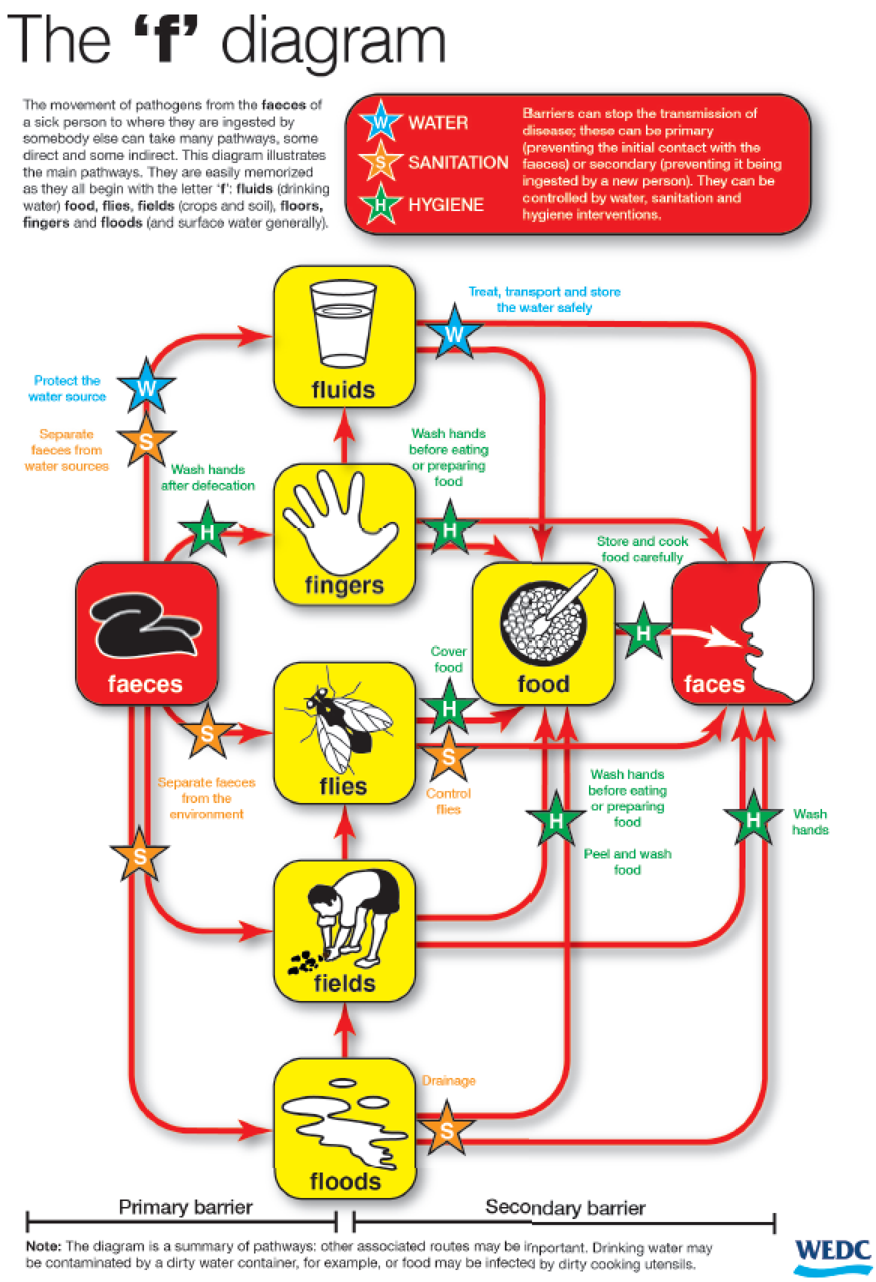


Figure 1: The F-diagram (WEDC, Loughborough University)

WATER-BASED

Water-based diseases differ from waterborne diseases in that water is not just the transmission mechanism for the disease, but is necessary for the pathogen's life-cycle. An example of this would be schistosomiasis (Fenwick and Webster 2006; Stothard et al. 2017; LoVerde 2019; Tchuem Tchuenté et al. 2017). The schistosome larvae or miracidia invade water snails, in which they grow into sporocysts which then release many cercariae, thereby multiplying, which in turn infect humans by burrowing into the skin. Neither the miracidia nor the snails themselves are pathogenic to humans, but control of the snail population will break the life cycle. In contrast, guinea worm infection or dracunculiasis (Cairncross, Muller, and Zagaria 2002; Greenaway 2004), needs water to complete its life-cycle, but only multiplies in the human host. The female adult worm, living under the human skin, produces eggs which develop into larvae before being shed into the water. Both guinea worm and schistosomiasis have complex life cycles. In the case of guinea worm this complexity has enabled targeted interventions, for example, changing the design of well-heads, and the near eradication of the disease (Molyneux and Sankara 2017; Hopkins et al. 2013, 2018). Schistosomiasis, on the other hand, is still widespread. That infection can occur percutaneously through bathing in or just walking through contaminated water, rather than though ingestion as in the case with guinea worm, makes control much more difficult.

INSECT VECTOR

The diseases in this class are those transmitted by insects that breed in water, or bite near it. This includes infections carried by mosquitoes, such as malaria, dengue and yellow fever, and of more recent emerging concern, Zika virus (Plourde and Bloch 2016; V. Sharma et al. 2020; Weaver et al. 2016). Due to the high contribution that malaria makes to the global burden of disease, mosquito control programmes are often conducted outside the WASH purview. These environmental control programmes, involving large-scale land management interventions and the use of DDT, before its disadvantages were realised (Curtis and Lines 2000) were hugely successful, with malaria being successfully eradicated from areas where it was previously endemic (Gentry 1967; Carter 2009; Kouznetsov 1977; Brown 1986). Water-related insect vector diseases in general and malaria in particular, tend not to be considered in WASH programming: WASH programmes tend to work at household or community level, whereas the geographical scale at which insect vector control programmes usually operate is larger. Water supply interventions have the potential to make an environment more amenable to breeding insects (Kibret et al. 2019). Inadequate drainage around pumps, supplying piped water to an area without consideration of the removal of waste or grey water, or irrigation programmes, can create a breeding environment for malaria vector mosquitoes.

Conversely, open household water storage to offset unreliable water supplies supports the breeding of *Aedes aegypti* mosquitoes, the vector of yellow fever, chikungunya, dengue and Zika fevers. As drug resistant strains of malaria evolve, of particular concern being Artemisinin-resistant *falciparum* malaria in southeast Asia (Phyo et al. 2012; Noedl et al. 2008; Wongsrichanalai et al. 2002) and climate change increases temperatures in areas previously too cold for mosquitoes to thrive (Pascual et al. 2006; Rossati et al. 2016; Liu-Helmersson et al. 2016, 2019), the environmental fight against malaria is becoming more difficult. But even with the increased focus on vaccine development (Moorthy, Good, and Hill 2004; Crompton, Pierce, and Miller 2010; Schuerman 2019) environmental control of insect vector diseases and how this links to WASH programmes should not be neglected.

The Drawers of Water study (White, Bradley, and White 1972) in which the classification system was first presented can be seen as highly influential in the run up to the UN's Mar del Plata conference in 1977 and the subsequent action plan (Falkenmark 1977) which led to the 'International Drinking Water Supply and Sanitation Decade' (1981 to 1990). Having water-related diseases classified in this manner made it much easier for non-clinicians to engage with them. Bartram and Hunter (2015) observe that the Bradley Classifications were explicitly developed in a tropical rural context, and their suggested useful modifications and additions to them, such as a new class of 'Engineering Water System Associated' which would include diseases such as Legionella. Notwithstanding this valid critique of their completeness and Bradley's own assertion that the classifications "have received perhaps more attention than they really deserved"[3], that the Bradley classifications are in widespread use nearly half a century later is a testament to their usefulness (Cairncross and Thompson 2002).

This study is considering water use patterns, and assessing the extent to which actions by those tasked with maintaining pumps might improve the health of water users. It is not intended to be a clinical study, having neither the expertise nor requisite approvals to be one. Its aim is to shed light on the extent to which actions within the scope of water service maintenance might affect health, rather than which specific pathogens may be responsible for morbidity in households. This focus on interventions and pathways makes the Bradley Classifications an appropriate framework for the consideration of water-related diseases for me to use in this study.

[3] Personal communication.

Health Impacts and Disease Burden

As interest in WASH (or WatSan as it was then called) increased in the 1980s and the so-called 'International Drinking Water Supply and Sanitation Decade' shone more light on the issue, and consequently resulted in more funding for both interventions and research. Steve Esrey and colleagues produced a number of review articles summarising research to-date on the effects of improved water supply and sanitation on the morbidity and severity of a range of diseases (Esrey et al. 1991; Esrey, Feachem, and Hughes 1985; Esrey and Habicht 1986). Esrey et al. (1991)examined 144 studies of the effect of improved water supply and sanitation on ascariasis, dracunculiasis, hookworm, schistosomiasis, diarrhoea and trachoma. For the more methodologically rigorous studies, around a third of the total examined, the average (and range of) median reduction in morbidities were:

Table 3: Disease reduction from improved water supply and sanitation*

Disease	Average reduction	Range %
Diarrhoea	26%	0-68
Trachoma	27%	0-79
Ascariasis	29%	15-83
Schistosomiasis	77%	59-87
Dracunculiasis	78%	75-81

** A review of 144 studies (Esrey et al., 1991).*

While these meta-analyses showed the unambiguous health benefits for water supply and sanitation interventions, of note is the range of median reductions in particular those for diarrhoea and trachoma, and that only a third of studies were viewed as methodologically rigorous. This would imply either the significant challenge of conducting rigorous studies in this field or the complexity of the problem itself, or both of these things. Focusing on those studies that investigated diarrhoeal disease reduction, Esrey et al. found that hygiene and sanitation interventions had the greatest impact, and water quality interventions the least:

1. Sanitation 36%
2. Hygiene 33%
3. Water and sanitation 30%
4. Water quantity 20%
5. Water quality and quantity 17%
6. Water quality 15%

More recently Fewtrell and colleagues have conducted a number of reviews and meta-analyses of studies of water, sanitation and hygiene interventions (Fewtrell et al. 2005; Fewtrell and Colford 2005). These studies confirmed the benefit of WASH interventions with effects broadly consistent with those shown by Esrey and his co-authors a generation earlier, with a few significant differences:

A. Water quality interventions had a greater impact than previously determined.

B. Water supply interventions (not related to water quality) were shown to have little, if any, impact of statistical significance.

C. Multiple interventions (i.e. those address a combination of water supply, quality, sanitation and hygiene) did NOT show a greater impact than individual interventions.

The first point is perhaps expected as between the Esrey and the Fewtrell analyses more emphasis has been put on improvement of water quality at household or point-of-use, rather than at source (Chiller et al. 2006; Reller et al. 2003; Crump et al. 2005), although systematic reviews have found that the benefits of certain point-of-use water quality and hygiene behaviour interventions are not sustained over the longer term (Waddington, Snilstveit, and White 2009; Arnold and Colford 2007). The second two findings are surprising, especially given that a reasonable water supply, in terms of quantity if not quality, is a prerequisite of certain good hygiene practises (Howard and Bartram 2003). While the distinction between the quality and quantity of water has long been considered as a critical one by health professionals—be they researchers or practitioners—they were not disaggregated in the technology-driven MDG target (Clasen 2012). The conceptual change from the infrastructure-oriented MDGs to the service-oriented SDGs, including the addition of the JMP's service ladder has aligned the global monitoring methodology more closely with the health benefits likely to be actually achieved by different interventions. This has coincided with more nuanced investigation into the actual health outcomes associated with different service levels and enabled this research to be situated in a clearer policy context.

The WASH Benefits study has tried to tease out some of these issues, focusing in particular on the impact on infants, through rigorously-designed, cluster-randomised trials conducted in rural Kenya and Bangladesh (Arnold et al. 2013a). These found no significant additional benefit from WASH interventions being added to nutrition programmes (Null et al. 2018; Stewart et al. 2018). This is consistent with third finding from Fewtrell and colleagues, noted above, (Fewtrell et al. 2005; Fewtrell and Colford 2005) which suggested that multiple interventions (i.e. those address a combination of water supply, quality, sanitation and hygiene) did not have a greater impact than individual interventions.

Wolf *et al.* (2018) caution against interpreting a minimal reduction in diarrhoea as indicative of an ineffective intervention, as an intervention may only target one of many pathways of faecal-oral transmission, making the individual intervention a necessary but not sufficient condition for reducing diarrhoea morbidity. Likewise, the increasing body of literature on water supply intermittency (Majuru et al. 2011; Hunter, Zmirou-Navier, and Hartemann 2009; Majuru, Suhrcke, and Hunter 2016; Hunter et al. 2005; Kumpel and Nelson 2016, 2013; Ercumen et al. 2015) illustrate that the full benefits of piped water can only be realised if supplies are reliable and a meta-analysis by (Wolf, Hunter, et al. 2018) showed that having high quality continuous piped water leads to a greater reduction in diarrhoea than intermediate service levels. In the context of non-piped supplies these may be intermittent due to poor maintenance and related governance issues, but users also often choose to switch between different water supplies based on seasonal availability and other factors (Elliott et al. 2017; Tucker et al. 2014; Pearson et al. 2016; Kelly et al. 2018; Thomson et al. 2019). Add to this the fact that source quality can vary based on seasonality and weather condition (Taylor et al. 2009; Kostyla et al. 2015) and it is clear that suggesting a simple stable link between the existence of a category of water supply infrastructure and a certain health outcome is unwise. The relationship between higher levels of service and better health outcomes is positive but the relationship is complex and non-linear, and evidence on this relationship is still emerging. Understanding the non-linearities and the points of inflection is vital when designing WASH programmes and interventions, to ensure the most effective use of—inevitably limited—resources.

Measuring the burden of disease

While the direct contribution to the worldwide disease burden from diarrhoeal disease is dropping (Wang et al. 2014), it is still considerable, especially in Africa where many still enjoy very poor water service provision. Diarrhoea itself contributes to the burden of disease for individuals and consequently to the Global Burden of disease: It is the cause of 1.31 million deaths worldwide, with 303,045 of those being of children under five in sub-Saharan Africa; for that same demographic it also causes 27 million Disability Adjusted Life Years (DALYs) (Troeger et al. 2017), which corresponds to around one in every seven DALYs[4]. This figure may significantly underestimate the disease burden from diarrhoea, and in turn from poor WASH. Diarrhoea interacts with nutrition,

[4] http://ghdx.healthdata.org/gbd-2017

reducing nutrient absorption (Lindsay 1997; Schlaudecker, Steinhoff, and Moore 2011). This is especially egregious in children as undernutrition can have long-term non-recoverable negative impacts on physical and cognitive development (MacIntyre et al. 2014; Lorntz et al. 2006; Patrick et al. 2016; Crookston et al. 2011) which can lead to long-term economic impacts and related policy choices (Connolly et al. 2012; Muangchana et al. 2012). Troeger *et al.* (2018) estimated the long term impacts of this interaction, finding that the DALYs in under-fives attributable to diarrhoea were potentially underestimated by 39% as a consequence of not taking these long-term effects into account. However, the authors of this study note that their calculation of this underestimation only included symptomatic diarrhoea, and not Environmental Enteric Dysfunction (EED).

Environmental Enteric Dysfunction, also referred to as Environmental Enteropathy, is a condition first identified in the late 1960s (Desai et al. 1969; Schenk, Samloff, and Klipstein 1968), the physiological manifestation being shortening of the villi in the patient's intestine resulting in the patient having an impaired intestinal function resulting in reduced ability to absorb nutrients. The condition is not fully and unambiguously defined, but can be described as "Subclinical Malabsorption" (Lindenbaum, Harmon, and Gerson 1972). A sub-clinical condition and thus one with no obvious direct symptoms or outwardly visible signs, it is believed to be endemic in areas of the world where water supply, sanitation and hygiene are generally poor. It is also believed to be a significant cause of child stunting (Crane, Jones, and Berkley 2015; Budge et al. 2019). Moreover, as well as being a cause of malnutrition itself, EED reduces the effectiveness of nutrition interventions. EED and the role that poor WASH play in it are the subject of the Sanitation, Hygiene, Infant Nutrition Efficacy (SHINE) project, a large multi-site study led by Johns Hopkins University (Humphrey et al. 2015). That EED is widespread and asymptomatic means that adverse gastro-intestinal health impacts of ingesting poor quality water may be larger than those captured by measuring diarrhoeal disease alone. This will be an issue for the DALY estimates for diarrhoea included in the Global Burden of Disease and any local measures (Troeger et al. 2018; Rogawski and Guerrant 2017). On the other hand, it may also follow that the benefits of improving water supplies are in fact greater than the effect seen when using diarrhoea as the indicator, but take longer to appear, as the recovery from EED is not measured in days and weeks as recovery from diarrhoea might be, but in months and years (Lindenbaum, Gerson, and Kent 1971), which may be longer than the period between an intervention and a study assessing its impact. This finding of the need for a long recovery time is consistent with the findings from modelling, discussed later on, that suggest a persistent negative impact of short-term ingestion of pathogen-contaminated water (Hunter, Zmirou-Navier, and Hartemann 2009; Brown and Clasen 2012).

Chemical Contamination

While most WASH interventions, and this study, address diseases caused by drinking water being of poor biological quality, health effects associated with the chemical quality of water should not be ignored. The “essential priority chemicals” defined by the WHO (Thompson 2007) are nitrate, fluoride, arsenic and selenium. Although some nitrates are naturally occurring, their presence is often indicative of contamination from excreta or industrial processes (Ward et al. 2005; Mansuri 2004; Fan and Steinberg 1996). In rural areas where much of the land is used for either animal agriculture of fertilised arable production, there is a risk of groundwater contamination by nitrates (Menció et al. 2016). Source protection and catchment management can be effective tools in reducing this. Conversely, most fluoride found in drinking waters is naturally occurring, and while low levels of fluoride contribute to bone and tooth health (Li et al. 2001), high levels such as those found in the Rift Valley in East Africa, are toxic (Edmunds and Smedley 2005; Wambu et al. 2014) making the natural groundwater quality deleterious to human health. While no level of heavy metals is beneficial to human health (Jarup 2003; Kim et al. 2011; Argos, Ahsan, and Graziano 2012), levels that are harmful are often naturally occurring. In such situations, rural water supply inventions based around source protection, which can be very effective in reducing bacteriological contamination, will have no impact, and the issue may be that local groundwater is fundamentally unsuitable as the main source of drinking water. The most egregious example of natural arsenic in drinking water is the case of Bangladesh (Acharyya et al. 2000) where rural households are presented with the unenviable choice of consuming bacteriologically contaminated surface water, or groundwater high in arsenic that will result in long-term arsenic poisoning (Edmunds, Ahmed, and Whitehead 2015; Alam et al. 2002; Kapaj et al. 2006). The fourth of these priority chemicals is selenium, less commonly found in natural waters, generally occurring in arid or semi-arid areas, and associated with uranium deposits (Hem 1985). Like fluoride, it is beneficial to human health in small doses – indeed, Brazil nuts are touted as being high in selenium - but is toxic in high concentrations, having been responsible for livestock deaths in the western United States.

Beyond the WHO’s four essential priority chemicals there are numerous others that are unwelcome in drinking water. A high-profile example is from the municipal water in Flint, Michigan, in the USA caused by a change to lower pH source water leaching lead from pipes (Hanna-Attisha et al. 2016; Pieper, Tang, and Edwards 2017; Bellinger 2016). There is emerging evidence that lead can be derived from the water system in small-scale rural systems as well (Fisher et al. 2021). Uranium is naturally occurring but the mining process releases it so that it finds its way into water supplies, as well as becoming airborne in the form of dust. Uranium is toxic both due to being radioactive and as a heavy metal and contamination from uranium mining is a particular problem in the southwestern USA, which disproportionately affects the Navajo Nation (Hoover et al. 2017; Blake et al. 2015). Of increasing concern globally, but more so in the urban context are emerging chemical contaminants, which may be by-products from industrial processes or pharmaceuticals excreted by humans (and livestock). This is an ever growing problem as industrial processes create new chemicals faster than regulatory bodies can assess them, and we do not yet have long-term data to assess their immediate or long-term toxicity. Some of these are Disinfection By-Products (DBPs) created during the treatment of wastewater, a process which perversely can create by-products that are more toxic than the original industrial chemicals which have been released into the water system or environment (Heberer 2002; Zhang et al. 2015; Richardson et al. 2007). In the absence of advanced wastewater treatment systems, DBPs are less likely to be an issue in the rural areas which are the subject of this thesis.

Finally, groundwaters can have different levels of salinity, either naturally or as a result of human intervention. High blood pressure may often be considered a diet-related health issue so mainly of concern in more wealthy countries, but is an increasing cause of DALY's in LMICs[5]. But high salt intake through drinking saline drinking water can also lead to hypertension in LMICs. In some cases pumped groundwater can be naturally saline, for example in the Maji ya Chumvi formations in the southern part of the Kwale study site. In other cases, groundwater salinity can be anthropogenic: over abstraction from coastal aquifers, or reduced river flows in delta regions, can cause saline intrusion into shallow aquifers used by communities for drinking water causing an irreversible increase in the salinity level of drinking water (Edmunds, Ahmed, and Whitehead 2015; Luh et al. 2017). This salinisation of wells is irreversible, and can cause health impacts beyond hypertension. Studying maternal health in coastal Bangladesh, (Khan et al. 2011) showed a link between urine sodium and drinking from saline groundwater, and increased (pre)eclampsia in prenatal women drinking saline groundwater compared to those drinking rainwater (Khan et al. 2014).

Modelling Approaches

Esrey, Feachem and Hughes (1985) proposed a model linking the level of ingestion of diarrhoea-causing pathogens to level of diarrhoea. By the authors' own account the model was "tentative and grossly simplified" but was "consistent with several established facts". To support the second assertion, the paper in which it was proposed also contained a review of 67 studies of WASH

[5] http://ghdx.healthdata.org/gbd-results-tool

interventions and their effects on diarrhoea morbidity and mortality, and it was discussed in light of those studies. In modern parlance, this would be considered a conceptual model, as distinct from a numerical model, and one that provides insights rather than answers, and is echoed in Robb *et al.* (2017) who also discussed the non-linear nature of the relationship between the reduction in faecal contamination and consequent reduction in diarrhoea. Numerical modelling has appeared more recently, with the application of Quantitative Microbial Risk Assessment (QMRA) to the rural water context (Enger et al. 2012; Hunter, Zmirou-Navier, and Hartemann 2009; Howard, Pedley, and Tibatemwa 2006; Brown and Clasen 2012). Such techniques allow scenarios to be modelled and the effects of planned interventions tested prior to implementation, all quickly and at low cost. Hunter, Zmirou-Navier and Hartemann (2009) used modelling to estimate the effect on health of unreliable water sources and conclude that very short term failures (a few days) resulting in water supply contamination can erase the annual health benefits of having a safe water supply in the first place. Similarly, Brown and Clasen (2012) modelled the effect of household water treatments to reduce bacteria, viruses, and protozoan parasites in water on water-related DALYs and found that a small decline in treatment adherence led to a disproportionate reduction in the possible health gains. The lengthy recovery period for EED (Lindenbaum, Gerson, and Kent 1971) may go some way to explaining the apparent inconsistency between this modelling and observed data, which has often used only symptomatic diarrhoea as its outcome variable. This raises the question of the usefulness of diarrhoea as an indicator for gastrointestinal disease.

Haas, Rose and Gerba (1999, 2013) in what is widely regarded as a key text on QMRA, however, caution against using this technique as a tool to predict actual health impacts and suggest that more validity should be placed in “actual” data from epidemiological studies than in “hypothesised outcomes”. This caution may be even more important when considering rural water supply. QMRA was originally developed in a very different context. A technique that has been applied to assess the risk of an outbreak scenario in an industrialised country may not necessarily transfer easily across to considering rural point sources. Pitchers (2011) also raises concerns about the dose-response relationships used in QMRA citing three issues: (a) the studies used to create these relationships often had few subjects, (b) extrapolation from large infective doses downwards may not be valid, and (c) cumulative exposure and immunity are not accounted for. Points (a) and (b) reinforce the warning from Haas et al. about using QMRA as a predictive tool rather than a technique for making a risk/no-risk assessment or accept/reject decisions. Pitchers’ point (c) is directly pertinent to the validity of using such a technique in the rural water context. A dose response curve generated from exposing test subjects to a pathogen of which their immune system has little or no previous experience (DuPont et al. 1971; Hass, Rose and Gerba 2014) may be appropriate for assessing the risk to a population used to fully treated drinking water in the event of, say, a failure of a chlorination unit at a water treatment plant. However it may not be representative for the situation where a population has been exposed to a low quiescent level of the same, or different, pathogens over some time, either from contaminated water or other exposures, such as food or proximity to animals. Such water supply and immunity issues will be writ large across rural Africa. Equally, dose-response relationships have generally been used to characterise an acute relationship between an input (pathogen) and an output (clinical symptoms) so are less likely to be able to characterize the less obvious, but deeply serious problem of EED.

Supply Intermittency

Intermittent water supplies are an uncertainty that households and individuals have to adapt to, and—like many uncertainties and complexities—the effect of these is often regressive in that it is easier for the well-off than the less well-off to adapt to them. For someone with their own storage tank in their compound, a pump to fill it and a housekeeper or watchman to switch said pump on, an intermittent supply is barely an inconvenience. For the less well-off water insecurity, including intermittency of supply, can result in a worry and emotional stress (Wutich et al. 2013; Bisung and Elliott 2017; Young et al. 2019). Intermittency's contribution to water-related disease prevalence has been acknowledged for some time. Esrey *et al.* (1991) identified studies from Nigeria, India and Burkina Faso that had noted a link between water supplies that were intermittent or unreliable and dracunculiasis transmission, as water users switched to sources where guinea worm resided. In the context of piped water supplies, the effects of intermittency on microbial water quality, and in consequence, diarrhoeal disease, are estimated to cause over 100,000 DALYs per year globally (Bivins et al. 2017). In piped systems intermittency can cause supply contamination from leaks when the pressure gradient reverses and material from the outside is brought in and when stagnant water facilitates microbial growth (Kumpel and Nelson 2014); this degraded water quality is likely to contribute to higher incidence of water-related diseases. Kumpel and Nelson (2016) found 15 studies that examined water quality at various points in systems that had outages: the studies looked at different system types; the characteristics of the intermittency was different, with supply time ranging from a few hours per day to 18 hours per day. They found no clear relationship between supply time and water quality: On the one hand Mermin et al. (1999) found 97% of samples from an 18 hours per day supply testing positive for faecal coliforms: on the other only 4% of samples tested positive in the study of a supply that only gave a few hours of water per day (Eshcol, Mahapatra, and

Keshapagu 2009). The reasons why intermittent water supply is bad and could lead to increase incidence of waterborne diseases are uncontroversial; the systematic study of intermittent water supply is difficult.

The specific study of the health impacts of supply intermittency has only begun to develop in more recent years, and is arguably even more difficult. In what the authors believed to be the first study to rigorously approach this issue, Majuru *et al.* (2011) conducted a prospective epidemiological study to measure the benefits of a new piped water supply system being installed in two villages. By chance, one of the supplies was highly unreliable, and thus somewhat by accident it became a study of supply intermittency. The finding was that while the health benefits from this system were lower than from the reliable system, the cases of diarrhoea associated with the unreliable system were still significantly lower than those for the reference community. This was a better outcome than previous modelling work that predicted that failures of only a few days could erase the annual health benefits of having a safe water supply (Paul R Hunter, Zmirou-Navier, and Hartemann 2009). There was anecdotal evidence that people used household water treatment when the system was in failure, and the authors also suggest that residual immunity might account for the better than expect outcomes, which is plausible in this case as the water supplies of the communities in question had just been upgraded, so immediately prior to the study would have had the same supply as the reference community. Conversely, a study comparing continuous and intermittent urban supplies in India, Ercumen *et al.* (2015) found only a difference in the more severe forms of water-related diseases (bloody diarrhoea and typhoid) and only in lower-income households. The authors also suggested that household-level treatment, which was more prevalent in high-income households, may have been the reason for only observing a difference in lower-income households. Considering cholera in eastern DRC, Jeandron *et al.* (2015) found that on the 12 days following a water supply outage, suspected cholera incidence increased by 155%, with 23% of cases attributable to the problematic water system.

By examining actual patterns of rural handpump use and the health impact of pump breakdown and repairs, this PhD aim to add to the literature on rural water intermittency more broadly as well as providing actionable information for the maintenance service provider working in the specific study area.

Chapter 3 – Project Background

Introduction

This PhD is situated within ongoing research at the University of Oxford's School of Geography and the Environment, and its sister institution the Smith School of Enterprise and the Environment. This work started in 2011 as part of the Smart Water Systems project, funded by the UK's Department for International Development (DFID) and continued with subsequent grants from DFID, UNICEF and UK's Economic and Social Research Council (ESRC), and Natural Environment Research Council (NERC). The kernel of this work is technological, starting from the research question of whether new information—in the form of mobile data—can improve rural water services, and the engineering innovation of the Smart Handpump that would become the research tool around which this question could be interrogated. This portfolio of research is not about the technology itself: it is social science research being conducted from a Geography department, with the technology being an essential part, but the mean not the end. It has supported five successful PhDs, which have studied topics from rural welfare and institutional design to groundwater modelling and machine learning.

As well as starting this work with my MSc thesis in 2011, my role in this has been as Co-Investigator and project manager, developing research ideas and turning them into fundable grants and then running these projects full-time. At the same time I have been design authority on all the engineering and technical aspects of this work. This part-time PhD evolved in parallel to this work, after I identified the possibility of using the technology that I had created and projects that I was running to generate detailed empirical data on handpump use and repairs and link these with weather patterns and household health. The work I was doing—both in leading the technological development and in setting up the handpump maintenance service—generated large quantities of data on handpump use and detailed records of the repairs undertaken by the projects mechanics. Combining these with data generated from multiple household survey rounds the project provided a unique opportunity to shed some light on the specific question of health benefits brought by faster handpumps repairs, and more generally, the relationship between water supply intermittency and health.

Smart Handpumps Project

As a response to the issues of rural water sustainability that will be reviewed in Chapter 3, and to address the specific issue of generating near real-time information able to trigger a professional maintenance response, I designed and built a prototype Waterpoint Data transmitter in the summer of 2011 (Thomson, Hope, and Foster 2012a). The main design choice for this was a primary sensor that would detect and determine pump use. A traditional flow sensor was rejected as this was unlikely to prove accurate when used with a handpump as flow sensors are designed to be used in pipes that are full and are constantly pressurised. Handpumps tend to raise water up into a small reservoir in the body of the pump, which then flows into the spigot under gravity. While it is possible to fit a flow sensor onto this spigot the flow through it will be intermittent, with the pipe never full thus giving an unreliable reading. While it might be possible to calibrate the actual volume abstracted by the pump against the volume indicated by the flow meter, the only way to do this accurately would necessarily involve restricting the flow of the water creating a potentially unacceptable back pressure that would affect the users' experience.

A second option was to use a pressure sensor or another means of detecting water in the reservoir. This would produce a binary - "water"/"no water" - measure which would show if the pump is being used. However, due to variations in manufacturing and installation, some of the reservoirs in the pump head do not fully drain into the spigot leaving some water remaining, which could hypothetically cause false positives. The strongest argument against the use of such a sensor is when pump maintenance is considered. This is the area of the pump that gets most attention and sees the most traffic of parts being removed and replaced, such as the rods and centralisers, so anything installed here is at risk of interfering with the maintenance process, or more likely, being damaged by it. This last factor was a compelling reason for using an accelerometer in the handle as the primary sensor. The handle is largely unaffected by maintenance actions, in most cases simply removed and set aside, so embedding an accelerometer in or on the handle minimised risk of damage to the sensor during repairs. An accelerometer was also viable from a cost point of view and small solid-state accelerometers are now ubiquitous in mobile phones and games consoles[6].

The final prototype design used an accelerometer to sense change in the tilt angle of a handpump pump handle, accompanied by a low-power microprocessor to package up these data and transmit them via SMS message. Initially aiming simply to monitor usage as a binary variable ("in

[6] some of the initial testing used a Nintendo Wiimote

use” vs. “not in use”), proof of concept testing in Zambia showed that the movement of the handle could be translated into approximate volumetric abstraction and that there were other artefacts in the data that had the potential to provide further useful information (Thomson, Hope, and Foster 2012a).

This attracted funding from DFID to run an operational trial. The prototype used for the initial proof-of-concept testing in Zambia was not viable as an operational piece of equipment: it was a grey box containing various Commercial Off The Shelf (COTS) parts that was strapped onto the pump and whose battery needed charging each evening as it would only last one day of testing per charge. The DFID funding enabled me to develop an operational version that could be fitted inside the handle of an Afridev pump. The key design criteria were: (a) power consumption and battery life to last a year; (b) ability to withstand an operational environment, in particular regarding temperature rain/moisture and constant use; (c) resistant to accidental damage or vandalism. The last factor had already been considered at the earlier design stage, being closely related to the need to not interfere with either pumps users or the mechanics operating and repairing the pump, and was one of the drivers behind using an accelerometer as the primary sensor.

The field-ready prototype took around a year to design, develop and manufacture, and took advantage of the fact that the Afridev pump handle was made from a length of steel tube, into which the electronics and battery could fit: This provided the dual benefits of protection from the environment and making this device unobtrusive, thereby reducing the likelihood of vandalism and theft. In order for the data being generated by the Waterpoint Data Transmitters (WDTs) to be able to trigger a repair we had to make the data available in a format that was useful for the mechanic and the wider project team; in parallel to the development of the hardware we developed a database and accompanying interface to present the data in the most useful way possible. To complement the WDT hardware, a database system was developed to capture the SMS data being sent, decode it and present it in way that intuitively showed handpump use and could be used by the maintenance team. Further description of the database can be found in Appendix 2.

Kyuso Trial Summary

Sixty six of these units were deployed for a year-long field trial in eastern Kenya in autumn 2012. This trial, funded by the DFID grant, was designed to link the automatically generated data on handpump use to a rapid maintenance service and see if such a data-driven maintenance service could deliver faster repairs and how the data contributed to any improvement in performance. We set up an office at the study site in Kyuso, in Mwingi-North sub-County, recruiting a local fundi[7] who had extensive experience of installing and repairing handpumps in this area. Half of the pumps were "actively managed" meaning that the repairs were triggered by the research team identifying a possible issue from the data, or by community members calling in. The other half was "crowdsourced", with repairs only triggered by the community and the data analysed only after the trial was over.

This trial was successful, reducing the average downtime of a handpump to less than three days, an order of magnitude improvement with respect to the baseline of a 27 days (University of Oxford 2014). At the very least, this reduction in days represented a significant benefit to the communities using these handpumps by reducing the burden of collecting water from alternative sources further away than their usual handpump. The results also showed that the "actively managed" group of handpumps had slightly shorter times to repair, although given that the selection of the two groups was not random there is a limit to what could be inferred from this.

[7] The Swahili word for mechanic

It was not possible to investigate question of health impacts as part of the Kyuso trial. On a practical level there were constraints on funding and timing, and the simple fact that until the trial was well underway we did not know how effective—if at all—the data-driven maintenance service would be in reducing pump downtimes. More fundamentally, even once the operational impact of the service became clear the number of handpumps and households involved in the Kyuso trial was not large enough to be able to convincingly reveal any health effect linked to this, even if there were one. Given an expected realistic size of any health effect, the population was not large enough for a study to have sufficient power to be statistically compelling.

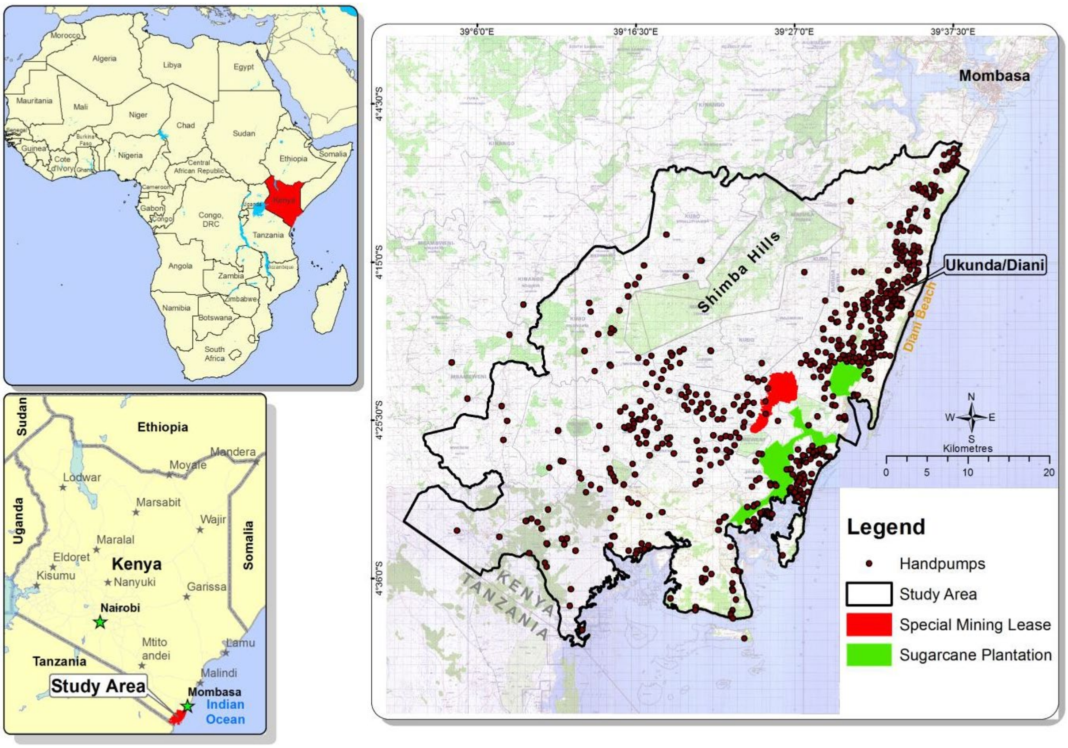
Fortunately, the Oxford team were successful in securing further RCUK grants to expand the Smart Handpumps research beyond the relatively simple technical and operational trial conducted in Kyuso. The first grant, the ESRC/DFID funded "New Mobile Citizens for Waterpoint Sustainability" project looked at rural poverty and water service provision, focusing on social and institutional aspects. The second grant, "Groundwater for Growth and Development" was part of the UPGro programme, jointly funded by NERC, ESRC and DFID. This built on the first but shifted focus to look at the linkages between rural poverty and groundwater through the lens of sustainable resource management, and the risks and trade-offs between economic growth and poverty reduction. While I was a Researcher Co-I and project manager for both of these projects, most of the data used in this PhD was generated under the "New Mobile Citizens for Waterpoint Sustainability" grant. Significantly this grant allowed us to deploy a large number of Waterpoint Data Transmitter and provide a free handpump maintenance service to communities for 18 months. This project was originally planned to be conducted in Zambia, but during the initial scoping phase, it became clear that the institutional environment was not conducive to new ways of thinking about rural water services. Instead we returned to Kenya, this time to Kwale County on Kenya's south coast[8].

Kwale County Background

Kwale County is located on the south eastern coast of Kenya, immediately south of Mombasa, Kenya's main port. It covers an area of around 8,300 km^2 and has a population of 720,000 with over four in five people living in rural areas (82%) and a poverty rate seventh highest out of Kenya's 47 Counties (Commission on Revenue Allocation 2013). While Kwale County covers a large area further

[8] How this initial phase of the project unfolded and led to the decision not to work in Zambia is interesting in its own right, but is beyond the scope of this thesis.

inland including Kinango sub-County, the study area for our research projects covered only 2,200 km^2 in Msambweni and Matuga sub-Counties nearer the coast. While these were not the primary factors in the decision to conduct the research here, the higher density of both population and handpumps than in Kitui/Kyuso made the handpump-related element of the research easier.



Picture 3: Kwale County study site and handpump location map

The coastal climate has a bi-modal rainfall pattern with an average annual precipitation of 1,400 mm with significant inter-annual variability. Around 50% of the annual precipitation falls in April, May and June. Rainfall is heaviest in the south and along the coastal strip, declining towards the north and inland. The study area straddles all or parts of three surface water catchments: The Mwachema basin in the northern part of the study area, which drains into the Indian Ocean north of Ukunda; the Mukurumudzi basin in the central part of the study area, flowing into the sea at Gazi; and the naturally brackish Ramisi river basin in the south of the study area, which discharges into Funzi Bay. These three rivers are perennial but exhibit large flow variation. Smaller ephemeral streams exist across the study area. The study area has two aquifers: a shallow unconfined aquifer, from which the handpumps draw their water; and a deeper confined aquifer from which larger abstractors take water using motorised pumps.

Major livelihood activities include agriculture, fishing and tourism largely based around the town of Ukunda and the international resort of Diani Beach. Recently two major new economic actors have arrived in Kwale. Kwale International Sugarcane Company Limited (KISCOL) has begun rehabilitation of 5,500 hectares of sub-surface irrigated sugarcane, as well as developing an outgrower[9] programme, feeding a sugar production plant near Ramisi. This has involved some deforestation for sugar cane planting, with sub-surface irrigation being serviced by both new surface water storage infrastructure and boreholes abstracting groundwater. The sugar produced here is targeted at the domestic market as Kenya's domestic demand of over 900,000 tonnes of sugar is currently around 50% imported (Mati and Thomas 2019). Sugar was previously produced in this area but faced a number of challenges, one being that the water from the Ramisi has naturally elevated salinity due to the Maji ya Chumvi formations in that area. The use of groundwater is in part to overcome this issue, in addition to providing extra volume of water for irrigation.

Picture 4: Sugarcane fields in Kwale (credit: KISCOL)

Further north in the study area is Base Titanium's Special Mining Lease. This is Kenya's largest mining operation, run by Base Resources Ltd., an Australian mining company. Aeolian deposits of titanium ore are taken from one of two dunes within a Special Mining Lease area of 1,660 hectares, processed by centrifugal concentration and partially dried before being taken by road to the port at Likoni and transported abroad for further processing. The first bulk shipment departed in February 2014 and, as of June 2019, the total mineral resources were estimated to be 285 million tonnes, the majority of this being Ilmenite[10]. The majority of the mine's output is shipped to Asia to be processes

[9] Independent farmers with contracts to sell cane to KISCOL for processing into sugar.
[10] http://basetitanium.com/kwale-project/project-overview

to make white paint pigment for white goods manufactured in Asia. This mine does not use chemicals as part of its primary process, but the centrifugal concentration process requires a lot of water in order to turn the raw material into a slurry before separating out the titanium ore. Around three quarters of the water used by Base Titanium is recycled, but this does nonetheless constitute a significant new water demand. All of Base's groundwater is drawn from the deeper aquifer, while KISCOL pumps from both the shallow and deep aquifers for irrigation. Further north, outside the study area, Kwale and Ukunda's municipal supplies are also drawn from a wellfield in the deep aquifer. Further details of the study site's geology can be found in Appendix 4.

Picture 5: Base Titanium processing facility (credit: Caitlin McElroy)

The time scale for sugar farming is indefinite, whereas the mine has a finite life, dependant on the mineral resources found and the rate they are extracted. Therefore the mine has an extensive environmental plan for rehabilitating the mine site and dunes when mining operations are completed, in addition to controlling the environmental impact of operations. This includes handing over their water storage infrastructure to the Kwale County government.

Table 4: Study Area Characteristics

Characteristic	Kwale/Msambweni	Kitui/Kyuso
Location	Coastal, 50km S of Mombasa	Inland, 250km NE of Nairobi
Study area	2,200 km^2	1,800 km^2
Annual rainfall	1,300 mm	780 mm
Elevation (a.m.s.l.)	0-90 m	~750m.
Population density	80 ppl/km^2	40 ppl/km^2
Pumps in study	300	66
Geology	Sands and corals	Pre-Cambrian basement

New Mobile Citizens for Waterpoint Sustainability grant

The premise of the ESRC-funded New Mobile Citizens research project was that a systemic information deficit has been a fundamental constraint to rural water supply sustainability. Having completed a technical proof-of-concept study in Kyuso that demonstrated that the Waterpoint Data Transmitters could generate data to assist mechanics to make faster repairs, the New Mobile Citizens grant aimed to examine whether this innovation help to promote accountable and transparent institutional and regulatory innovations for the rural water sector, by integrating this technology into a wider institutional and management context, and examining willingness-to-pay for professional services. The specific questions being investigated in this research project were:

1. Can real-time, low-cost, data provide useful information on waterpoint performance metrics to inform professional maintenance services?
2. Can transparent information on performance and payments help redesign new policy and regulatory regimes for rural water services?
3. What can a more detailed analysis of user payments tell us about the financial viability of professional maintenance services?

Operationally, this project included a number of interlinked elements designed to provide the information and data. The first was a waterpoint mapping exercise which recorded all the handpumps in the study area, both functional and non-functional. This was undertaken in August 2013. The second was a household survey conducted in October and November 2013 with 2,508 households who had access to a functioning handpump. The survey questionnaire included questions on: household make up and demographics; socio-economic status including key consumption and wealth indicators; basic self-reported health indicators for each household member; water use, collection and storage; waterpoint institutional arrangements, payment policies and behaviour. Households were randomly selected from those using each functional handpump identified during the earlier waterpoint mapping exercise (mean of 6.3 households per waterpoint, 4.6 residents per household). Third, we installed 300 waterpoint data transmitters between December 2013 and February 2014 to generate use data on for the handpumps and feed into the rapid maintenance service. These generated data over the next 12-18 months, the period in which we were providing a free rapid repair service. Fourth, the two fundis and their manager who were providing this service kept detailed records of all repairs undertaken, the most significant details being when the repair was first identified, when they attended, when the repair was competed, the nature of the failure and the spare parts used to effect the repair. Another household survey was conducted in March, April and May 2015. This was essentially a repeat of the first survey, the aim being to see what had changed for the communities in the study area during the time of the project, specifically in relation to the pump repair service. Elements of these household surveys will be used as a source of data for this PhD, but not all. The question of handpump use and breakdown, and their impact on the health of households using these pumps, is only one of a number of avenues of research that used these household surveys, which were collaboratively designed by the research team to fulfil the needs of the project and three other PhD studies based in the same study site in Kwale.

The overarching research questions were: (1) whether a hypothesised data-driven maintenance model for rural water could work; (2) how this would impact rural poverty and welfare (3) and what was the institutional context in which this could operate in the long term. The final point, encompassing the local context and financing of rural water to the national legal context and international discourse on rural water are key considerations when looking at the long term sustainability of the management model. This took the technological side as a given, both in terms of the Smart Handpump data, but also mobile payments in particular and the existence of mobile communications more generally. While interdisciplinary, and having technological innovation at its core, this was primarily a social science research project.

Chapter 4 – Related Research and Prior Art

While this PhD represents a distinct piece of research, as an active researcher at Oxford University working on a number of projects prior to starting this PhD. Through these I authored a number of publications in the broad field or rural water service provision, some of which are closely linked to this PhD—and cited in it—and others only tangentially. This section lists related publications that I authored before and during the course of this PhD, and outlines how they relate, or not to the work presented in this thesis. (Given the nature of review and publication timelines the publication dates provide only a limited indication of which work preceded which.)

Prior Art related to the work undertaken during this PhD:

1. Thomson, P., Hope, R. and Foster, T. (2012) GSM-enabled remote monitoring of rural handpumps: a proof-of-concept study. Journal of Hydroinformatics, 14(4): 829-839.
2. Thomson, P., Hope, R. and Foster, T. (2012) Is silence golden? Of mobiles, monitoring and rural water supplies. Waterlines, 31(4): 280-292.
3. Hope, R., Foster, T. and Thomson, P. (2012) Reducing risks to rural water security in Africa. Ambio, 41(7): 773-776.

The first two papers (Thomson, Hope, and Foster 2012a, 2012b) respectively describe the engineering/technical theory behind the water points data transmitters developed to monitor handpumps, and the conceptual as aspects of monitoring rural water systems. Technical aspects that build directly on the first paper are included in the appendices of this thesis to give the reader an understanding of how some of the data used in this thesis was generated and what the professional maintenance service provider would be using and what data it would have access to, but the existence of the technology is taken as a given for the purposes of this thesis and the papers that comprise it. While the cross-correlation method used in Chapter 8 (Thomson et al. 2019) will be familiar to signal processing engineers, there is no engineering in this thesis. The third paper (Hope, Foster, and Thomson 2012) addresses the problem of information asymmetry in rural water and how the use of data, in particular the Smart Handpumps, may be able to reduce this. While related to the other papers and the work contained in this thesis, this is not a necessary foundation for it as the other two are.

Related publications undertaken while working on this PhD (Social Science):

1. Koehler, J., Thomson, P. and Hope, R. (2015) Pump-priming payments for sustainable water services in rural Africa. World Development, 74: 397-411.

2. Koehler, J., Thomson, P., Hope, R. (2016) Mobilizing Payments for Water Service Sustainability. Chap. 6 in, Thomas, E.A. (ed.) Broken Pumps and Promises: Incentivizing Impact in Environmental Health. Springer International Publishing. pp. 57-76.
3. Foster, T., Willetts, J., Lane, M., Thomson, P., Katuva, J., Hope, R. (2018) Risk factors associated with rural water supply failure: A 30-year retrospective study of handpumps on the south coast of Kenya. Science of The Total Environment, 626: 156-164.
4. Koehler, J., Rayner, S., Katuva, J., Thomson, P., Hope, R. (2018) A cultural theory of drinking water risks, values and institutional change. Global Environmental Change, 50: 268-277.
5. Katuva, J., Hope, R., Foster, T., Koehler, J., Thomson, P (2020). "Groundwater and Welfare: A Conceptual Framework Applied to Coastal Kenya." Groundwater for Sustainable Development 10 (April): 100314.

These papers were part of the DPhil submissions of three Oxford University graduate students, whom I supported as both an academic colleague and through managing the research projects their studentships were linked to. Both the ESRC-funded New Mobile Citizens grant and NERC-funded UPGro project had linked studentships. The doctoral research projects studied: (a) the financial sustainability of handpumps through examination of user payments and methods of charging; (b) the institutional aspects of water user committees and whether users would pay for a professional maintenance service; (c) links between household welfare/poverty and groundwater, taking an analytical approach using GIS and principal component analysis. These research projects were undertaken at the same time and in the same place as mine, using different data from the same household surveys. None of these DPhils addressed handpump use patterns, the operational aspects of FundiFix or the health aspects of the professional maintenance service. The project PI's own research which investigated preferences for different management models and payment modalities for rural water service provisions, did not address these issues either.

Policy papers with a loose link to this PhD:

1. Hope, R., Thomson, P., Koehler, J., Foster, T. (2019). Rethinking the economics of water in Africa, Oxford Review of Economic Policy, 36(1): 171-190.
2. Hope, R., Foster, T., Koehler, J., Thomson, P. (2019). Rural Water Policy in Africa and Asia. In Dadson, S.J. (Ed.), Water Science, Policy and Management: A Global Challenge (pp. 159-179). Chichester: Wiley.
3. Charles, K., Nowicki, S., Thomson, P., Bradley, D. (2019). Water and Health: A Dynamic, Enduring Challenge. In Dadson, S.J. (Ed.), Water Science, Policy and Management: A Global Challenge (pp. 79-117). Chichester: Wiley.

4. Thomas, E., Jordan, E., Linden, K., Mogesse, B. Hailu, T. Jirma, H., Thomson, P., Koehler, J., Collins, G. (2020). “Reducing Drought Emergencies in the Horn of Africa.” Science of the Total Environment. Elsevier B.V.

As a research team we collaborated on policy papers on topics linked to rural water supply. These policy papers contain no original research. They are informed by the work the research team did over a number of years and grants, including by some of the work in this thesis. There are some similarities in the broad themes and arguments in the later sections of this thesis.

Related publications undertaken while working on this PhD (Machine Learning):

1. Colchester, Farah E., Heloise G. Marais, Patrick Thomson, Robert Hope, and David A. Clifton. 2017. “Accidental Infrastructure for Groundwater Monitoring in Africa.” Environmental Modelling & Software 91 (May): 241–50.
2. Greeff, Heloise, Achut Manandhar, Patrick Thomson, Robert Hope, and David A. Clifton. 2019. “Distributed Inference Condition Monitoring System for Rural Infrastructure in the Developing World.” IEEE Sensors Journal 19 (5): 1820–28.
3. Manandhar, Achut, Heloise Greeff, Patrick Thomson, Rob Hope, and David A Clifton. 2020. “Shallow Aquifer Monitoring Using Handpump Vibration Data.” Journal of Hydrology X, June: 100057.
4. Sharma, P.; Manandhar, A.; Thomson, P.; Katuva, J.; Hope, R.; Clifton, D.A. Combining Multi-Modal Statistics for Welfare Prediction Using Deep Learning. Sustainability 2019, 11, 6312.

The first three of these papers (Greeff et al. 2019; Colchester et al. 2017; Manandhar et al. 2020) were outputs of the work with Oxford University’s Institute of Biomedical Engineering (IBME). This collaboration was started to further develop the idea of using the vibration noise data generated by the Smart Handpumps for aquifer monitoring and failure prediction. I knew that this was possible but lacked the expertise to pursue it any further unaided. This thesis does not contain any research into machine learning or artificial intelligence. The papers above are cited in Chapter 9 (Thomson 2020) and the later sections of this thesis. The final paper (P. Sharma et al. 2019) applies machine learning techniques to welfare data to see if more advanced analytics and reveal more from the data that more established techniques, and is related to this thesis in that it refers to the same study site and uses some data from the same household survey.

Chapter 5 – Project Rationale and Approach

Introduction

The WHO/UNICEF Joint Monitoring Programme began in 1990 at the end of The International Drinking Water Supply and Sanitation Decade and was the obvious body to take on the task of monitoring progress towards the Millennium Development Goals (MDGs) when they were agreed ten years later, goals we hoped to reach by 2015. Bartram *et al.* (2014) provide a review of the JMP's role and the evolution of the monitoring process over this period. The MDG target of halving the proportion of people without access to an improved water supply was met, and met early. The Joint Monitoring Programme (JMP) stated that MDG target 7c was met in 2010, with an estimated 89 percent of the world's population having access to "improved" water sources compared to 76 percent in 1990. While easily measurable simply by observation, "improved" merely defines the source and not the water emanating from it. This limitation was acknowledged as the MDGs gave way to the 17 Sustainable Development Goals (United Nations, 2015), the greatest conceptual difference between the MDGs and water SDGs can be summed up as a shift from thinking about infrastructure to thinking about services, a shift from focusing on things to focusing on people.

Under the SDGs the new water and sanitation Goal 6 is to "ensure access to water and sanitation for all" and the water supply target 6.1 beneath goal 6 now mentions "safe" water thus directly referring to the water itself and not just the source, stating "by 2030, achieve universal and equitable access to safe and affordable drinking water for all". The JMP's experience in monitoring the MDGs made it the natural lead in the debate over monitoring progress towards the SDGs and the definition of the indicators to be used. While "safely managed water" is the formal SDG indicator by which progress is measured, the JMP's methodological note also describes a "service ladder" starting with the use of surface water, to unimproved water, then to basic water and finally to "safely managed water" and states that: "Countries will need to reach universal coverage with a basic level of service before universal coverage of 'safely managed services' can be attained, and progress towards universal basic coverage should be seen as an important and necessary step towards reaching the SDG targets." Debate about how to achieve the SDGs, and how to monitor progress beyond 2030 continues, with an acknowledgement that progress and the monitoring of progress and not independent (Bartram *et al.*, 2018).

This thesis and the research described in it engages with this issue. The availability of data has created an opportunity for a substantial rethink of how were address both the delivery of these water services, and how we monitor them. Chapter 6 (Thomson and Koehler 2016) addresses this, in particular examining ideas around using the same monitoring for both operational and M&E

purposes, and the role better data can play in being more responsive to user preferences, preferences that may not be captured in current measures of performance. Crude measures of reliability and availability may not in fact reflect users' preferences or their health-influencing responses. For example, the household storage needed to cope with a pump that regularly breaks but is always repaired within a day is less than what would be need for a pump that breaks less often, but takes a week to be repaired.

The Smart Handpumps project has developed around the premise that better data flows can enable a redesign of rural water service delivery leading to more reliable water supplies, in the form of reduced handpump downtimes. This has successfully passed the proof-of-concept phase and further research into the service delivery and financing models is continuing alongside practical development and implementation. The repair service set up as part of this project, FundiFix, guarantee repair within three days. This is based on choice experiments undertaken with the communities in question, which suggested that households did not value a service that took more than a few days to complete a repair (Hope, 2015), and a consensus on what we thought was "good" and operationally possible. Other than assuming that the shorter the downtime the better, the choice of a three day was not based on a detailed understanding of how the benefit to pump user vary with time to repair. We have little information on how the utility to the household changes over these days other than that the utility drops to zero at five days. Some of the benefit from faster repairs can be quantified in terms of costs avoided. For example, if the next nearest handpump is 550m away from the one that is broken, as is the case in the study site, each day of downtime would generate more than a kilometre of extra walking for each trip made to the pump.

But one of the reasons—if not the main reason—that improving rural water services is viewed as so important is the expected health benefits that these improvements will bring to households. The negative impacts of supply intermittency or unreliability, short-term outages that may lead households to use less safe sources, is under-researched in the rural context. Chapter 7 examines the relationship between the performance of the handpump repair service, in terms of the speed of repair or handpump downtimes, and diarrhoeal disease. In doing so it is hoping to generate empirical evidence to support or refute the evidence from modelling that points to a non-linear relationship between operational performance and health benefits, that requires very high performance to realise health gains (Paul R Hunter, Zmirou-Navier, and Hartemann 2009; J. Brown and Clasen 2012).

The JMP's definition of "safely managed water" includes the requirement of being on-premises. Being off-premises by definition, *community* handpumps are unable to provide "safely managed water". But the evidence as to the health benefits of water services at intermediate levels is ambiguous; generating additional evidence to help fill this gap can inform WASH policy and practice. Better understanding the cost-benefit ratio of providing different levels of water services will allow for better informed allocation of resource. In the light of the non-linear relationships discussed above, the allocation of resources aimed at broadly the same problem will yield very different results depending on the specific focus of the intervention. These are not hypotheticals trade-offs. There is an acknowledgement that we are not on track to achieve SDG 6.1 by 2030 (United Nations 2019; Sadoff, Borgomeo, and Uhlenbrook 2020). This raises the uncomfortable question off what proportion of effort is best spent moving people up the JMP's service ladder from lower to intermediate levels versus from intermediate levels to the top? Data and evidence are essential to be able to make difficult decisions. Taking the specific case of handpump maintenance services, this translates into a concrete operational question: what would be the benefit of guaranteeing, say, a 48 hours repair or a 24 hour repair instead of the 72 hours currently guaranteed? The cost of providing a service with such guarantees goes up as the guarantee time goes down, and will likely do so non-linearly; given the unpredictable nature of pump breakdowns, as the guarantee time goes down, the need for excess capacity to meet that guarantee increases. This makes the marginal operational cost of moving from 48 hours to 24 hours greater than that associated with moving from 72 hours to 48 hours, even though both represents the same improvement in uptime.

I primarily developed the WDT to generate data to support handpump maintenance. During this development process I realised that the WDT could also be used as a research tool, as it provided unprecedented granularity on handpump use. Once data started to be generated in large quantities, the details of handpump use patterns were revealed, and crucially the heterogeneity between pumps and variability over time in these use patterns became clear and fascinating. This variability is not random, but the result of thousands of individual decisions by pumps users, based on factors of supply and demand. When do they want water? How much water do they need? Do livestock need watering? Do they wish to avoid queuing or go to the pump when they know other people will be there? Do they know if the pump working? Is it producing sufficient water? How does that water taste at this time of year? Do I think that the water is safe to drink? Do I have an alternative? The aggregate of some of these decisions may be indistinguishable from noise, but one clear signal that came through from the data was that there was a relationship between pump use and rainfall, over both short and long timescales. Chapter 8 (Thomson et al. 2019) looks at this relationship in detail, disaggregating the short-term and seasonal effects. The latter is well-known but rarely quantified; the former is one that is not widely reported, and has implications for the other topics addressed in this thesis, namely the nature of how Basic water services are actually used and the health consequences of how they are used and maintained. The health implications of an *involuntary* break in handpump use, i.e. a breakdown, are addressed in Chapter 7. But the drop in pump use quantified in Chapter 8 may be a result of *voluntary* breaks in use. These too may also have health and service level implications. How these elements interact is discussed further in Chapter 10.

Chapter 9 (Thomson 2020) is a review of the field of the remote monitoring of rural water systems, and its role in improving the performance and sustainability of rural water services. This field is dominated by only a handful of actors, not all of whom publish peer-reviewed work. This makes for a review that is simultaneously thorough and limited. Despite much of this being my own work I have tried to examine it critically[11]. This PhD was also an opportunity to apply a range of data gathering and analysis techniques, some traditional, some novel, and some taken from different disciplines, to a set of related questions. Interdisciplinary research is difficult as it requires those undertaking it to have a range of knowledge and experience, and the ability to knit those together (Barthel and Seidl 2017). While the four individual papers to all contain elements from more than one discipline, they do sit fairly tightly within boundaries defined by their fields and the journals that published them. Chapter 10 of this PhD thesis bring connecting threads from these different elements together to draw some wider conclusions that were not possible in the individual papers alone.

[11] This paper was not published at the time of the original thesis submission. What was the original submission's Chapter 3 (Rural Water Supply Literature Review) is now contained in this paper.

Questions and Data

The philosophy behind this research was that of an observational study, centred on handpump use and breakdown. Handpump have been breaking down and being repaired across rural Africa for decades, with billions of litres of water pumped each week. Firstly, I have data on actual handpump use at an unprecedented scale and level of granularity: hourly data for almost 300 pumps for 18 months. This provides insights into patterns of use in both temporal and spatial dimensions, from daily to seasonal patterns for individual pumps and across multiple pumps. These patterns can speak to the question of how the presence of water supply infrastructure translated to the actual water services provided by said infrastructure, a key consideration for SDG-era.

The second key dataset generated during this project was detailed records of all the repairs undertaken as part of the free maintenance service provided to 200 of the 300 handpumps over nearly two years. These records included when the repair was first identified, when the mechanics attended, when the repair was competed, the nature of the failure and the spare parts used to effect the repair. Handpump breakdowns will have health impacts, but, due to the level of certainty and granularity required for any rigorous examination of the link between the two, these have to-date been unobservable at an individual pump level. A study that stopped handpumps working and then observed the consequences of this would be unacceptable from an ethical standpoint. If combined with household health data, the detailed repair logs created the opportunity for an observable natural experiment. The breakdown of the handpumps was effectively random in that it was unpredictable by either the study participants or investigators, but observable; the length of the breakdown, and thus time the communities in question were without water, while not random, was variable. The household surveys being undertaken as part of the wider research project generated the outcome variable of self-reported health data, as well as data on potential confounding factors to be used for adjustment at the analysis stage.

Experiment vs. Observation

The maintenance service was clearly an intervention, but as a study this was effectively an observational trial, one that Blum and Feachem (1983) would call ‘opportunistic’. While set up by the same person, the intervention was not undertaken for the purpose of the study: the intervention was not designed around the needs of the study; households were not controlled or influenced in any artificial way other than receiving the free maintenance service; and there were no different variations/strata of intervention applied to different households; the survey enumerators and mechanics were managed independently and blinded to each other's activity and data. As all households in the treatment area received the free service and households who said that they did not use the handpump as their main source of water were excluded from the analysis, it was arguably more akin to an efficacy trial than an effectiveness trial, even though this was not a trial undertaken in a controlled or laboratory environment.

An observational study, using the handpump use data, was clearly the most appropriate choice for investigating short-term and seasonal variations in handpump use. To investigate the impact that breakdowns and repairs might have on health, a different type of study might be preferred. Randomised control trials (RCTs) are considered the gold standard for evaluating the efficacy of an intervention in clinical settings, be that a drug trial or even surgical procedures and emergency medicine (Beard et al. 2015; Bell et al. 2015). RCTs offer statistical validity by eliminating potential biases and averaging out the effects of confounding factors. They lend themselves well to trials with large sample sizes in well-controlled environments, especially where blinding or double-blinding are possible. RCTs have been used on non-clinical setting for many years (R. A. Fisher 1960) but they have gained particular favour recently, in the poverty reduction and policy spheres (Pearce and Raman 2014), not least on account of the success and exposure of the MIT-based Abdul Latif Jameel Poverty Action Lab (J-PAL), whose principals were awarded the 2019 Nobel Prize for Economics (Abhijit Banerjee et al. 2019; Abhijit Banerjee, Barnhardt, and Duflo 2018; AV Banerjee, Banerjee, and Duflo 2011; Das et al. 2016). Such is the support for RCTs, there is currently a sentiment expressed by some that they are the only study design from which causality can legitimately be inferred.

With WASH at the nexus of poverty reduction and medicine, RCTs have also been used to evaluate WASH interventions (Arnold et al. 2013b; Crump et al. 2005b; Luby et al. 2006; Reller et al. 2003; Aw et al. 2019; Cameron, Olivia, and Shah 2019; Hammer and Spears 2016). However, RCTs for WASH have been difficult to implement in practice. Cairncross et al. (2010) found inadequate randomisation, a lack of placebo and no assessment of compliance in a number of RCTs or quasi-RCTs evaluated for a systematic review. When evaluating WASH (or indeed nutrition) interventions, full randomisation by individual or even by household is not usually feasible or even theoretically valid: it is impossible to ensure that treatment and control households don't interact, e.g. by sharing or trading the intervention, and for many interventions related to hygiene and disease the causes and effects can be at community level. Likewise blinding and the use of placebos for evaluating WASH interventions, often difficult even under more favourable conditions (Colford et al. 2002, 2005, 2009), is practically very challenging in a rural LMIC context and extremely problematic from an ethical standpoint, given issues of education level and literacy, and informed consent.

Cluster randomisation can be used to address some of these issues. This can substantially increase the required sample size, and consequently the cost, or require the collection of covariates for statistical adjustment of the analysis afterwards. And the more an RCT deviates from the ideal RCT in this way, the weaker is its claim to be freer from bias than other study designs (Fuente and Whittington 2012; Deaton 2010). If great efforts are made to ensure that a study conforms to the archetypical RCT, it may be that the study delivers a very rigorous average treatment effect and little else (Deaton and Cartwright 2018). A statistically robust top-line number may sometimes be what is needed, but a stand-alone field trial of a WASH intervention is costly and time consuming, whether an RCT or any other type. Piggy-backing research on existing WASH intervention programmes makes practical sense. It can be messy from a strictly scientific standpoint, due to numerable confounding variables and the difficulty of disaggregating the effects of often combined interventions (e.g. water supply improvement plus hygiene behaviour education). But in dealing with this messiness, an observational study or evaluation can glean additional knowledge and understanding, often qualitative and sometimes innumerable. This additional nuance and context can be of huge benefit to the practitioners and policy makers who researchers hope will pick up their studies and implement their findings. Despite, in some cases, and I would argue that this is one of those cases, observational studies being the only practicable option for undertaking research and generating empirical evidence, they are nonetheless currently considered the poor cousin to RCT, in spite of the limitations outlined earlier (Fuente and Whittington 2012; Deaton 2010; Deaton and Cartwright 2018). Where observational studies sit within the generally accepted hierarchy of evidence generates added pressure to justify the choice of an observational study and ensure its rigour.

Beyond the general reasons why RCT are problematic in certain contexts, in this project there were specific compelling reasons why an RCT was not appropriate. Ethical reasons made intentionally randomising breakdowns out of the question, but randomising the repair service itself was also unacceptable, as making a random assignment of the free handpump repair service would have co-located controls close to treatment handpumps getting the free service.

1. This could have biased the results as control handpumps could have been abandoned in favour of treatment handpumps after the first control failure, in what could be viewed as a reverse John Henry effect. This is a risk in the coastal strip in particular, where pumps

are often extremely close together. Full randomisation would likely have resulted in a treatment pump being only a few hundred metres from a control pump.

2. Such co-location could also have generated local tensions, potentially between communities, and certainly for our mechanics. It would have been extremely difficult for them to travel past a broken handpumps which they were not going to repair, on their way to those they were going to repair free of charge. There would have been great pressure for the mechanics to undertake repairs.
3. Related to previous point, such a random assignment would have generated ill-feeling towards the project as a whole, and so potentially towards the enumerators when they were conducting the second household survey. This could have created a loss to follow up bias, which would have affected all the survey responses, impacting the other PhDs and research using this survey data.

Taking the intervention or exposure to be the breakdown of a handpump and its subsequent time to repair, while we could not control that exposure, I did have available detailed information on the nature of that exposure, in the form of the mechanics' records. If pump breakdowns were effectively random (i.e. unrelated to the outcome and its possible covariates, if not truly random), this observational study was in effect a natural experiment. Observational studies that take the form of "natural experiments" have a long history in epidemiology with perhaps the best known, and most directly relevant to this study, being John Snow's investigations of the outbreaks of cholera in London in 1853 and 1854. The anecdata of the infamously unlucky lady from Hampstead taking water from the Broad Street pump and the workhouse with the separate well tend to get more attention in the public consciousness (Johnson 2006; Stanwell-Smith 2015), but the natural experiment which generated the most compelling epidemiological data was as a result of there being two water suppliers, Southwark and Vauxhall, and Lambeth, who respectively had their water intakes further downstream and upstream. These two companies supplied their water to the same areas of London with an apparently random assignment (Hill 1953; Godwin 1859), but with a ten-fold difference in mortality rates. Arguably I did not have an entirely natural experiment. Unlike the situation in south London in 1853 and 1854, this was not an "unwitting experiment on the grandest scale" (Hill 1953). This was an experiment that I had designed, but I did not have control over the key exposure variable. The key advantage here was that having control over the start of the intervention period, if not the individual interventions/exposures, allowed for a baseline survey to be conducted before the experiment began.

Covariates and observational rigour

A modern version of Snow's study—if it were funded (Rothman 2016)—would have certainly collected covariates and adjusted the analysis for age, sex, co-morbidities or socio-economic status. Analysis of these may have revealed more insights into the risk factors for dying from cholera, but are unlikely to have had a significant effect on the primary finding, that those consuming water drawn further downstream on the Thames were more likely to die from cholera. I was fortunate to have access to more data. The initial trial in Kyuso generated unprecedented data on handpump use and demonstrated that a data-driven maintenance service can greatly reduce pump downtimes. It was not accompanied by an extensive household survey. It generated insights into handpump use patterns, but it could not answer many "what does this mean?" questions. In contrast the New Mobile Citizens research project in Kwale County has generated a combination of datasets that provide a means to dig into these questions. These surveys, matched by household, generated longitudinal data, before and during the trial. These generated further observational data that provided important covariates and enabling the identification of confounding factors.

A case-control design is another study option for examining the possible causes of disease. This type of design would have been possible given the survey data, which would have allowed for the identification of appropriate controls. Case-control studies are more suited to situations where there is not a hypothesis for a causal suspect—in this case the breakdown—that one wants to test, but rather as an investigatory tool to find what the causes might be. So while a case-control study is not suitable here, a variation on the case-control study, the self-controlled case series (SCCS) (Petersen, Douglas, and Whitaker 2016; Farrington et al. 2011) will be a useful addition to this study. Assuming that any benefits from the repair service will have washed through in the intervening period, the timing of the household surveys, i.e. one before the repair service started and one 18 months later, allows for this analysis. The key advantage of this study type is that by using the same units (in my case households) from an earlier period as controls for themselves, potential confounding from time-invariant factors is removed. This type of study, in comparison to a case-control study, also eliminates possible control selection bias which can be common with case-control studies. A SCCS study will allow for additional analysis along a temporal dimension to complement the natural experiment that will make comparisons between different households over the same period. Given the gap in the literature on this subject and the inherent messiness of conducting research is this area, I don't expect answers to come easily. Probing this question in different ways over different dimensions is more likely to lead to a compelling answer than attacking it only on one front.

Chapter 6 – "Performance-oriented monitoring for the water SDG – challenges, tensions and opportunities"

Thomson P. and Koehler J. 2016. "Performance-Oriented Monitoring for the Water SDG – Challenges, Tensions and Opportunities." Aquatic Procedia 6:87–95.

The ambitious drinking water Sustainable Development Goal target of achieving *universal and equitable access to safe and affordable drinking water for all* by 2030 has been set. How indicators for this target are defined and monitored will be key to ensuring that resources are most effectively deployed to benefit those currently without access to safe drinking water. This paper discusses opportunities and challenges associated with the proposed indicators, and suggests that monitoring must move beyond the monitoring and evaluation paradigm and be linked to surveillance systems that can potentially improve operational performance and financial sustainability of water services at a local level.

Chapter 7 – "Consistent repair of handpumps within 24 hours is associated with lower diarrhoea morbidity in children: A self-controlled case series approach in southern Kenya"

Thomson P., Stoler J., Byford M. and Bradley D. [Submitted to BMJ Global Health, July 2021]

Objective: To assess whether improvements in operational performance from the professional maintenance of rural handpumps operating in southern Kenya leads to improved household health outcomes.

Design: A combination of self-controlled case series (SCCS) and cross-sectional study.

Participants: A stratified random sample of households whose handpump had been under professional maintenance (n=1,451).

Primary outcome measure: Two-week period prevalence of WHO-defined diarrhoea in children, reported by the adult respondent for each household, before and after a period of improved handpump maintenance.

Results: Reported diarrhoea in children was lower in households whose pumps had been repaired within 24 hours (Odds Ratio 0.34, 95% Confidence Interval 0.24 to 0.48). This effect remains robust under multiple logistic regression models. No reduction was seen in households whose pumps had longer downtimes.

Conclusion: Only pump repairs consistently made within 24 hrs of failure led to a reduction in diarrhoea in the children of families using handpumps. While the efficacy of reduction in diarrhoea is substantial, the operational challenges of guaranteeing same-day repairs limits the effectiveness of even best-in-class pump maintenance. Maintenance regimes that cannot guarantee continuity of service may struggle to generate health benefits. This finding has implications for qualifying the possible health benefits of WHO Joint Monitoring Programme-defined basic water services.

Chapter 8 – "Rainfall and groundwater use in rural Kenya"

Thomson P., Bradley D., Katilu A., Katuva J., Lanzoni M., Koehler J., and Hope R. 2019. "Rainfall and Groundwater Use in Rural Kenya." Science of The Total Environment 649:722–30

This study examines the relationship between rainfall and groundwater use in rural Kenya, using automatically transmitted hourly data from handpumps (n=266), daily rainfall records (n=19), and household survey data (n = 2508). We demonstrate a 34% reduction in groundwater use during the wet season compared to the dry season, suggesting a large shift from improved to unimproved sources in the wet season. By cross-correlating handpump and rainfall time series, we also reveal substantial short-term changes in groundwater pumping observed immediately following heavy rainfall. Further investigation and modelling of this response reveals a 68% reduction in pump use on the day immediately following heavy rain.

We then investigate reasons for this behavioural response to rainfall, using survey data to examine the characteristics, concerns and behaviours of households in the area where the reduction in pump use was most marked. In this area rainwater harvesting was widespread and only 6% of households reported handpumps as their sole source of drinking water in the wet season, compared to 86% in the dry season. These findings shed light on the impact increasing rainfall variability may have on the Sustainable Development Goal of "universal and equitable access to safe and affordable drinking water for all". Specifically, we suggest a flaw in the water policy assumption that the provision of improved sources of drinking water—in this case community handpumps—translates to consistent use and the associated health benefits. We note that failure to understand and account for actual water use behaviour may results in adverse public health outcomes and maladapted WASH policy and interventions.

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Chapter 9 – "Remote monitoring of rural water systems: A pathway to improved performance and sustainability?"

Thomson, P. 2020. "Remote Monitoring of Rural Water Systems: A Pathway to Improved Performance and Sustainability?" WIREs Water e1502

The presence of the mobile phone network in rural areas where there is little other infrastructure has opened up the prospect of automatically monitoring rural water systems, something previously possible only in person and perhaps only on foot. The technology to monitor these systems continues to develop: basic systems are now leaving research and being implemented in operational WASH programs; machine learning is making pump failure prediction possible. With the move from the previous infrastructure-focused community management paradigm, to a service-delivery approach to rural water, remote monitoring has salience with its potential to inform professional maintenance services. This is not without cost. To justify its use in rural water service delivery remote monitoring must generate benefits for service providers: (1) it must be integrated into management systems, and help redesign them; (2) it must contribute to increases in performance that produce real improvement in outcomes for water users; (3) it must open up new transparent sources of funding previously unavailable to the rural water sector. If remote monitoring can do these three things it has a role to play in achieving SDG 6.1; if not it will join the list of development techno-fixes that failed to make an impact despite the best of intentions.

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Chapter 10 - Discussion

Introduction

At the centre of this thesis are four journal articles, presented here as chapters 6, 7, 8 and 9. Chapter 6 (Thomson and Koehler 2016) discussed the opportunities and challenges for rural water provision in relation to the JMP indicators for assessing progress towards SDG 6.1. Specifically it suggested that the move to the service-oriented approach intrinsic to the SDGs is an opportunity to rethink monitoring and use it for operational management in addition to Monitoring and Evaluation. Technological advances enable data to be part of a tighter feedback loop that is especially suited to professionalised maintenance approaches, and with the cost of generating, transferring and processing data becoming ever cheaper this may also improve cost-effectiveness as well as efficiency. Chapter 6 also proposed using the same raw data sources to improve oversight and even bring new finance into the sector, again, now possible due to the low marginal cost of presenting the data used by operational managers to regulators, government and funders, albeit aggregated differently to suit these users' needs.

Arguing that reducing the burden of disease is one of the main drivers behind effort to improve drinking water services Chapter 7 (under review with BMJ Global Health) presented evidence to help answer the question of whether a data-supported, professional service could lead to improved health outcomes for those receiving such a service. Specifically it looked at the impact on diarrhoeal disease in children in households that were receiving a rapid, professional handpump maintenance service. The main finding was that the faster handpump downtimes which resulted from the professional repair service did reduce diarrhoea, but only when the repairs were consistently fast. That only the highest performance led to reduced diarrhoea indicates that in practice handpumps abstracting groundwater will not be capable of contributing to the achievement of SDG 6.1, even though relatively shallow groundwater can in theory be a safe source of water, and a private on-premises pump could meet the definition of "safely managed" water.

Chapter 8 (Thomson et al. 2019) examined pump use in response to rainfall, looking at both seasonal and short-term timescales. This provided further empirical and quantified evidence that handpumps are critical infrastructure in the dry season, with households having more possible sources available in the wet season, a well-known phenomenon. It also showed a marked decrease in handpump use immediately following heavy rainfall, something hitherto less well established and certainly not examined to such a detailed extent. Both these have implications for assumptions about handpump use in favour of other sources, in particular the short-term drop that was observed; whether this indicates a switch to rain or surface water from a contaminated source, this most likely represents a switch to a source of lower quality.

The final paper (Thomson 2020), included here as Chapter 9, reviews the progress of the field of remote monitoring of handpumps, from its inception a decade ago to the state of play today; in doing so it reflects on the issues discussed in the previous chapters, specifically the integration of data into management systems, and its contribution to increased performance in a way that improves (e.g. health) outcomes for water users. The following section of this thesis will expand on findings beyond those captured in the individual papers and discuss linkages between these papers.

Handpump use variation

Chapter 9 showed that handpump use is highly variable, building on work that preceded this thesis. There are patterns that average figures based on survey data cannot capture. These occur over a range of time scales. A pump might be being operated at a fraction of its design capacity when considered over a 24 hour period, but may be at full capacity for the three or four hours of peak demand in the morning and afternoon; variation in abstraction between seasons is large (Thomson, Hope, and Foster 2012a; University of Oxford 2014). Here I showed that pump use in the dry first three month of 2014 was over 50% higher than use once the rains came. The seasonal variation and switch away from using handpumps in response to heavy rainfall shown in this study may well be optimal from the household perspective given current information and constraints, but is likely be a consequence of long-term experience and an intuitive understanding of the local environment rather than a formal understanding of water-related diseases or of the hydrological cycle. This study has added hard figures to phenomena that are widely known.

What is new is the finding that pump use changes in response to short-term rainfall, showing large drops in use immediately following heavy rains. The link between heavy rainfall and diarrhoea for users of basic and unimproved water systems is established (Taylor et al. 2009; Howard et al. 2003; Carlton et al. 2014; Eisenberg et al. 2014) and has also observed in users of piped, treated water (Setty et al. 2018). The short-term drops in pump use following heavy rainfall presented in this study may point to the mechanism for this beyond that of usual supply sources becoming contaminated as a result of the rainfall. But switches away from handpumps in response to rainfall may not necessarily correspond to large changes in the nature of the water that households drink. Some households reported continuing to collect a small volume of water from the handpump for human consumption, while using water from other sources for other purposes. In some cases this decision to continue using pumped groundwater for drinking, rather than water from other cheaper and more convenient sources was reported to have been as much related to taste as to health considerations. Nonetheless, if a day that a handpump is not used due to rainfall—or any other reason—is analogous to a day when a handpump is not used as it is broken, the finding that the benefits from multiple rapid repairs are undone by a single slow repair may be applicable to any day when the pump is not being used. If this is the case, it has significant implications for the health benefits that handpumps may or may not be generating for the households that use them, implications that reach beyond the context of the few hundred pumps in Kwale that are considered in this study.

Is professionalization enough?

Chapter 6 urged a re-thinking both how we use data and how we consider performance in the rural water sector. This is essential if we are to achieve SDG 6.1 but, aside from the specific definitions of the SDG indicators, also how we are going to improve operational and financial sustainability of rural water services. Evidence from Chapter 7, suggesting that the number of repairs was not important, supports the suggestion from Chapter 6 that multiple breakdowns that are quickly repaired may be preferable to infrequent but lengthy failures. The evidence from Chapter 7 also suggests that, from a health point of view at least, how we have generally been viewing performance is inadequate. System uptimes of 90% and downtimes of a few days may reduce, for example, the burden of water collection, but will not lead to diarrhoea reductions. We should be thinking an order of magnitude higher.

The professionalised maintenance service was to some extent a study tool, as only a professional service would have been able to generate the accurate data on pump breakdown timings required by this study. But the implication of the main finding was that professional maintenance is a necessary but not sufficient condition of achieving this required improvement in performance. From an operational perspective, the performance of a maintenance service which reduced pump downtimes by an order of magnitude would be viewed as excellent by most people in the rural water sector, or even best in class. Similarly, any WASH intervention that achieved a reduction in diarrhoea of over 50% would be view as an unbridled success. Under the repair service in operation during this study, only the pumps with the lowest downtimes are associated with this level of health benefit. Thus the statistic—a 60% reduction in diarrhoea achieved by a rapid repair service—represents the best possible outcome for a best in class service, not an average or likely outcome at scale, and there is little evidence to suggest that community maintenance can consistently achieve these performance levels either.

The households using handpumps that had received very rapid repair saw a 60% reduction in diarrhoea, but those households corresponded to only the 15% of pumps where all repairs were completed in under 24 hours, lowering the overall reduction in diarrhoea morbidity to under 10% for all the *households receiving the repair service*. The repair service was also a voluntary engagement: most who offered the services agreed to it but not all. Viewing the repair service as a health intervention, a Number Needed to Treat (NNT) can be calculated, in this case the number of households needing to have a fast repair in order to have one fewer households reporting diarrhoea. The NNT for those households that had a 24 hour repair delay is 15 across a two week period, the recall period in the survey. Again, taking into account that only 15% of households who were receiving the repair service had a total repair delay of under 24 hours, the effective NNT for the repair service as a whole is around 100. This corresponds to 13 cases of diarrhoea averted each for year of each handpump under FundiFix's care. FundiFix currently maintains around 100 handpumps in Kwale[12], suggesting that FundiFix could be reducing cases of diarrhoea by 1,300 per year for a population of around 7,800 children up to the age of 15 who rely on these pumps for their water, equivalent to a case averted each year for every six children.

Diarrhoeal disease causes 1.31 million deaths worldwide, with 303,045 of those being deaths of children under five in sub-Saharan Africa. For that same group it also causes 27 million DALYs (Troeger et al. 2017), which corresponds to around one in every seven DALYs. Moreover, for under-5s there is evidence that this is a low estimate as it does not take into account of long-term sequelae DALYs due to reduced growth for under-5s. In the case of Kenya, it is estimated that diarrhoeal disease causes between 104 and 152 DALYs per 1,000 children under the age of five, 40% more than when the long-term sequelae are excluded (Troeger *et al.* 2018). This is likely to be a major issue in Kwale, which has a stunting rate in under-5s of 30%, higher than the national average of 26% (Kenya DHS, 2014). If one accepts that it will be many years before all rural communities such as those in Kwale enjoy piped, treated water then handpumps will remain an important part of the water provision landscape beyond 2030. The modest reduction in diarrhoea prevalence that has been shown to be achievable here has role to play in reducing the burden of disease, in particular for children, over the next decade at least. Writ large, the 6% of DALYs from diarrhoeal disease that repairing all handpumps within a day of their breakdown could avert, would come to 1.6 million DALYs across sub-Saharan Africa or to 36,000 DALYs in Kenya alone.

If professionalising handpump operations and maintenance to minimise pump downtimes can have the health impacts demonstrated in this small study, it can have a substantial impact of the burden of disease if it becomes the norm. But this will only be the case if such professional services

[12] As of the start of 2020 (FundiFix now offers a heavily subsidised service to communities in Kwale and Kitui counties, serving over 80,000 people).

can (a) maintain continuity of service and keep downtimes to almost zero, and (b) increase their covered to higher level than is currently the case. This study and FundiFix's performance in Kenya has shown that this can be done, but is extremely difficult. The maintenance service, which went on to be set up as an independent entity, was designed to be a scalable. But the way it operated during this study is not representative of a scaled version of itself: It has been designed, set up and incubated by the Oxford University research team; its two Kenyan directors have respectively an MSc and PhD from Oxford University; while developing as a business it continues to be financially supported by the research, and continues to have members of the Oxford team supporting in an advisory capacity. FundiFix has contracted with about 30% of the communities involved in this study: from a business development point of view this is a success; its success as a public health intervention is less sure. FundiFix is now running fairly autonomously, but during the period when this study was taking place it was effectively entirely under the control of the research team. I had almost daily telephone and email contact with the team and made multiple field visits each year. Despite the additional burden of reporting that served research purposes as much as operational ones, this attention and support is most likely to have resulted in increased performance, if only by the Hawthorne effect (Landsberger 1958)[13]. Considering the effort put into running the maintenance service, it would be difficult to sustain the level of performance achieved during this trial at scale and in the long term. The non-linear nature of the repair speed-health relationship means that a small drop in operational performance will result in a much larger drop in the health benefit of such a maintenance service; the reduction in morbidity seen here is very likely to be a best case scenario. This is not to discount the non-health benefits of rapid repairs, such as reduced collection time caused by having to walk to an alternative pump, which may well be linear with respect to the speed of repair, but the relationship between speed of repair and health impact is painfully non-linear. The operational performance level required to effect reactive repairs quickly enough to achieve the morbidity reduction, on a consistent basis, is extremely high. Repairs taking just a day longer, due to scheduling/capacity issues, unavailability of spares or additional labour for more involved repairs, will not have the same health benefits.

Whether advanced use of data, specifically Machine Learning for pump failure prediction as proposed in Chapter 9, is a way to achieve and maintain the necessary higher level of performance across more pumps is still an open question. But taking the findings presented in Chapters 7 and 8 together might lead one to believe that even that may be futile, if households move other sources

[13] The productivity of workers at the Hawthorne electrical plant seemed to increase as a result of them knowing they were being studied rather than due to the intervention. It is debatable if this inference could have been drawn from this study, but the term "Hawthorne effect" seems pertinent.

under certain weather conditions even when their primary source is fully functional. Weather is not the only reason people chose sources other than the safest available to them. If the groundwater abstracted by handpumps has an undesirable taste, such as that due to salinity or naturally elevated iron, people may chose not to drink it. A problem in some areas of Kwale was the use of inappropriate materials (galvanised iron as opposed to stainless steel) in areas where the water is low pH or saline (Foster and Hope 2016), although this was somewhat mitigated by switching to stainless steel pump rods. That pump users make these choices, and may continue to do so no matter how reliable their handpump is, has implications for WASH policy and practice and role handpumps may play in delivering rural water services.

WASH related diseases are diseases of poverty

In addition to the impact of fast repairs, the analysis on Chapter 7 showed that three other factors remained fairly consistent as potential protective factors against diarrhoea through the logistic regression models, although with a high level of uncertainly ($p>0.05$). These were the presence of an improved floor and roof, and the growing of crops. The analysis excluded households who had not been receiving the free maintenance service. When this was relaxed the protective effect of these three factors became more statistically compelling. Growing crops was associated with lower levels of diarrhoea, albeit with a large confidence interval. Widening the inclusion criteria to include households whose pumps had not had access to free repairs made this apparent effect more statistically significant (OR 0.591, 95% CI 0.518 to 0.675, $p<0.001$). Due to the nature of the survey, we do not know whether these crops were for subsistence or sale, although given knowledge of the study area, the former is more likely, suggesting a link with nutrition beyond the one-way link briefly described earlier in this thesis. This is consistent with the finding of the WASH Benefits trial (Null et al. 2018; Arnold et al. 2013a) that infants in the nutrition arm of that study had higher length-for-age Z scores, and the more general understanding of the benefits of a varied diet and diverse gut biota and child development (Rah et al. 2010) and general health (Heiman and Greenway 2016). The same analysis showed a similar effect for having an improved floor (OR 0.500, 95% CI 0 0.329 to 0.758, $p=0.001$), thereby demonstrating an apparent effect that was not reliant of the effect modifier of an improved toilet. The mechanism for this leading to lower diarrhoea is likely to be that it is easier to clean, reducing the opportunities for children getting faeces, human or animal, on their hands and then into their mouths. This finding is consistent with those of Cattaneo et al. (2009) and Koyuncu et al. (2020). The latter also found that self-reported diarrhoea was reduced by the presence of an improved floor, irrespective of the household having access to an improved water source or not.

The households that were subsequently found to use extensive rainwater harvesting, as described in Chapter 8, were not in an area that was offered the repair service so those households were not included in the analysis in Chapter 7. When they were, having an improved roof, a requirement of extensive rainwater harvesting, was associated with reduced diarrhoea (OR 0.845, 95% CI 0.756 to 0.944, p=0.003). Rainwater harvesting provides a plausible pathway from an improved roof to reduced diarrhoea. Having an improved roof, i.e. metal sheet rather than makuti, is a necessary part of an effective rainwater harvesting system, which can provide another improved source of water. Households with good rainwater harvesting infrastructure will either be able to use it as their primary source of drinking water or as the next best source when their handpump breaks.

An Integrated Approach to WASH

Having harvested rainwater as well as pumped groundwater is an example of the reality of rural water, with users collecting water from different sources for different uses (Elliott et al. 2019). While this may be at odds with the single-source approach we enjoy, using potable water to flush our toilets and water our plants, this implicitly risk-based approach may in many cases be a very well-considered, rational response to the constraints these households face and the information they have. Given the difficulty in achieving the pump reliability required to reduce diarrhoea, it may be more constructive to consider these dwelling factors as mechanisms for achieving health benefits rather than as factors to be adjusted for in a statistical analysis. The corollary of this is that traditional WASH interventions should be considered as part of wider poverty reduction efforts. WASH interventions and programmes are likely to be more effective if they work with the grain of this complex reality. If we take a more holistic approach we are more likely to be able to maximise the health benefits available from intermediate, “basic”, water services.

This study suggests that having an improved roof may contribute to reducing household-reported diarrhoea. This may be less than the reduction seen from a rapid handpump repair, but the reduction due to the repair service was only from households whose pumps had a total repair delay of less than a day. Considering what an operational intervention or programme might realistically achieve, the reduction from rainwater harvesting may be comparable to that of professional maintenance of handpumps. Having an improved roof is a prerequisite for a good rainwater harvesting system that can provide potable water for regular use or provide a source of potable water in the event of a handpump failure, avoiding the risk of a switch to an unsafe source. Like the groundwater from handpumps, harvested rainwater is defined as an improved source. It is likely to be a safer source of drinking water than surface water, but is certainly not without risk of both microbial and chemical contamination (Lye 2002; Boelee et al. 2013; Gwenzi et al. 2015; Ahmed et al. 2008; Ahmed, Gardner, and Toze 2011; C. Stewart et al. 2016). Indeed, a systematic review by Bain et al. (2014) found collected rainwater more likely to be contaminated with faecal indicator bacteria than water from boreholes.

Rainwater harvesting and handpump maintenance are also complementary from and operational point of view. Expanding the remit of an organisation like FundiFix beyond pump maintenance to cover rural water provision more generally including rainwater harvesting, has much to recommend it. Like handpumps, the safety of the drinking water from these systems is dependent on them being both well designed and built, and used and maintained according to the proper procedures (Lye 2009), conditions which are not likely to be fulfilled in all instances. Failure to discard the “first flush” of rainwater, especially after a period without rain, will increase the likelihood of pollutants and pathogens ending up in the harvested rainwater water (Yaziz et al. 1989; Lye 2009). In the same way that professional maintenance can improve the reliability of handpumps, it could improve the effectiveness of rainwater harvesting systems. The cost and logistical effort to install, maintain and operate good household rainwater harvesting infrastructure may well be lower than what is required to get further marginal gains from running a higher performance handpump maintenance service. And due to the non-linear nature of the relationship between drinking poor quality water and health, having an effective rainwater harvesting system in place—even one that only provides a modest volume of water—could make the difference between a household switching to a unimproved source of water while their handpump is out of commission or continuing to drink water from an improved source. Mechanics installing or maintaining rainwater harvesting systems could be called away from those jobs at short notice to repair handpumps. As these mechanics would have to be employed anyway to be on-call for rapid repair jobs, this could be done without increasing staff costs and contribute towards a more integrated approach to rural water services.

The other dwelling factor that was associated with reduced disease was flooring. Having a cement or concrete floor in an otherwise basic dwelling makes cleaning much easier, even by dry sweeping, reducing the likelihood of ingestion of pathogens, especially human or animal faeces brought in from outside. Moreover, an improved floor makes the distinction between outside and inside sharper, potentially encouraging hygiene behaviours such as removing shoes. Enhancement of people’s homes would not be viewed as a traditional WASH intervention (Whittington, Radin, and Jeuland 2020), but may have the same impact as a traditional WASH intervention, or in this case necessary to ensure the effectiveness of a traditional WASH intervention. A programme of laying concrete floors in homes may seem like a blunt instrument but has a number of practical attractions: (1) the training or sensitisation necessary for it to have an effect would be minimal; (2) it would truly require no follow-up as a properly laid concrete floor would require no maintenance under standard domestic use conditions; (3) it could be appealing at a local political level as it could be framed as a very overt, pro-poor poverty alleviation programme.

Taking a similar argument to that made for developing integrated institutional and managerial capacity in order to meet the SDGs (J. Bartram et al. 2018; Ait-Kadi 2016), integrating these WASH interventions into other programmes which contribute towards meeting other SDGs will lead to a broader foundation from which we can build towards the ultimate SDG goals. Moreover, literally building foundations of homes and logging their locations is a necessary condition for bringing piped water to those homes to achieve "universal and equitable access to safe and affordable drinking water for all" (Target 6.1), and giving households "access to basic services, ownership and control over land and other forms of property" (Target 1.4). It will also improve those homes, directly contributing to "access for all to adequate, safe and affordable housing and basic services…" (Target 11.1). The SDGs correctly recognise the integrated nature of the challenge, but the way we tackle them can still sometimes be fragmented and siloised. This is a messier strategy to improving communities' water-related health, and may be less satisfying at a policy level than declaiming that we will provide everyone with piped treated water by 2030 or the next election, but it is an approach that may lead to incremental improvements for more people than concentrating resources on fewer, transformative interventions.

Chapter 11 – Limitations

Study Rigour

Blum and Feachem (1983) identified methodological issues commonly found in WASH studies by reviewing 44 studies that examined the impact of water and sanitation interventions on diarrhoeal disease. They were prescient in their suggestion that RCTs were likely to become more regularly used for impact evaluations, at the same time acknowledging the difficulty of randomisation in practice: “environmental interventions are not as a rule introduced on a random basis, but rather as a result of political, economic, humanitarian and other considerations”. The eight methodological problems that they identified provide a framework for reviewing the limitations and weaknesses in this study. They are:

1. Lack of adequate control.
2. One-to-one comparison.
3. Confounding variables.
4. Health indicator recall.
5. Health indicator definition.
6. Failure to analyse by age.
7. Failure to record facility usage.
8. Seasonality of impact variables.

Lack of adequate control and “one-to-one comparison”

This study was reasonably well controlled for an observational study, as it adopted a self-controlled case series (SCCS) approach. This enabled one-to-one comparison between the same households 18 months apart. The matching of households allowed for this method to be used, as opposed to, say, a difference in differences analysis that does not require matching, but consequently has less power. The matching was not perfect as we included household that were matched, but where the respondent was different between the two surveys. This will have introduced some error, but I believe it is unlikely to have introduced bias. The issue of one-to-one comparison as described by Blum and Feachem (1983) is that of WASH being a community issue rather than an individual issue. Households within the same village or community may not be truly independent units of analysis. In the most egregious case, cited by Blum and Feachem (1983) and giving rise to this being named the “one-to-one comparison problem”, there is one treatment village and one control village, making the statistically valid sample size more likely to be one than related to the number of households in the study. While the issue of intra-village non-independence holds for this study, the check of clustering by pump, a proxy for community, which did not produce a different result, suggest that this was not a major issue. The study included a sufficiently large and diverse number of communities, and there was no obvious bias in the speed of repair related to other community characteristics that might have invalidated comparisons.

Confounding variables

The household surveys collected a range of data, which enabled adjustment for possible confounding variables. The way the surveys were conducted meant that biases that might have arisen due to poor blinding and concealment are unlikely to have been an issue. Effort were made to ensure blinding and concealment when collecting the data. Trials with subjective outcomes, not just outcomes related to diarrhoea, tend to exaggerate effects (Wood et al. 2008), even in RCTs, with blinding and concealment the best way to reduce this. Confirmation bias, both on the part of the survey respondents and enumerators (Althubaiti 2016), was a risk with this study and steps were taken to mitigation the possibility of such a bias with blinding. The enumerators were blinded to the intervention as, other than knowing that the mechanics were operating in the area and funded by the same people who had recruited them, they had no knowledge of which pumps had been repaired when. While the households were certainly not blinded to whether or not they had had a repair, it would not have been readily apparent to participants that the questions about their household members' health were to be linked to the repairs, because the health questions were part of a large questionnaire, and any questions about the pump were intentionally asked after the health questions. This is not to discount the possibility of courtesy or social desirability bias, but any under- or over-reporting of the health indicators is unlikely to have been correlated to the intervention.

Mirroring the enumerators, the mechanics were aware that a household survey was taking place that was broadly connected to their work, but were not in any way involved in it. It could be argued that the mechanics—along with chance and various other factors, measurable or otherwise—were effectively making the treatment allocation. So while the breakdown of pumps was not truly random and efforts were made to adjust for potential factors that might have affected this, the "assignment" of pump failures and their subsequent repair was uninfluenceable and unknowable by anyone involved in the trial. Perhaps more importantly than actual randomness, there was concealment in these allocations because, as far as they were concerned, the mechanics were not part of a study.

It is inevitable that some confounders were not collected. For example: I saw some people washing clothes at the pump whereas others are likely to have washed clothes at home, but we did not collect data that would distinguish between which water stored at the home was used for drinking and what was used for non-consumptive purposes. This may have varied considerably across the study area depending on different laundry practices in different areas. To mitigate this, the standard errors in the logistic regressions were clustered by geographic zone, the characteristic most likely to be associated with unobserved confounders[14].

Health indicator recall and definition

Self-reported disease indicators are far from ideal when investigating disease morbidity. This was a necessary limitation of this study. The New Mobile Citizens project was an ESRC-funded social science study, making the collection of clinical indicators for disease that one might have gathered if this had been a medical study impossible, for example, stool samples or intestinal tissue for biopsies. Self-reported diarrhoea questions included in the household survey were the primary source of data on the conditions covered. Self-reported data, especially for diarrhoea, has a number of drawbacks, and while the WHO definition of diarrhoea was used, the outcome measure was self-reported and thus ultimately subjective. I did investigate with the local public health officials in Kwale the possibility of using their data to supplement the data generated by the household surveys. They were open to this, but the data available was essentially administrative, with various issues that would have made it a challenge to integrate. The most relevant issue was that even though data was available for individuals when they presented at their local health centre, it was not possible to trace this back to specific villages/communities, and thereby link these data to our own geo-referenced household and pump data.

Failure to analyse by age and failure to record facility usage

The issue Blum and Feachem describe as “failure to analyse by age” is effectively a statement that diarrhoea has higher incidence and higher impact in children, and so children should be the focus when studying WASH interventions. Due to the long term, persistent impact of diarrhoea on children, this study focused on children. This study would be open to the criticism of failing to record facility usage, i.e. only recording the existence and self-reported use of facilities, in particular water sources and sanitation facilities, rather than specifically confirming use for each household. This was a known issue, but given the large scale of the household survey, and thus the limited time that we

[14] A repeat of the analysis clustering SEs by pump, the other candidate for unobserved variations, was not substantively different to an analysis without clustering, and did not result in any substantial changes in the findings.

were able to give to each household, it was viewed as difficult to make this distinction in a way that would be both accurate and not insensitive, and it was not possible to observe this directly as one might in a more in-depth anthropological study. The survey response about soap, however, was based on the enumerators observing soap in the household's handwashing area, rather than a statement by the respondent.

Seasonality of impact variables

A shortcoming of this study is that the household surveys were not done at the same time of year (Wave 1 in November/December 2013, Wave 2 in March to May 2015). Having had the repair service running for longer mean there were more repairs, and so more exposure data, at the expense of comparability of some of the confounders. Certain responses would be expected to have seasonal variations. Other things being equal, an increase in diarrhoea would have been expected shortly after the start of the rains, based on conversations with local public health officials, echoing literature on the subject (Kostyla et al. 2015). The 2015 survey showed a slight increase in reported diarrhoea over the 2013 survey at 9% over 8%, but McNemar's test indicated that this was not a significant difference. Because there was a slight increase in overall diarrhoea in the second survey when the repair service was in play, this may in fact have produced a slight advantage as reduced diarrhoea in the intervention group was unlikely to be attributable to seasonal factors.

EED and Immunity

Both immunity and EED are unknowable in a non-medical study, and relying on self-reported diarrhoea as the outcome variable is far from ideal. Immunity is not a confounder in that its protective effect is real, but may vary across the study population thereby adding an additional source of unknowable variation within the study and means care must be taken when generalising beyond the study in question. Frost *et al.* (1998, 2005) describe such a situation, in this case involving *Cryptosporidium* in Oregon, USA. One community was suffering from a disease outbreak that was traced to *Cryptosporidium* in the water supply. The authorities took the seemingly sensible step of trucking in water from a second nearby community which was not experiencing an outbreak of cryptosporidiosis. This did not alleviate the situation as hoped as it transpired that this water also had *Cryptosporidium* present, but at a low level to which the second community had developed immunity, and were thus asymptomatic.

The likely presence of EED in the study population also needs to be considered, given that it may be present in study participants both with and without symptomatic diarrhoea. How it will bias the results is not clear as EED could be present in apparently unaffected baseline/control study subjects, and will interact with immunity. As the outcome indicator was diarrhoea, strictly speaking the prevalence of EED would have no impact on the validity of this study. Given that EED has the same causes as diarrhoea the presence of unmeasured EED may have made no difference, but is likely to have resulted in an underestimate of the benefits of pump repairs. Adding to this the social desirability bias of not reporting diarrhoea, it is likely that the overall impact of poor quality water on household's gut health was under-represented in this study. This may have resulted in a slight underestimation of the effect sizes of the various predictors, but there is little reason to believe that this created a systematic error that would affect the direction of the key finding on repair speed.

Low level GI problems may not be reported as diarrhoea, especially in studies that use the rigorous WHO definition of three or more loose or liquid bowel movements per day, leading to under-reporting in a similar way to that of EED, an issue foreseen by Esrey, Feachem and Hughes (1985).

Rainfall data

Chapter 8 examined the relationship between rainfall and pump use which also had a number of limitations that need to be considered when assessing both its internal validity and before any generalisation beyond describing the situation in Kwale can be made. Firstly, the protocol for measuring rainfall is to take a daily reading at 09h00 and classify that as the previous day's rainfall. A lot of handpump use comes first thing in the morning, starting around 06h00. In this way rainfall early in the morning when pumping is taking place could be counted as rainfall from the previous day, thereby creating an error in the apparent temporal relationship between the two. For one rain gauge in the study area, monitored by Base Titanium, readings had been taken twice per day. On 1st December this rain gauge showed that 80% of the rainfall classed as falling on that day did in fact fall on 1st December, indicating that our approach and findings remain valid despite this source of error.

Secondly, the survey in the transect area was undertaken exclusively for this part of the study after the apparent pattern of pump use had been observed and analysed. As a result of this, and resource constraints that prevented it from being done earlier, it was conducted two years after the main household survey. This limits the comparison that can be made, and care has been taken in this regard. The economic situation between these two periods was variable. From the high-profile Westgate attack in Nairobi in December 2013 until the end of 2015 when attacks seemed to subside, there was increasing Al-Shabaab activity in Kenya. One of the major industries in Kwale is tourism and the security situation impacted that industry heavily. There will have been knock-on effect of this throughout the county from this. On the other hand, at the same time two new economic actors, Base Titanium and KISCOL were increasing operations, with corresponding positive economic impacts (Ferrer et al. 2019, 2020). It is unclear how these different factors will have combined across the study area, but it is certain that the socio-economic situation was not stationary during this period (Katuva et al. 2020).

Thirdly, handpump and water use are influenced by many factors unrelated to rainfall, and no attempt has been made here to account for these; what is presented here is only one part of a complex picture (J. Thompson et al. 2001; S Cairncross and Thompson 2002; White, Bradley, and White 1972; D. Blum et al. 1987; Tucker et al. 2014; Elliott et al. 2017; Kelly et al. 2018). The aim here has not been to produce a predictive model but to construct the simplest model possible to illustrate the relationship between handpump use and rainfall, and so no model calibration has been undertaken. The implicit assumption of linearity and superposition that comes with generating an impulse response to describe this most certainly does not reflect the full complexity of reality. The merely “satisfactory” assessment of this model against goodness-of-fit metrics (Moriasi et al. 2007), while confirming the relationship, underscores the fact that there are many other factors at play and serves as a caution against over-inference.

These sources of error all point towards exercising caution before generalising the findings beyond Kwale, or suggesting that the same study undertaken in Kwale in another year would yield the same model and the same goodness-of-fit to that model. The particular impulse response observed/calculated may well change, but I would expect the broad finding that heavy rainfall influences handpump use to hold. This is the key point from a policy and practice perspective. The mere existence of improved water sources does not guarantee that households are drinking the water from that source all the time. Given the findings of Chapter 7 about the health response to all but the shortest of pump downtimes, and the other literature on the subject that suggests short term deviation from drinking uncontaminated water has disproportionate effect, the exact profile of the response to rainfall is not essential to this study’s relevance to WASH policy and practice. Similarly, whether or not causality can in fact be inferred from this study and where this study sits in the debate about observational trials vs. Randomised Control Trials is not critical when considering the possible impact this work might have in informing WASH policy and practice. More important is whether the study has been conducted with sufficient rigour to generate compelling evidence that can be translated into action at a programmatic level.

Literature on costs and benefits or monitoring

Finally, the greatest limitation encountered with Chapter 9 was that there was lack of peer-reviewed literature on the topic. The Oxford team (of which I am part) and the team lead by Dr Evan Thomas, previously of Portland State University and not of CU Boulder, have both published peer-reviewed paper on their research into remote monitoring. The other large player in the field, charity: water, has not published in peer-reviewed journals. The approach I adopted to be able to include them in this review without relying solely on marketing material was to use their published financial accounts. Within these their large grant from Google, which funded their remote monitoring work, was reported separately enabling a credible calculation of costs to be made, even if little could be inferred about performance.

Chapter 12 - Reflections

Inferring causality from an observational study

Chapter 7 of thesis has shown an association with between handpumps being consistently and promptly repaired and reduced diarrhoea in the children of households using these pumps. Causality does not necessarily follow an association, no matter how strong. In the case of this finding in this study, more important than proving beyond reasonable doubt a chain of causality from a broken pump to an bout of diarrhoea, is whether rapid repair handpumps is *one way* that diarrhoea can be reduced in the household that use these pumps. Considering such an "abative hypothesis" (Renwick 1973), takes the question from one that might get bogged down in philosophical debates on what types of study allow for the possibility of inferring causality to a more practical, to one about practical steps that can improve the health of those still only with access to basic water services.

The evidence from this part of the study points to a combination of biological and behavioural mechanisms for the observed effect. The study was not able to disaggregate these two effects because it did not continuously monitor household water user over an extended period of time. Causation and abatement are not reciprocals of each other (Renwick 1973) so while lacking a key element of the causal chain, such as identifying specific pathogens in the water, a case for abatement can still be made. In Chapter 5 I touched on the debate about whether causality can be inferred from anything other than the most rigorously designed RCTs. Sir Austin Bradford Hill addressed the issue of determining causality from observational studies in two lectures given over half a century ago. The first, referred to earlier in reference to John Snow's cholera study, was the Cutter Lecture at Harvard University (Hill 1953). The second was to the Royal Society's new Occupation Medicine group in London (Hill 1965), and has become particularly relevant when considering causality. In this talk Hill introduced nine considerations for deciding if causality can be inferred from observational studies, asking *"What aspects of that association should we especially consider before deciding that the most likely interpretation of it is causation?"* Despite this modest phrasing they have erroneously become known as Hill's *criteria*, a phenomenon critiqued by Rothman (2020) who asserts that Hill's talk was *"certainly was a provocative and thoughtful after-dinner talk, but it does not merit the status of scripture, especially not for the reasons it is so revered."* As well as pointing readers towards the earlier talk and conceding their usefulness Rothman notes that Hill himself never used the word 'criteria' and is scathing of those who give them undue weight. In this spirit, and avoiding entering the debate on how causality can be strictly claimed or not, I take them as issues to consider when debating whether a specific example of abatement may be more generalizable. They are, in the order Hill referred to them in the lecture:

- Strength
- Consistency
- Specificity
- Temporality
- Biological gradient
- Plausibility
- Coherence
- Experiment
- Analogy

These nine "aspects of association" provide a framework for assessing an observational study such as this, and I will discuss aspects of the results of this study with reference to Hill's list, addressing all of them for completeness. The study design was one of an **experiment**, with a baseline survey prior to the intervention being initiated and then another survey 18 months later. This was a semi-experimental study, through which Hill suggests "the strongest support for the causation hypothesis may be revealed". The baseline and endline surveys also address **temporality**, in the limited and specific sense used by Hill. These two surveys enabled a before and after comparison of diarrhoea reported in the same households.

The evidence from this study shows that only fast repairs of handpumps reduce household diarrhoea morbidity. While the overall *effectiveness* of the repair service is lower than the observed *efficacy* of rapid repairs, as not all repairs are completed within 24 hours, a 60% reduction in diarrhoea indicates a high efficacy and a substantial **strength** of association. In global health, and WASH in particular due to the high prevalence of diarrhoeal disease, even modest effect sizes can have large impacts: the WHO recommends zinc supplements for reducing the length of diarrhoea episodes in children[15] based on systematic review showing a reduction of around 15% (Lazzerini and Wanzira 2016); Tiono et al. (2018) demonstrated a 12% reduction in clinical malaria in children sleeping under nets with a new chemical formulation, viewing this as a substantial result. The logistic regression was used primarily to adjust for other factors (e.g. dwelling construction and sanitation facilities) that might affect health, in order to be sure that the unadjusted relationship observed between downtime and the self-report health indicators was a real effect. Hill himself warns against over-emphasising **specificity**, noting that many diseases have multiple causes (Hill 1965) as is the case here. These other factors that the regression calculated as having an impact on diarrhoea

[15] https://www.who.int/elena/titles/zinc_diarrhoea/en/

deserved discussion on their own merits as there is not a single cause of diarrhoea or a single intervention that will abate it. That the unadjusted odds ratio from the rapid repairs only varied slightly from the adjusted ones suggest it was independent of the others and adds weight in term of the specificity of the main effect.

Although this study has not included any disease modelling or QMRA, the main finding shows a similar temporal dose-response relationship, or **biological gradient**, between the intervention and the outcome as the modelling work by Hunter, Zmirou-Navier, and Hartemann (2009) and Brown and Clasen (2012). While this study doesn't provide enough evidence to confirm the assertion by Hunter and his colleagues that short term failures of water systems resulting in water supply contamination could erase the *annual* health benefits of having a safe water supply, it is consistent, or **coherent** in Hill's terminology, with the more general assertion that short failures have disproportionate and persistent negative health effects. Likewise, it concurs with Brown and Clasen (2012), whose quantitative microbial risk model predicted that a small decline in adherence to a household-level water treatment would lead to a disproportionate reduction in the possible health gains from that treatment. It should however be noted that the key outcome variable of diarrhoea two-week period prevalence is based on observations during a single period in during the rainy season in 2015, in order for the weather and other conditions to be as similar as possible for all households at the time of being interviewed. While there is nothing that suggests that this rainy season was not typical caution must be used in projecting the apparent effect seen during this period over the entire year and more widely. It is likely that in some cases we were rapidly repairing handpumps that were abstracting contaminated water, meaning that some rapid repairs were not averting a switch to substantively worse water source than that which the households were usually drinking. The likelihood of EED being present also complicates the observed and actual impacts. These factors, combined with the fact that some users potentially switched to another handpump when theirs broke, means that these results may well be less extreme than those that would be found in a study of the impact of switching from a contamination-free source, such as piped treated water, to a typically contaminated surface water source. The extent of the agreement between the finding of this study and the aforementioned models will be confounded by these factors. While hypothetically, the difference between modelled and empirical work could shed light on EED and acquired immunity, doing so would be challenging to say the least, given the study limitations on one side and modelling assumptions on the other. What could be feasible, as future work to tie these two strands of work together, would be to use the extensive operational data this study generated on handpump repairs and usage to generate a QMRA model for the communities that use handpumps in Kwale and see how that differs from these empirical results. The biological mechanisms for the observed effects are well-understood in light of our knowledge of pathogens present in water and their effect on humans when consumed, contributing the **plausibility** of the main finding: while it is non-linear and unforgiving, it is clear and consistent with our understanding of these biological mechanisms. While relying on evidence that may be more context-specific than that of the biological mechanism, the behavioural explanation presented is also plausible.

Hill's final consideration is **analogy**. The literature review revealed that there has been related research on supply intermittency, generating empirical evidence for piped systems in the urban context (Majuru et al. 2011; Majuru, Suhrcke, and Hunter 2016; Paul R Hunter, Zmirou-Navier, and Hartemann 2009; Paul R Hunter et al. 2005; Kumpel and Nelson 2016; Ercumen et al. 2015; Kumpel and Nelson 2013). These are also well-understood analogous situations for other diseases that have a similarly unforgiving dose-response: one can contract malaria following a single encounter with an *Anopheles gambiae* mosquito. There is further consideration, another way of considering **coherence**, although more in relation to the study than the key finding. In addition to the novel finding about pump downtimes that this study produced, this study also found an association between other factors that are generally accepted to have an impact on water-related disease. Information about these may have been collected during the household survey and then used in the analysis in large part as factors to be used in the statistical adjustment process, but mathematically (as well as biologically) there is no distinction between these covariates and the primary factor of interest. Finding factors to have an association with water-related diseases in the direction that would be expected may not add to the understanding of the subject but does serve to confirm the credibility of this study. This is especially important given that this is a unique study, so **consistency** is not a factor that can be cited in its favour, although there is nothing to suggest that Kwale is unique in ways relevant to this study. The situation in Kwale is broadly typical of rural sub-Saharan Africa in term of its water supply situation. Nonetheless this is only one study conducted under a unique set of circumstances. A similar study conducted elsewhere would strengthen any claim to causality.

Considered with regard to Hill's nine points, this study can make a compelling claim that fast handpump repairs can reduce household diarrhoeal disease, and that this may be generalizable beyond this study site, even if the exact causes for the diarrhoea being abated are not completely clear. This side-steps the arguments about study design and inferring causality; the strongest advocates of RCTs might well dismiss this study as an un-rigorous and under-controlled observational study. This PhD *does* hope to contribute to the understanding of water-related diseases, making the formal discussion of causality not unimportant, but its primary goal has been to provide actionable evidence that can be used to inform WASH policy and practice. For this the criteria for inferring causality are less strict: Does this study provide evidence compelling enough for those making decisions about WASH policy and operational design to change those policies and practices in places other than Kwale based on this study? The weight of evidence suggests that it does.

Reflections of the findings of this PhD

The finding that only the very fastest of repairs would bring health benefits surprised me, and as the person who set up the handpump repair service and so knows how hard it is to repair pumps that quickly, I found it slightly deflating. I came to this thinking that a repair delay of two or three days would have some benefit. This was based on a number of factors. Firstly, the findings of a choice experiment conducted earlier in Kenya that showed that water users valued a service that could repair pumps within two days, but not one that took five days (Hope 2015). While there are many other reasons why household might take that view, I had assumed that there was a health element to this. Secondly, I assumed that households would not need to switch to an alternative source until their storage was used, and the survey data showed that the mode days of storage was two. Thirdly, there may have been an element of wishful thinking as I knew that FundiFix was capable of completing the majority of repairs within three days, but would struggle with a shorter timeframe. Finally, I was somewhat sceptical of the modelling by Hunter, Zmirou-Navier, and Hartemann (2009) and Brown and Clasen (2012), modelling with which this study's findings turns out to be consistent. Having lived in areas like Kwale for a number of years, working for communities similar to those in Kwale who rely on handpumps for their drinking water, my interpretation of the implication of these models, that there would be much higher *visible* morbidity, did not chime with my experience. This scepticism was wrong. My findings have challenged the assumptions and views I had at the beginning of this process.

That I have generated a result that is not the one I expected or wished for, makes the result more compelling for me. This was opportunistic research, not a study implemented according to a rigorously designed, reviewed and published protocol. I was exploring different possible associations and correlations, such as the number of repairs, but that I didn't come out of this with my preferred result suggests that I did conduct this work with rigour and objectivity. The key finding remained robust as more covariates were included in the logistic regression model, but was ultimately determined by very few observations. The key contingency table turns on seven households having the fast repairs and still reporting diarrhoea. The unadjusted effect remains significant at the 5% level if two more households were to have reported diarrhoea, but not if three were. The adjusted effect derived from the logistic regression would only have required a single additional household to have reported diarrhoea for the result to have been called into question if the standard—albeit contested—metric of $p<0.05$ had been the one dictating whether or not the result was valid or not. Over 3,500 households were interviewed in the household surveys, the number included in the analysis dropping to less than half that after exclusions. That such a large sample size was required to be able to come to a robust result is indicative of how hard WASH research is. This is apparent from the inconclusive findings from the SHINE and WASH Benefits trials, some of the most rigorously thought though WASH studies ever conducted (Prendergast et al. 2015; Humphrey et al. 2015; Null et al. 2018; Arnold et al. 2013b).

The data used in this study was generated during the period when the repair service was being provided free of charge to 200 communities, so during this time around 40,000 people were directly benefiting from our activities. That FundiFix is now independent and serving over 80,000 people across Kwale and Kitui, who are paying for this—heavily subsidised—service, suggests that people were gaining real benefit from it. These benefits were almost incidental to the academic research, but the findings presented in this thesis also have the potential to have an impact. Acknowledging that groundwater from handpumps is certainly superior to many alternatives, my findings call into question whether they generate the health benefits that many have assumed they do. In doing so I have also cast an unforgiving light on the way handpumps are managed. From a scientific point of view providing empirical data to test or validate (or refute) previous models is a very valid exercise; as is generating hard numbers on the variability in pump use.

I hope that this work contributes to the literature on the subject, but whether or not this influences policy and operational and decisions in Kenya or more widely is a separate matter. Under the Water Act 2016 the County government has the mandate to provide water to the citizens of Kwale, which was defined as a human right in the 2010 Constitution. County governments are also relatively new entities, keen to wrest power from Nairobi and be seen as effective. When presented with these findings about handpumps the reaction was polite indifference. These hard numbers didn't tell them anything they didn't already essentially know. They know that handpumps are an interim solution; they understand that community management is inferior to professional maintenance; they appreciate that NGOs turning up in their County and rehabilitating pumps on a fairly random basis will undermine efforts at professionalization. But they believe, probably correctly, that the effort spent grinding out marginal gains from improving handpump maintenance would be better spent developing piped water systems from newly-identified groundwater resources. NGOs will keep coming to fix pumps based on good intentions and scant data, with minimum effort required from the County Government. The World Bank, on the other hand, may well fund their plans for two new municipal water systems if the right preparation is done and a compelling case is presented. Within this context, the benefit of a study suggesting that handpumps are even less effective than one might have thought is of no benefit at all, perhaps even unhelpful.

I am in no doubt that the handpump users of Kwale and Kitui have benefited from our work with them. Whether I have benefited from working with them more than they have benefited from working with me is unknowable given how different our experiences are. What is disquieting is the feeling that this exchange has had some level of equity in spite of the academic incentive system rather than because of it. The issue extractive research has gained more attention in recent years (Kouritzin and Nakagawa 2018; Sultana 2015) with the creeping realisation that IRBs and university ethics approvals, while important, can be somewhat superficial and presuppose the larger question of who is benefiting from the research. The elements of my work that have benefited others are not those that have helped my career trajectory or improved my h-index. From a career point of view, the time and effort spent on ensuring research has impact would arguably be better generating another paper from the data gathered here, or spent writing a policy piece skilfully articulating what everyone within your field already knows for an audience of those outside it. With a handful of more substantive research papers published, and thus established as a "thought leader", one can move onto the next thing, what Hirschman (1970) might sarcastically call another *"exciting" theoretical "insight"*. This rests on the conceit that a compelling case presented in a high-impact journal or book from a prestigious publisher trickles down through a magical pathway to those, unspecified people who implement our "world class" science. RCUK's recent decision to scrap the "Pathways to Impact" section on research proposals is a welcome step in that it implicitly acknowledges that these were at best optimistic and unenforceable and at worst fanciful[16], as was the UK Governments Global Challenges Research Fund. Along with the increasing importance of impact with the Research Excellent Framework hopefully these will lead to changes in the conduct and culture within academic research.

WASH research is not basic research. It has a clear goal of improving the world. It is praxis in the Marxist as well as the broader sense. This makes it an appealing field to work in. It is also necessarily interdisciplinary, another appealing feature. The ability to combine fields as diverse as hydrology, epidemiology and political science in order to achieve something useful is a motivator for many in the sector. And many are happy to trade career advancement for their work to have non-academic impact. But the desire and incentives to demonstrate novelty and move quickly seem to

[16] https://www.ukri.org/news/pathways-to-impact-impact-core-to-the-uk-research-and-innovation-application-process/

have another effect that has become apparent during the course of doing this PhD. Much knowledge seems to get forgotten and then rediscovered. Older literature seems to give up insights that should really be embedded in the collective knowledge. I have made a conscious effort to go back to earlier literature and build a case and a way of approaching this issue from more foundational work, which have helped me consider how to approach the issues as much as providing evidence on which to build. Hill's nine considerations, for example, were a very helpful framework for assessing the validity of the results of this study, a refreshing contrast to the dogmatic current debate.

Likewise, Blum and Feachem (1983) provided an useful review of interventions studies and their limitations, allowing the reader to glean lessons from the shortcomings of earlier studies when designing their own. Modern equivalents to these seem to be more focused on abstruse statistical errors that may help marginally increase rigour at the analysis stage. I would have no issue with this if it were not for the fact that I have a feeling that some of these earlier papers are no longer read. Esrey, Feachem and Hughes (1985) proposed a simple conceptual model for the dose response relationship between enteric pathogens ingested and diarrhoea in children. Three decades later a very similar model is presented and cited as novel. This is not to criticise the authors of the later paper—it is impossible to read and cite all the relevant literature—but given that WASH research is focused on effecting positive change, lost knowledge and repeating old mistakes comes at a cost; programmes that are implemented and repeat old mistakes waste resources and potentially cost lives. Moving from research towards implementation of projects involving handpumps, Arlosoroff *et al.* (1987) remains the most important paper ever written on the subject and should be issues to anyone who has any decision-making power about anything to do with handpumps: it is an embarrassment that our sector has spent millions of dollar installing India Mark 2 pumps in community managed setting when Arlosoroff *et al.* (1987) explicitly say that it is unsuitable for VLOM[17]; similarly, ensuring the appropriate choice of pump variants and materials depending on the groundwater they will be pumping remains an issue today despite being raised in the 1980s (Arlosoroff et al. 1987; Langenegger 1989).

The limitation of having a day job while working on the PhD over seven years has given me the luxury of being able to learn about the subject over a longer period of time while working on projects that have given me first-hand knowledge of handpump use and put me in contact with the authors of some of the seminal pieces of work. Had I been on a three-year time table or an NGO worker having to deliver a WASH project over a tight timescale there is no doubt I would have made

[17] The India Mk.2 can pump from deeper than the Afridev making it necessary in some cases, but in these it must be accompanied by an appropriate management regime.

the errors I raise above. Even from the privileged position I now find myself in, I probably have still made some of them. Another advantage of taking longer over this PhD is that I have had time to change my mind. I did come at this with certain ideas and expectations in mind. But elements of this thesis generated results that were not what I was expecting. I was expecting a non-linear relationship between pump repairs and health, but not the brutally short one I seem to have found. I had expected to be able to make the case that community management would not generate the health benefits we might wish for, but I had hoped to be able to make the case that professional maintenance of handpumps could unambiguously generate the health benefits that community management will not. The work presented in this PhD suggests that this may not the case.

Chapter 13 – Conclusions

This PhD set out to examine the limits of performance of rural handpumps, empirically investigating actual use patterns and how they are affected by weather, and the impact on diarrhoeal disease of what could be viewed as the highest level of service likely to be obtainable with handpumps, that achieved by a well-resourced professional maintenance service. Based on the empirical findings, I then discussed the implications for the handpump—and the way in which pumps are managed—with reference to the Sustainable Development Goal for water, in particular the JMP's service ladder[18]. This PhD sits at the nexus of research into professionalization for rural water service and the health impact of intermittent water supply, an area where there has been little empirical research to date. While the technology that enabled this study may have been cutting-edge, the approach I have taken is in some ways rather traditional, using observational study and quasi-natural experiments in an effort to make the research reflect—as much as was possible—a realistic scenario. I briefly discussed the debate on experiment vs. causality, but maintain that the debate on causality is secondary to whether a finding is compelling enough to give policy makers and practitioners pause for thought about what they are doing and a pathway to improvement that they can feasibly implement.

I took a multi-disciplinary approach, combining engineering, epidemiology and social science research methods and analysis techniques. One empirical element involved an innovative epidemiological study around the professional maintenance service; the other used signal processing methods to combine data from experimental monitoring technology with that from traditional manual rain gauges. The two elements then respectively used well-established statistical techniques from epidemiology and hydrology to validate the findings. Data were generated from novel mobile technology, manual rain gauges and traditional household surveys. The variability in pump use, both temporally and spatially, was demonstrated using innovative pump monitoring in the first large-scale study to use this technology as part of a truly multi-disciplinary study. The empirical work in Chapter 7 has shown that handpump use varies widely and in response to rainfall, both seasonally and immediately following heavy rainfall. The former finding is not a surprise, but the latter had not to my knowledge been described in previous literature.

[18] While acknowledging the debate around SDGs, for the purposes of this PhD I have taken SDG 6.1 as a worthy aim. However, the relevance of my findings is not contingent on the validity of the SDGs.

The specific reasons for this response to rainfall were considered, but the broader implication of this is that the assumption that water users will consistently use an improved source throughout the year if it is provided to them does not hold: handpump users get water from multiple sources, some of them almost certainly of inferior quality. Climate change is likely to make such fluctuations in use more pronounced or more frequent, making weather-induced behaviour change analogous to those presented here more likely and widespread. Moreover, institutional interventions may be based on what has been effective in the past rather than designed for an expected future. With effective adaption dependent on scale (Vincent 2007) and institutional arrangements (Agrawal and Perrin 2008), maladaptation is possible or even likely if these behaviour changes are not actively considered (Barnett and O'Neill 2010). While climate-induced changes in disease are well studied, albeit contested (P.R. Hunter 2003; Patz et al. 2005; Liang and Gong 2017; Watts et al. 2017; Wu et al. 2016), there is less research on the actual health impacts of the environmental or operational shocks that may become more common. Weather-induced changes in the behaviours of households and individuals may in turn cause second-order changes in disease patterns and morbidity beyond those caused by, for example, increased temperatures creating a better habitat for insect vectors.

The provision of a high-quality maintenance service may have made handpumps more favourable as downtimes were reduced, but the shifts from groundwater to other water sources that were observed across the study area shows that the increased reliability of these pump did not eliminate people's use of multiple sources. Some households made use of harvested rainwater; other will almost certainly have used surface water, thereby exposing themselves to an array of possible contaminants and pathogens. Chapter 8 set out to test the health impact of short-term changes in water availability in a rural setting, and to determine the health benefits, if any, of the rapid maintenance service that was being established and trialled as part of the wider study. For this epidemiological study the exposure was the quasi-random distribution of pump breakdowns and repairs undertaken by the mechanic employed as part of a professional pump maintenance service, and—more importantly as it turned out—the delay in those pumps being repaired. The outcome health data was derived from interviewing households in a large-scale survey, the same survey generating a range of possible confounders and effect modifiers that were used in the subsequent logistic regression. While blinding was impossible in the strictest sense, efforts were made to blind the study is much as possible to minimise bias. This study has shown that only keeping pump downtimes to an absolute minimum will confer health benefits onto the households that use those pumps. The mechanisms for this are considered, but the "what" has implications that do not depend on the "why". Consistently repairing handpumps the same day they break down is very challenging from a logistical and operational point of view. Going beyond a simple examination of the health benefits of the repair service, the epidemiological study also shed light on the consequences of households choosing to use water supply infrastructure selectively, whether that is due to breakdowns or for reasons of cost, taste or convenience. It showed that there are adverse health impacts from all but the shortest of handpump outages. If similar health effects may be caused by other, voluntary, switches to alternative sources, the assumed health benefits of an improved water supply are likely to be reduced. This is consistent with the existing literature on the subject that suggested that even the short periods of drinking from unsafe sources that would be associated with the reduction in handpump use seen here could have disproportionate effects on health, in particular diarrhoeal disease. Much of this was from either modelling or empirical work in urban settings. This study has made an important addition to this field of research by studying the issue in a rural context.

Implications for Policy and Practice

Finally, in Chapter 9 I circled back on some of the themes first proposed in Chapter 6 and further developed in a WaSH Policy Digest produced for the UNC Water Institute in 2018. Specifically, this considered whether the benefits of remote monitoring of rural water services—in support of the professionalization of these services—is worth the cost and can contribute to sustainable services. This looked beyond the Kwale study site and the empirical work featured here, but a key point of convergence was considering whether failure prediction is the key to consistently eliminating pump downtime and thereby ensuring the continuity of service needed to accrue health benefits.

The various elements of this study have implications for the policy and practice of rural water services, firstly in the role of professionalization of services and the use of data in this, and more fundamentally in questioning the role of handpumps themselves. Professionalisation is necessary to be able to deliver the most from a given class of water infrastructure, be that handpumps or any other. Maintenance that removes community members from some technical decisions does not results in an erasure of community management and participation (Kelly et al. 2017). The community must organise to contract and pay a professional service provider, which requires a different set of skills. I would argue that a contractual relationship with a professional service provider is a more equitable and empowering relationship than the one that would typically be associated with a provider of external support, be that local government of an NGO. It also doesn't eliminate the need for external support, but changes the nature of it. Terms of service between communities and service providers can still consider opportunities for non-monetary contribution to maintain the water system (Behnke et al. 2017). FundiFix, for example, relies on the support of community members when undertaking major handpump repairs, such as those requiring removal of the rising main. To be able to act on water quality information promptly and effectively, and to implement Water Safety Plans in the context of community water sources requires engagement with those communities (Nowicki, Koehler, and Charles 2020; Charles, Nowicki, and Bartram 2020). Capacity building must still address local water institutions and acknowledge the tension between service sustainability and performance, and universal access to ensure that nobody is left behind, even if we no longer train pump mechanics village by village.

One aspect of improving performance as services are professionalised is the use of data. Integrating data and data-driven maintenance in rural or small-scale systems will also reduce the leap from running these systems to operating larger more complicated ones, which have to be operated based on expert response to data, be that pressure sensors in a piped system or chlorine dosing in a water treatment plant. Better use of operational data can also contribute to SDG monitoring. The metrics required for policy and operations are different, especially in the way they are aggregated and presented, but at their core should be derived from the same raw data that captures system functionality and service level. If policy and practice are informed by substantially different data there is a risk that of dislocation between policy and practice. High-level monitoring no longer has to rely on infrequent, periodic surveys collected exclusively for this purpose. This was previously the only means possible, but only captured the situation at a single moment in time. This study has shown the variability in use of rural water systems, both by user choice and due to failures, and suggested that metrics used to measure progress towards SDG6 should consider the actual temporal and spatial variations in water use and system functionality if they are going to truly reflect the level of service people are receiving.

There are now monitoring technologies for rural water systems designed to improve system performance by putting near real-time data into the hands of those managing and maintaining the system. These same systems can also provide data on use patterns and system downtimes to inform policy and support SDG monitoring (Thomson, Hope, and Foster 2012b; Nagel et al. 2015; Thomson and Koehler 2016; Wilson, Coyle, and Thomas 2017). In addition to saving costs from not having to have parallel monitoring systems, linking Monitoring and Evaluation to Operations and Maintenance will reduce the risk of high-level reporting being based on a caricature of actual practice—and this caricature becoming the basis of policy—the consequences of which can only be poor outcomes and wasted resources.

As well as improving the performance of basic water services, professionalisation of basic water services can also be viewed as an investment in training for the transition to safely-managed services. We do not currently have the trained staff to operate the large-scale piped water systems, water treatment plants, and wastewater treatment plants that we will need to build in order to reach SDG 6. Just as military pilots who go on to fly jet aircraft start their training on single engine propeller planes, it would be natural to draw the managers and operators needed for more advanced water systems from cadre of managers and operators who have years of experience running and maintaining smaller systems. Alternatively, the *organisations* set up to run small-scale water systems, be they commercial, non-profit or government, can graduate from smaller operations to taking on larger ones. FundiFix provides an example of this: Having started out in Kitui maintaining only handpumps, FundiFix now operates motorised boreholes and automatic water kiosks on behalf of communities[19]. Being well established in its AOR with good relations with its local customers, FundiFix would be well-placed to take on the management of an expanded piped water supply to the area if one were built. Improving the performance of handpumps is not an impediment to communities getting a higher level of service, it can be stepping stone towards it.

Handpumps and improved sources

The usefulness of the concept of the improved water source is contested. The definitions now being used to monitor the SDGs are more nuanced and service oriented than they were for the MDGs (World Health Organization and UNICEF 2017, 2015). Nonetheless the improved water source remains a key concept and has effectively been carried over into the SDG monitoring framework in the form of "basic water". While only one of a number of improved sources, handpumps abstracting water from boreholes or protected hand-dug wells remain a means of providing water across much of rural Africa, and will continue to be for some time to come despite efforts to achieve "Safely Managed" water, implicitly interpreted as providing piped, treated water to the home. Handpumps are still used operationally in rural water programmes, be they implemented by governments, NGOs or development agencies to provide a low-cost and resilient means of supply and so understanding their actual performance and use remains important. The assumption that if infrastructure is built it will be used must be challenged. Even "basic" water services must be managed *if they are to be service*s and how well they are managed will affect the service actually delivered to water users. It is possible for "basic" water services through access to a well-sited, well-maintained handpump that

[19] This was designed into the FundiFix model from the start.

accesses uncontaminated groundwater, to provide potable water. But if slow repairs, seasonal effects or just a single day of heavy rainfall results in people effectively having only an “unimproved” source of water for even a short period of time, the putative health gains of having even “basic” water may never be realised.

This PhD adds further evidence that handpumps—and certainly the community managed handpumps—will not in the vast majority of cases give rural household acceptable drinking water than brings them health benefits. In the absence of the very best performing maintenance service, household using handpumps will effectively move some households down the JMP’s service ladder, either temporarily or, in some cases, permanently. I say “effectively” as a household with access to a handpump of average performance (in terms of repairs and downtimes) and a total collection time of less than 30 minutes has “Basic water” under the JMP’s definition. An identical household that uses a more reliable handpump, but has a longer collection time, would be classed as having only “Unimproved water”. The evidence presented here, and the existing literature cited on this issue, would suggest that the second household is less likely to suffer from water-related illness. This distinction is very unlikely to be captured in the household surveys that will be used to measure household water services. This is not to say that time spent collecting water is an inconsequential factor that we should not endeavour to shorten[20], or that other factors discussed in this study are not important, but the reliability of water systems is a much more critical metric, on account of its impact on the health of the children, than time spent collecting water which receives special mention in SDG 6.1.

Reliability and intermittency are heart a management issue, be that poor management of adequate resources or heroic management under difficult circumstances, the systems under study may well not be being managed as per best practice, or according to operating procedures or guidelines. An urban piped system that is liable to be intermittent is unlikely to be delivering water with the correct level of chlorination when it is nominally functioning well. In this case the assumed default scenario from which the intermittency may be a deviation from may not be as expected or even consistent. Moreover, adaptive behaviours may produce the effect that an intermittent supply may not in practice be one with binary states of “good” vs. “bad” or “functioning” vs. “non-functioning. All of this adds up to make the study of intermittent supply a particularly murky corner of water supply research, and perhaps one that gets less attention because from an operational and

[20] The arbitrary metric of 30 minutes for collection time is also extremely problematic given actual behaviours of women collecting water, e.g. voluntary “queuing” for social reasons and washing clothes at the pump in order to reduce the volume of water that needs to be carried home.

policy perspective, as we will tend to assume that we are running systems as they were designed to be run.

The operational reality of handpumps and handpump maintenance has been known by many in the sector for a long time, and many will be unsurprised by the conclusions that handpumps and the system under which they operate aren't reliable enough to reduce diarrhoea under the current default management models. With the health benefits of "basic" water precarious, it is tempting to redouble efforts to push towards "safely managed" water for all. There are dangers associated this, one associated with a simplistic interpretation of "safely managed" and one related to how metrics are considered. Handpumps may not be a technology that can be relied upon to deliver safely managed water, but what is at issue here is arguably not the handpump. It is the wider system in which the handpump operates. The pump, or other water infrastructure or technology, may be at the centre of the system but the issue is not about the technology per-se. It is about the service that the technology and the system around it provides to people, and specifically what the system does when the technology fails, both in terms of management interventions and water use practices.

We enjoy piped, treated water, but even that sometimes fails. When it does we have many options available to us, from header tanks and bottled water we keep for just such an eventuality, to the water company providing water to us for during longer outages. In each case we do experience an outage, but we do not have to resort to unsafe sources of water to cope with these outages because there are contingency plans managed in. While each have their advantages over handpumps, switching to solar powered pumps over the same boreholes, or even piped water, without considering the overall management and behavioural system within which that technology operates is unlikely to reduce household diarrhoea, as that diarrhoea turns on what happens when there is an system breakdown, rather than on the situation when the system is operating well. This understanding is reflected in the SDG goal for drinking water being framed in a service delivery paradigm as "safely managed" rather than merely stating the assumed technology that will deliver water of a certain quality when operating well. It is to the JMP's credit that the "safely managed" definition does not explicitly or implicitly specify a technological solution. That the definition includes the word "managed" makes it clear that what is needed is not merely infrastructure, but also, and just as important, the management and institutional environments around that infrastructure. The lessons learnt, and experience and skills gained from efforts to professionalise handpump maintenance should not be viewed as futile.

A second risk is that of purely focusing effort on an operationalised definition of “safely managed” which will likely be getting treated, piped water to people’s homes in order to reach a target. This could result in starving resources from communities, systems and services that are unlikely to make it to “safely managed” by 2030 and cause subsequent backsliding down the ladder from “basic” water. The perfect must not become the enemy of the good; “basic” water services must also be strengthened, despite their shortcomings. This can be through proper resourcing of the parts, tools and personnel that maintain these systems, and considering institutional reform and management redesign that moves away from the community maintenance paradigm, which has not resulted in sustained high levels of service (Golooba-Mutebi 2012; Chowns 2015; Foster et al. 2018; Cronk and Bartram 2017; Foster 2013). Even if these technologies have inherent limitations to the level of service that they can provide and may be incompatible with reaching a state that is “safely managed”, if they are well managed they can provide a higher level of service than if they are not.

Both these risks can be addressed by focusing more attention on management and institutional structures, even those around handpumps and other lower technology systems that may not make the grade of “safely managed”. As well as increasing the performance and benefiting the users of these systems, developing management capacity around more rudimentary systems can be a foundation for having effective management for more advanced systems. This should not be controversial as it is in line with how operations management and professional development takes place in most sectors, including the water sector, acknowledging that much of operational management and service delivery is technology-agnostic. Putting efforts into genuine capacity building, in the form of appropriate training and progressive responsibility, will further support efforts to recast rural water as a service delivery problem. This will help the move towards safely managed water as a reduced focus on infrastructure will lessen the concern that certain infrastructure investments might have been wasted as we eventually but inevitably transition to new or more advanced technologies.

Poverty reduction

Perhaps more fundamentally, this study has shown that water-related diseases are diseases of poverty. This is not news, but considering the factors that were—and were not—apparently protective against disease is informative. Factors pertaining to the quality of housing in the Kwale study area were associated with reported disease. In contrast hygiene factors did not seem to play a role. Having an improved toilet only had an effect when there was also an improved floor. Treating water didn't seem to have an effect and the presence of soap only marginally so. Higher density households and those reporting no income reported higher disease incidence. These findings point to classic WASH interventions being of little benefit if not part of a more generalised effort to reduce poverty. Are programmes that introduce market forces into WASH, such as much-vaunted sanitation marketing programmes and even FundiFix, successful because they are riding a wave of poverty reduction as much as being the cause of that wave? Even with heavy subsidies to align personal social benefits and discount rates, such projects select out the poorest of potential beneficiaries as the very poorest do not have the means to become customers. This is not to say that such programmes are not beneficial, but they will leave the most vulnerable *behind by their very design*.

The Sustainable Development Goals are imperfect and easy to criticise from whatever standpoint one choses to take, be that philosophical, conceptual or practical. But they do at least recognise the interconnected nature of development and poverty. Unfortunately, in the attempt to be comprehensive and trackable, if not achievable, the targets and metrics within each goal give enough for most practitioners and policy makers to work on within their own field or silos, without looking at that interconnectedness other than in the preamble of policy documents or funding proposals. This PhD started out trying to answer a very specific question very much within the specific silo of SDG 6.1, but in getting to that answer it demonstrated this interconnectedness. It has shown that water, sanitation and hygiene interventions cannot be considered in isolation from wider issues of poverty, housing and livelihoods. Just as WASH projects and programmes must be integrating into wider development efforts, the value of future WASH research will be limited if it is not undertaken in a more holistic manner, reaching out of its thematic silo. Approaching water this way will be a challenge for researchers and academics as it may not lend itself to the meticulously designed and well controlled studies that are the hallmark of "world class" research. In a world where science is under threat and evidence-based policy making seems in retreat, we must strive to generate evidence that speaks to the needs of those we hope will use it. We must remain rigorous, avoiding any temptation to slip into generating policy-based evidence, but scientific purity will be no defence against irrelevance if we do not present our evidence in language that policy-makers can understand, and give them recommendations that they can act on. As WASH researchers we can be at the forefront of reducing poverty and improving the lives the individuals, household and communities with whom we work, and to whom we have a duty.

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Appendix 1 - Authorship

Status of papers

In addition to the chapter that are solely part of this thesis, this thesis includes four papers, as per UoR guidelines that states that "the normal expectation is that there would be at least three papers included". Three of these have already been published, with the fourth submitted to BMJ Global Health, again in compliance with UoR guidance that "papers may be published, in revision, or submitted".

1. (Thomson and Koehler 2016) was an invited submission by Robert Bos of SIWI following my presentations at World Water Week 2015. I asked my colleague, Johanna Koehler, to be a co-author. The concept of this paper is around 80% my contribution, with the writing around 60%.
2. (Thomson et al. 2019) is a multiple author paper as it involved data collected by a number of people, whose contributions I wished to recognise. The conceptualisation and data analysis in this paper is over 90% mine, writing around 80%. Much of the improvement from my original draft came as a result of the peer-review process.
3. The paper that is Chapter 7, on the link between the speed of pump repairs and household diarrhoea, has been submitted to BMJ Global Health in June 2021. The conceptualisation is 90% mine. I conducted most of the data analysis (80%), but had significant support from co-authors in refining it and ensuring its rigour, as well as advice on reducing the initial thesis chapter draft to a size and structure more suitable for a stand-alone paper. Writing was 80% mine, but my co-authors made significant contributions in improving the text.
4. The final paper (Thomson 2020) is a single author piece, although it too benefited from the input of one particularly rigorous reviewer.

Declaration of original authorship

[Notwithstanding the above] "I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged."

Patrick Thomson, August 2021

Appendix 2 – Smart Handpumps Database

Original Database Structure

The Smart Handpumps database was designed and built to receive the messages generated and sent by the Waterpoint Data Transmitters as described in (Thomson, Hope, and Foster 2012a), and present them in such a way that they would be useful to the maintenance manager responsible for handpump maintenance in Kenya. There was also a need to be able to download the data from the system to process the handpump use data offline for research purposes. I was fortunate to be able to recruit a team of DPhil students from Oxford's Institute of Biomedical Engineering to build this database. The following section is adapted from Behar *et al.* (2013), where a more detailed description of the database can be found:

The SMS messages were received by a modem and sent to the database using FrontlineSMS, a software package that allows users to develop structured SMS messaging with a computer and a mobile phone or GSM modem. This enabled us to design and test the system in Oxford prior to deployment in Kenya[21]. Initially a PHP script decodes the raw SMS message to deposit the data contained in the message into the correct field in the database, and identify irregularities in the data (e.g. SMS with missing parameters, SMS out of order, repeated SMS) so that corrupted data or erroneous messages do not reach the database.

Each text is given an order number which, by counting forward every six hours from the device switch-on time recorded during installation, allows the system to plot pump use on an hourly basis. This method was used as initial limitations in the system prevented us from sending the timestamp of the message to our system. A duplicate of each text was sent three hours after the original is transmitted in order to have redundancy in the system in case messages were dropped. I later changed this to 18 hours as we found that phone mast outages often lasted longer than three hours. The relational database was designed and implemented using the open source MySQL relational database management system platform. The format of the data sent by the transmitters is structured as shown in Figure 8.

[21] We later adapted the system to use Africastalking, a Kenyan SMS gateway provider.

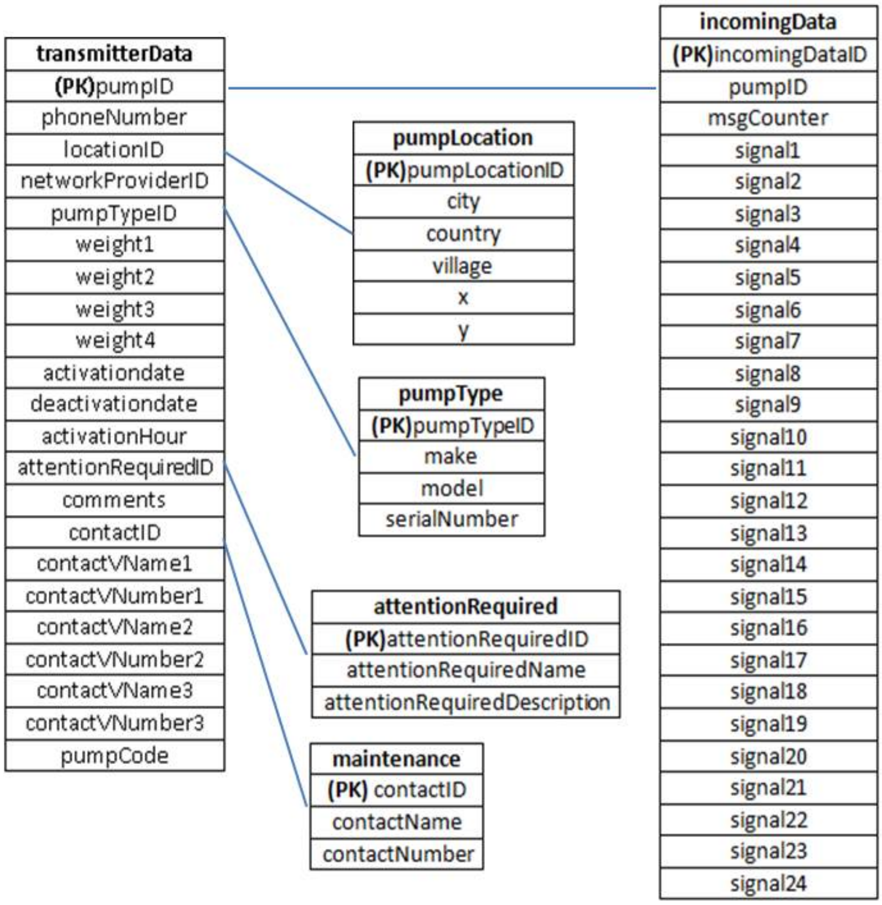


Figure 2: Smart Handpumps Database structure (from Behar et al., 2013)

The database consists of a number of tables, the three essential ones being transmitterData, pumpLocation and incomingData. The pumpLocation table holds geographical information about the physical location of pumps, generated during the survey, most critically the latitude and longitude and the village/location name. The hourly data coming in via Frontline or the SMS gateway is then held in the incomingData table. The table that ties this information from the SMS messages to the geographical location held in the pumpLocation table is the transmitterData table, making it the most critical element of the database. Information is stored under the following attributes: a unique ID, the phone number associated with the transmitter, a location ID that is linked to the pumpLocation. The table also includes an activation date and hour corresponding to the time the WDT unit was switched on and started sending messages. This is to ensure the data can be tracked in time and displayed correctly. The remaining fields in the transmitterData table hold the four weights assigned to each pump that allow for the conversion from handle movement into litres (Thomson, Hope, and Foster 2012a), and the pump maintenance contact details. In addition a code referred to as pumpCode is assigned to each pump in order to uniquely define the pump, this ID being the same used by the fundis and rest of the project team when identifying pumps on the ground.

The user interface was developed primarily to accommodate the needs of users that would interact with it on a day-to-day basis to determine the status of the pumps being managed. The location of the pumps was therefore identified as the key feature that would enable a user to identify a particular pump and take note or action as required. To represent this in an easily interpretable manner, an interactive map was integrated into the system using the Google API, and featured prominently on the first page. Each pump is represented by a marker on the map, showing its exact location, while the status of the pump (fully operational, needing checking, broken, or historic) is represented by the colour of the marker - respectively green, yellow, red and grey. Clicking on the marker, the user is redirected to the “Graphs” page, detailing the information specific to the pump in question, and allowing the user to determine if the pump is in need of a physical investigation based on interpretation of the data. In practice the “Graphs” page was the most used and the various members of the project team quickly learnt where all the pumps were, but the map remained useful when demonstrating the system to other stakeholders.

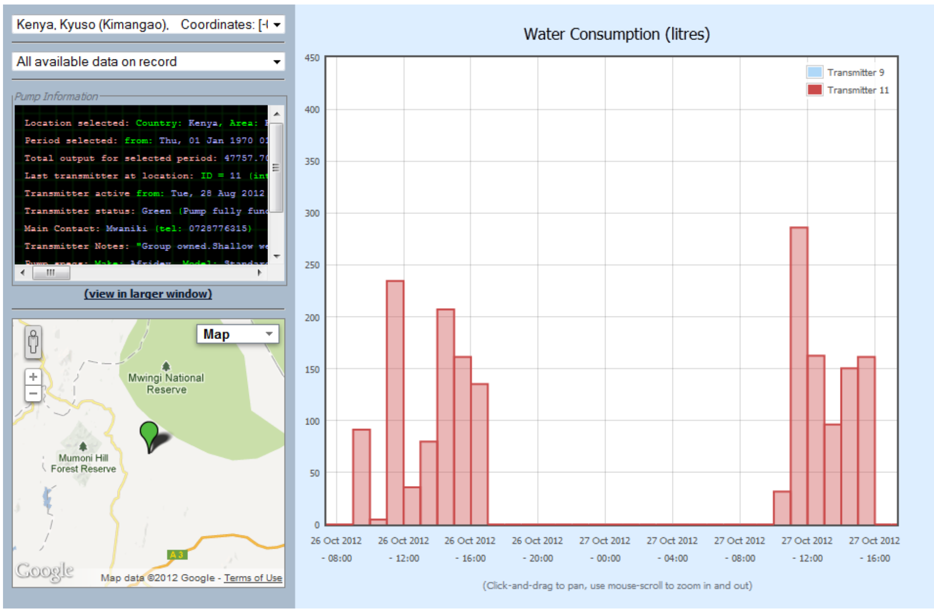


Figure 3: Smart Handpump database GUI

On the Graphs page pump locations are queried from the database and used to populate a drop-down menu. The descriptions and coordinates provided are sufficient to discriminate between the different location options. A separate menu is used to select a time period (48 hours, 7 days, 6 weeks, 12 months, or all available data) to generate and graph the time period of interest for the selected pump. An information window provides more details about the location and period selected, such as full location details, dates and total output or average water consumption corresponding to the selected period, and other information needed for managing the data system. Finally, the mini-map window contains a smaller version of the main map discussed previously section. While the main map became somewhat redundant, having the mini-map on the Graphs page was deemed to be useful by the team.

Machine Learning

A distinct area of study, which generated a new arm of this research, was to investigate what other information can be gleaned from the accelerometer data generated by the Waterpoint Data Transmitter. There are three areas of investigation that I identified early in the Smart Handpump project as being possible and worth pursing scientifically: (1) Handpump failure prediction; (2) Monitoring of the underlying aquifer; (3) Pump user phenotyping. This has work has been done in collaboration with colleagues at Oxford University's Institute of Biomedical Engineering, who have expertise in machine learning from projects focusing on aircraft engine and critical care hospital patient monitoring. These problems were analogous problems to the ones we were facing with handpumps, in particular condition monitoring. We wanted to identify patterns and signals buried in a very noisy waveform that indicated that the thing being monitored was deteriorating.

Crucially, the philosophy being these systems is one of novelty detection for decision support. They identify that there is a problem of some sort and flag this to an expert, rather than trying t to diagnosing the specific problem themselves, although that is clearly of benefit if it is possible. These are decision support tools for experts rather than machines hoping to replace or de-skill humans. In the same way that an algorithm cannot fit a patient with a catheter, it cannot replace a seal on a pump; for that we need trained nurses and experienced mechanics. The critical path to rapid and efficient repairs is logistical and thus largely independent of the exact nature of the failure. The value of an early, but non-specific warning is likely to be much greater than an exact diagnosis of the problem generated later. This strand of work has developed alongside this PhD and continues. It is referred to in the final paper that comprised this thesis.

Appendix 3 – Kyuso Smart Handpump trial

The initial trials of the Waterpoint Data Transmitter were undertaken in Kyuso District (what is now Mwingi-North sub-county) in Kitui County. This area was selected for a number of reasons. Firstly, it is an area where poverty, hydrological risk and handpump dependency broadly reflect conditions across semi-arid rural Africa, where handpumps are ubiquitous. Secondly, under a different project our Kenyan partner organisation, Rural Focus Ltd., had conducted a waterpoint mapping exercise in 2011 that had identified the location of the handpumps in the area. Finally, it was an area affected by the 2011 drought in East Africa that had been designated as Extremely Food Insecure by USAID. This made it an area where the need was paramount, and an easy case to make to DFID, who were funding this work at the time. Located 270 km north east of Nairobi with a population of around 27,000 households, the population is largely rural with two out of three households classified as 'poor'. The two towns in the area are Kyuso and Ngomeni.

This is a semi-arid area[22]. Average annual rainfall in the period 1961 to 2006 was 774 mm, with a bimodal rainfall pattern of "long rains" in March, April and May, and "short rains" in October, November and December. There are a number of rivers in the area, but these only flow for a few weeks each year. They are nonetheless important: even when the rivers are dry there are significant volumes of water stored in the sand beds and accessing water through sand scoops is common, and there is the increasing use of sand dams (Quinn, Rushton, and Parker 2019) to increase water retention. Moreover, handpumps are often sited near these rivers to take advantage of greater local recharge, in some cases, the site of the handpump being one key driver for locating a sand dam. February and September often see severe and extended dry periods. This area was heavily hit by the 2011/12 Horn of Africa drought, during which a number of reactive and large inadequate measures were undertaken to mitigate its effects, underscoring the importance of groundwater as a critical source of water in such areas. Livelihood systems are largely agro-pastoral with cattle and goat husbandry combined with low-value, rain-fed agriculture (primarily maize, beans and greengrams) cultivated on small plots. In addition to revenue from selling agricultural produce, many households rely on casual labour and remittances to supplement their income. Over half the population (54%) use unimproved water sources. Of the remainder, 39 per cent use wells or boreholes, which include around 70 Afridev handpumps installed over the last 25 years (University of Oxford 2014).

[22] https://wad.jrc.ec.europa.eu/patternsaridity

The trial involved installing WDTs onto 66 Afridev handpumps, split into two groups, based on mobile phone coverage. Both groups received a free maintenance service for a year, the difference being that the project team would monitor the data from the first group of “actively managed” pumps, triggering the maintenance response based on the data received each day, whereas the second “crowd-sourced” group would have to call in repairs themselves. In practice the distinction between the two groups was not as stark as it was in theory, with the “actively managed” households still being able to call the fundi to initiate a repair. For financial, operational and ethical reasons we were not able to run a trial with a formal control group. Instead as a comparator, we used data generated from a brief baseline survey, conducted in July 2012. This involved interviewing 124 voluntary respondents who were collecting water at 21 handpumps. Sampled respondents were mainly female (64%) and reported an average household size of 5.3 members. Findings from this survey (University of Oxford 2014) were that in the 12 months prior to the survey, 18 of the 21 handpumps were said to have experienced a failure, with the median repair time to fix a pump six days, and the mean 27 days. Of note, respondents also reported that handpump downtimes are aggravated by delays in raising money in 40 percent of cases with an average of 18 days to raise sufficient funds. The baseline survey also asked the respondents about their concerns w.r.t. their water supply and handpump in particular. The top three unprompted concerns about handpump management were:

1. Repairs are too expensive 19%
2. Repairs take too long 17%
3. Handpump breaks too often 17%

Notwithstanding the bias inherent in asking the respondents about their concerns while they were at the handpump collecting water, this showed pump maintenance to be a significant concern in Kyuso.

Appendix 4 – Geology of Kwale County study area

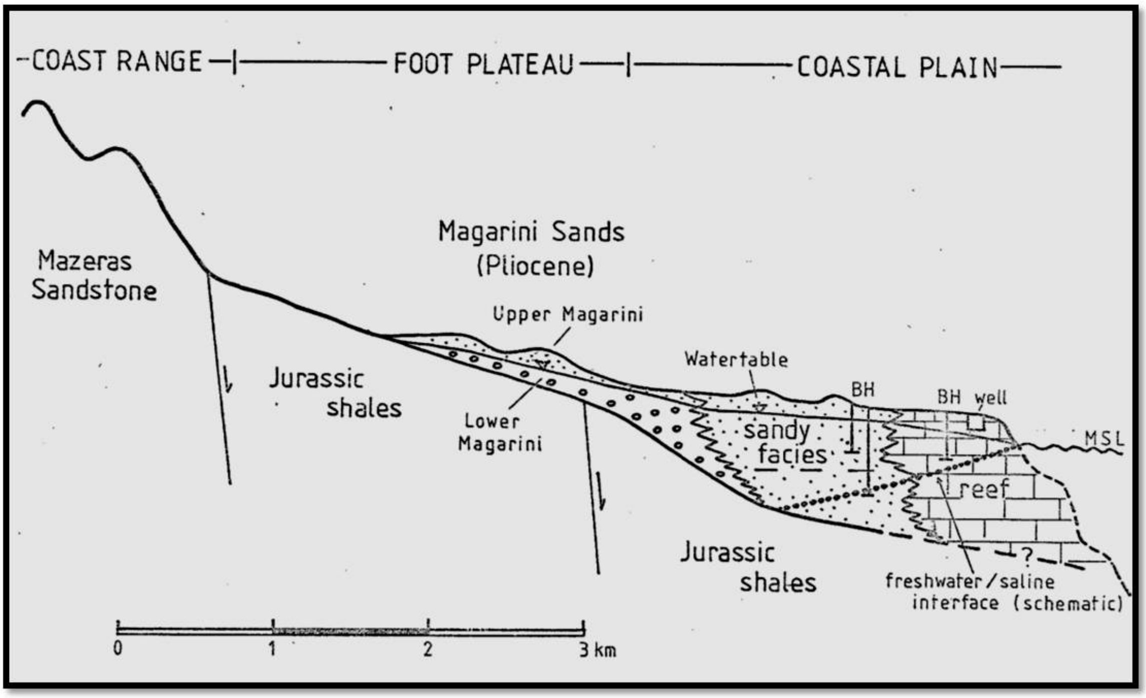
The geology of the study site is of note to this study as different areas of the study area and thus different handpumps and communities are located on different geologies. A number of research outputs were generated on the Kwale groundwater system during this research (Núria Ferrer et al. 2019; Nuria Ferrer et al. 2020) which contain detailed analysis and draw on previous work (Caswell 1953; Buckley 1981). The following is a summary adapted from a Gro for GooD project internal report:

The Shimba Hills, to the north west of the study area, comprise Lower Jurassic Mazeras sandstone and rise to 400 m above mean sea level. These dip to the east south east at between 5 degrees and 10 degrees (Caswell et al., 1953), and are down-faulted in the area of the Gongoni aquifer, where horst and graben have been discerned by resistivity tomography conducted during the UPGro study. They are overlain by Middle Jurassic Kambe limestones which in turn are overlain by Upper Jurassic to early Cretaceous Mto Mkuu Formation silty shales, sandstones, limestones and shales. These are unconformably overlain by Pliocene Magarini dune sands that host the titanium ore mined in the study area. These rise to a maximum elevation of 145 m and form the Coastal Hills. The area east of the Coastal Hills is characterised by subdued topography and is underlain by Pleistocene back-reef sands and coral limestones which give way to Pleistocene coral limestones that extend to the seashore, sloping gently eastwards from an elevation of 60m above mean sea level to the sea over a distance of 6 km to 10 km.

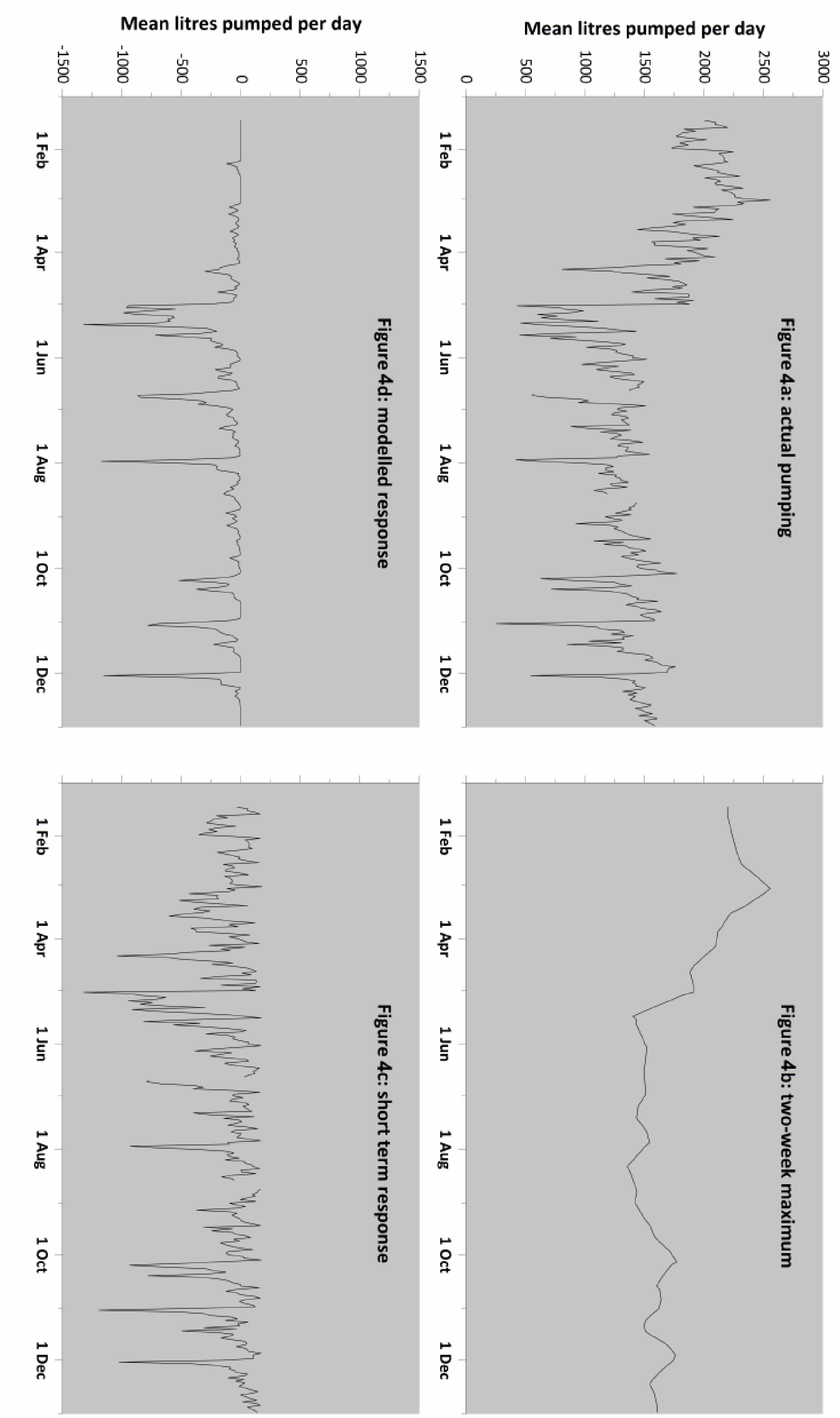
Within this there are two groundwater systems: an unconfined shallow aquifer system in the eastern part in which shallow wells and boreholes are constructed for handpump-based water supplies; and a confined deep aquifer system that underlies the shallow system and is separated by a clayey aquiclude. Pleistocene sandy sediments constitute the shallow aquifer system, directly recharged by rainfall. Survey by Base Titanium in 2013 indicates that these rarely exceed 18 m in thickness. East of the sands lie the Pleistocene limestones, which are known to be at least 90 m thick in the Mombasa area (Caswell 1953)*. The Pliocene sands constitute a poor aquifer west of Milalani and Ukunda. The deep aquifer comprises Jurassic sediments. These are recharged indirectly from the Shimba Hills, with groundwater flowing east under gravity head. This deeper confined aquifer unit is at least 60 m thick, and comprises sandstones, marine limestones and shales. The two aquifer systems are separated by an aquitard with some, albeit minimal and extremely localised, effect seen in the shallow aquifer when the deep aquifer is heavily pumped.*

The Kwale coastal groundwater system has long served domestic water needs and the tourism industry but now faces unprecedented groundwater and surface water resource demands. The concurrent establishment of two major, water-dependent industries presents significant challenges in balancing significant economic growth opportunities with environmental sustainability and equitable development. Major investments in new surface water storage (around 19 million m^3) for the sugarcane farm and mine are complemented by a distributed well-field of 30 boreholes ranging from 40 m to 150 m deep to supplement surface water and buffer through low rainfall periods. Projected maximum groundwater withdrawal is 12 million m^3 per year (80% irrigated sugarcane). The handpumps drawing shallow groundwater from between 5m and 30m depth provide water to communities, schools and health centres.

Figure 4: West to East section of study area (from Buckley, 1981)



Appendix 5 – Observed and Modelled Handpump use 2014



Appendix 6 – Kwale Household Survey

The questionnaire used for the household surveys has been deposited in ReShare, UK Data Service's self-deposit repository for social science research data from UKRI projects. The following text is taken from our accompanying submission on ReShare (Hope et al. 2019):

This dataset comprises of a longitudinal panel study monitoring socio-economic status and management of household water resources in Kwale County Kenya from 2013 to 2016. A sample of 531 handpump locations was used as a sampling frame for three rounds of household surveys in 2013/14 (November-January), 2015 (March-May) and 2016 (September-November). The survey generated a comprehensive dataset capturing information on a) demographic characteristics, b) socio-economic status of the household, c) household health status, d) main and secondary household water sources, e) waterpoint management, f) water payment, g) water resources management as well as h) governance and political engagement for each household.

For the first survey, a stratified random sample of households was selected within the service area of each of the 531 handpumps. In total, 3,361 households were surveyed. An average of six households was randomly selected in the vicinity of each pump (4.6 residents per household). Typically, between six and ten households were interviewed at handpumps that were functional at the time of interviewing or had been functional at some point in the previous 12 months. Typically, four to five households were interviewed at handpumps that had been non-functional for more than one year. In order to randomly select participating households, a sketch map of all dwellings within the estimated waterpoint service area was first drawn by an enumerator in consultation with a local community member. Each household was allocated a number, and the households were then chosen using a random number generator application installed on a tablet device. All the households surveyed were geo-referenced for mapping purposes. The survey/questionnaire took between 45 minutes to one hour to complete.

We recruited between 19 and 25 local enumerators spanning the study area for the three rounds, who demonstrated experience in survey work and had completed secondary education or had a college degree. One key criterion was that they were able to conduct the survey in the local languages (Swahili, 53.8%; Digo, 42.6%; Duruma, 2.1%; other, 1.5%). The survey instrument was translated into Swahili. Due to local circumstances (a Muslim dominated culture), the majority of enumerators were male. For each survey wave, the enumerator training had several components: a) providing a background about the purpose of the research, b) discussing all survey questions in detail *to ensure general agreement among the enumerators, c) translating the survey questions into the tribal languages to ensure cohesion for the delivery, d) training usage of the electronic tablets, and e) discussing sampling strategy. Enumerators were split into the three groups listed above – each of which was led by a team leader. These team leaders were trained separately to a) manage survey logistics, b) ensure the sampling strategy was followed, c) oversee survey delivery and d) conduct water quality analysis. One area of the wider study area was designated as the pilot area and any issues with the survey instrument or the sampling strategy were addressed then.*

A follow-up training was conducted and then the delivery of the survey began. At the beginning of each wave, a repeat training and piloting of the instruments were conducted. Data management and quality control for the delivery of the survey the software DoForms was used, which allowed the survey forms to be uploaded to an online platform and managed from Kenya and remotely. All surveys conducted throughout the day were uploaded every evening (on average around 100) to avoid data loss. The team examined all collected data on a daily basis to ensure the quality of data entry and responded immediately if any patterns of data inconsistency arose. These were discussed at weekly meetings with the enumerators. Incentives for best performance were provided.

The majority of the data used is this PhD referred to as the "Household Survey" was from what was called "Wave 2", conducted in 2015 using DoForms software on tablet computers. The questionnaire has an in-built logic, skipping certain sections based on previous responses. The survey was provided in Swahili (English translations are included in the Word rendering below). For completeness, the questionnaire used for "Wave 1", conducted in 2013 can be found here (the differences between these questionnaires are of no consequence to this PhD) [23]:

https://reshare.ukdataservice.ac.uk/853667/12/GroforGooD_Household_survey_questionnaire_Wave1.docx

[23] The survey continued into early 2014, to generated further socio-economic data for a different sub-study but none of those additional questionnaires were used in this PhD.

Wave 2 Household Survey

Unique ID
Mwandishi [*name of enumerator*]
Date
Nambari ya handpump (bomba la maji) [*Handpump ID*]
Kijiji [*location/town/village*]
Je bomba linafanya kazi? [Functionality status of handpump]

- ✓ Ndio, linafanya kazi [*yes, it works*]
- ✓ Halifanyi kazi (chini ya mwaka moja) [*it does not work for less than one year*]
- ✓ Halifanyi kazi (zaidi ya mwaka moja) [*it does not work for more than one year*]

Name of 2014 respondent at this handpump / Previous respondent
Wave 1 previous respondents / Names 2014
Nambari ya nyumba [*household number*]
Majina ya wengine wanoishi kwa numba hii [*Names of other household members*]

Introduction

Habari ya asubuhi/jioni, ninafanya utafiti kuhusu handpumps hapa Kwale nikiwa na ruhusa kutoka Wizara ya Maji na Baraza la kitaifa la Sayansi na Teknologia (National Council of Science and Technology). Jina langu ni _____________ na mimi ni miongoni mwa watafiti wanaoongozwa na kampuni ya xxx. *Good morning/day, I am doing research on handpumps here in Kwale with permission from the Ministry of Water and the National Council of Science and Technology. My name is___________and I am among researchers led by the company xxx.*

Tulikuja kwa nyumba yako mwaka wa (2013/2014)? (Hakikisha). *Did we come to your house in 2013/2014? (Make sure).*

Maelezo uliyotupa wakati huo yanasaidia sana kuimarisha usambazaji wa maji Kwale. Kwa mfano, mradi wa kurekebisha bomba za maji (hand pumps) kwa haraka umeanzishwa na unasaidia jamii nyingi. Tumerudi tena ili tupate maelezo zaidi kwa ajili ya kuimarisha mabadiliko na mda wa kurekebisha bomba za maji zikiharibika. Tunashukuru sana kwa usaidizi na mda wako. *The information you gave us at that time is very helpful in strengthening the Kwale water supply. For example, a handpump repair project has recentlt been developed and supports many communities. We have come back for more information for enhancing the change and timing of fixing the handpumps. We are very thankful for your support and time.*

Zoezi hili litachukua takriban dakika 30 na litatoa habari muhimu. *This exercise will take about 30 minutes and will provide important information.*

Maelezo utakayonipa yatakuwa ya siri na hakuna yeyote atakaye jua majibu yako. Maarifa haya yatapelekwa kwa Wizara ya maji ama unaweza nipigia simu kujua matokeo kwa hii namba xxxxxxxxx. *The information you give me will be confidential and no one will know your answers. This knowledge will be send to the Ministry of Water or you can call this number for the results: xxxx.*

Kushiriki kwa hili zoezi ni kujitolea na kama kuna maswali hautataka kujibu nitayaruka ama pia unaweza simamisha zoezi zima wakati utataka lakini natumai utashiriki katika hili zoezi kwa sababu maoni yako ni ya muhimu mno. *Sharing for this exercise is optional and if there are questions you will not want to answer I'll jump or you can stop the whole exercise when you want but I hope you'll participate in this exercise because your comments are very important.*

Je, kuna mhusika mwenye umri zaidi ya miaka 18?

Is there a respondent present at the household who is over 18 years? Kama la, umshukuru na uende kwa mwingine [*If not, thank them and go to another*]

- ✓ Ndio [*yes*]
- ✓ La [*no*] - Unavailable today (follow-up required)
- ✓ La [*no*] - Household moved closeby
- ✓ La [*no*] - Household permanently moved away

Conditional: if household moved closeby

Umeipata nyumba mpya (mahali alipo hamia)? *Found new location of household?*

- ✓ Ndio [*yes*]
- ✓ Ndio [*yes*] – but unavailable today
- ✓ La [*no*]

Chagua nyumba mpya iliyo karibu na utafute mhusika kwa hiyo nyumba.
If no, select a new household to interview in the vicinity.

Conditional: if household permanently moved away

Sababu ya familia kuhama? *Reason family has moved away?*

- ✓ Alipata kazi mahali pengine [*respondent found work elsewhere*]
- ✓ Alifiwa [*respondent was killed*]
- ✓ Nyumba iliharibika [*the house was damaged*]
- ✓ Shida za kijamii [*social problems*]
- ✓ Nyingenizo [*other*]
- ✓ Sijui [*don't know*]

Chagua nyumba mpya iliyo karibu na utafute mhusika kwa hiyo nyumba.
Select a new household to interview in the vicinity.

Je mhusika amekubali kushiriki? *Has the respondent agreed to participate?*
Kama la, umshukuru na uende kwa mwingine [*If not, thank them and go to another*]

- ✓ Ndio [*yes*]
- ✓ La [*no*]

Conditional: if respondent not willing to participate
Chagua nyumba mpya iliyo karibu na utafute mhusika kwa hiyo nyumba.
Select a new household to interview in the vicinity.

Je mhusuka alishiriki katika utafiti wa hapo awali (2014)?
Is the respondent the same respondent as last time (2014)?

- ✓ Ndio [*yes*]
- ✓ La [*no*] - but an adult from the same household
- ✓ La [*no*] - it is a new household

About the Respondent

"Sasa ningependa kukuuliza maswali machache"
"Now I'm going to ask a few questions about you"

Hakikisha majina kamili ya mhusika?
Confirm respondent's name? ___

Jinsia ya mhusika
Respondent's gender
- ✓ Mume [*male*]
- ✓ Mke [*female*]

Umri wa mhusika
Respondent's age in years ___

IT APPEARS THE RESPONDENT IS BELOW 18. IS THIS CORRECT?
Yes - Skip to end of survey
No - Age was incorrectly entered (return to previous question)

Umefikia kiwango gani cha elimu?
Level of education you have reached?
- ✓ Hakuna [*none*]
- ✓ Chekechea [*kindergarten*]
- ✓ Shule ya msingi [*primary school*]
- ✓ Chuo cha Ufundi [*technical college*]
- ✓ Shule ya upili [*high school*]
- ✓ Chuo cha mafunzo [*college training*]
- ✓ Chuo kikuu [*university*]
- ✓ Hajui [*you do not know*]
- ✓ NR [*no response*]

Conditional: if primary school
Ulifikia darasa la ngapi? *Highest primary school class completed?___*

Conditional: if secondary school
Ulifikia kidato cha ngapi? *Highest secondary school class completed?___*

What is your main religion?
- ✓ Mkristo [*Christian*]
- ✓ Mwiislamu [*Muslim*]
- ✓ Hana dini [*No religion*]
- ✓ Ingine [*other*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi? *Specify if other___*

Government

"Iwapo Serikali ya kaunti ingependa kusaidia kijiji hiki, ni mambo yapi matatu muhimu ambayo familia yako ingependekeza yafanywe". *If the County government would like to help this village, what are three important things that your family propose be done?*
Usimuelekeze mhusika. Chagua majibu 3 (Do NOT prompt. Tick only THREE)
___Concern 1 options:
- o Afya na huduma za afya [*health and health care*]
- o Usafi (vyoo na upitishaji wa maji machafu) [*sanitation*]
- o Usafiri na barabara [*transport and roads*]
- o Usalama na uhalifu [*security and crime*]
- o Huduma za umeme [*electrical services*]

- Kazi na ukosefu wa ajira [*work and unemployment*]
- Elimu [*education*]
- Usaidizi wa kilimo [*agricultural support*]
- Huduma za usamabazaji wa maji [*water supply services*]
- Nyenginezo [*other*]
- NR [*no response*]

___*Concern 2*
___*Concern 3*

Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other*___

Ni shirika gani la serikali linahusika na kushughulikia suala hili? *What level of government is involved in dealing with this issue?*

___*Concern 1 options:*

- Serikali kuu [*central government*]
- Serikali ya Kaunti [*county government*]
- Serikali kuu nay a Kaunti [*central and county governments*]
- Nyenginezo [*other*]
- Sijui [*don't know*]
- NR [*no response*]

___*Concern 2*
___*Concern 3*

Je, unadhani kampuni ya Base na/ama KISCOL inachangia katika kuleta maendeleo kwa Kaunti? *Do you think Base and/or KISCOL contributes to development in the County?*

Chagua yote yatakayotajwa. *Tick ALL that apply.*

	Base	KISCOL	Neither	Sijui [*DK*]	NR
Afya na huduma za afya *Health and health services*					
Usafi (vyoo na upitishaji wa maji machafu na mazingira) *Sanitation*					
Usambazaji / upatikanaji wa maji *Water supply*					
Stima *Electricity*					
Barabara *Roads*					
Shule *Schools*					
Kazi *Jobs*					
Chakula *Food*					
Nyinginezo *Other*					

Kama ni nyenginezo, tafadhali fafanua kwenya nafasi. *Specify if other.*___

Taja mambo matatu ambayo Serikali ya Kaunti imeimarisha tangu kuchaguliwa. *Name three things that the County government has strengthened since devolution.*

___*Response 1 options:*

- Usimamizi wa maji, mito, visima and chemichemi [*water management, rivers, wells and fisheries*]
- Usambazaji / upatikanaji wa maji kwa wanavijiji (bomba za maji) [*water supply / access to villagers (water pipelines)*]
- Ujenzi na usambazaji wa kliniki na huduma za afya katika vijiji [*construction and distribution of clinics and health care in the villages*]
- Miundombinu ya shule [*school infrastructure*]
- Ubora wa elimu [*quality of education*]
- Kuleta kazi [*employment*]
- Miundombinu ya barabara [*road infrastructure*]
- Nyenginezo [*other*]
- Hamna [*none*]
- Sijui [*don't know*]
- NR [*no response*]

___*Response 2*
___*Response 3*

Ni mambo gani yanakukera kuhusu hali ya usambazaji wa maji. *[What are your main water concerns?]*
Usimuelekeze mhusika. Chagua yote yatakayotajwa. (*Do NOT prompt. Tick ALL that apply*).

- ✓ Maji yanasambaziwa mbali sana [*too far*]
- ✓ Maji hayatoshi kwa matumizi ya nyumbani [*insufficient water for domestic use*]
- ✓ Maji hayatoshi kwa kilimo [*insufficient water for farming*]
- ✓ Maji hayatoshi kwa mifugo [*insufficient water for livestock*]
- ✓ Usambazaji wa maji ni ghali [*water supply is expensive*]
- ✓ Maji si salama kwa kunywa [*water is not safe to drink*]
- ✓ Hakuna mahali pa kuhifadhi maji nyumbani [*no place to store water at home*]
- ✓ Usambazaji wa maji hautegemeeki [*water supply is intermittent]*
- ✓ Maji ni ya msimu [*water is seasonal]*
- ✓ Mlolongo wa kupata maji ni mrefu sana
- ✓ *No concern*
- ✓ Nyenginezo [*other*]
- ✓ NR [*no response*]

Conditional: if other
Mambo mengine yanayokera kuhusu usambazaji wa maji? O*ther concern relating to water supply*___

About the Household Members

"Ningependa kukuuliza kuhusu watu wengine wanaoishi katika nyumba yako"
"Now I'm going to ask you about other members of your household"

Je, ni watu wengine wangapi wanaoishi katika nyumba yako? *What is the number of other people in your household?* (Mhusika asiwe katika idadi ya wanaoishi katika hiyo nyumba. Jumlisha wote wanaokula ama wanaolala kwa hiyo nyumba).___

"Tuanze na yule mkubwa ki umri"
"Let's start with the oldest member of your household"

Jina la kwanza? *First Name*___

Jinsia? *Gender*?

- ✓ *Male*
- ✓ *Female*

Umri wake? *Age in Years*___
Under 5? *Autoresponse*

Conditional: if <24
Je amehudhuria shule mwaka jana 2014? *Did they attend school last year 2014?*

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if >15
Anafanya kazi gani? *Job status?*

- ✓ Ameajiriwa [*employed*]
- ✓ Kibarua
- ✓ Amejiajiri mwenyewe [*self-employed*]
- ✓ Anasoma [studying]
- ✓ Hana kazi [*does not work*]
- ✓ Zinginezo [*other*]
- ✓ NR [*no response*]

Conditional: if >4
Amefikia kiwango gani cha elimu? *What level of education have they reached?*

- ✓ Hakuna [*none*]
- ✓ Chekechea [*kindergarten*]
- ✓ Shule ya msingi [*primary school*]
- ✓ Chuo cha Ufundi [*technical college*]
- ✓ Shule ya upili [*high school*]
- ✓ Chuo cha mafunzo [*college training*]
- ✓ Chuo kikuu [*university*]
- ✓ Hajui [*you do not know*]
- ✓ NR [*no response*]

Conditional: if primary school
Ulifikia darasa la ngapi? *Highest primary school class completed?*___

Conditional: if secondary school
Ulifikia kidato cha ngapi? *Highest secondary school class completed?*___

Conditional: if <15
Sasa nitakuuliza kuhusu hali yake ya afya (1)
"Now I'm going to ask you about the health of [NAME]"

Je, amewahi kuharisha ndani ya wiki mbili zilizopita (Kuwa na choo chepesi (kuhara) mara tatu au zaidi kwa siku)? *Has he/she had diarrhea in the last 2 weeks (loose stool three or more times a day)?*

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

    Conditional: if yes
    Je, kulikuwa na damu kwenye kinyesi? *Blood in stools?*
    - ✓ Ndio [*yes*]
    - ✓ La [*no*]
    - ✓ Sijui [*don't know*]
    - ✓ NR [*no response*]

Je, amewahi kuwa na ugonjwa wa kisonono/kichocho ndani ya mwezi uliopita? *Has he/she every had schistosomiasis or blood in urine in the last month?*
- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Je, amewahi kuwa na ugonjwa wa kukohoa ndani ya wiki mbili zilizopita? *Has he/she ever had a cough in the last 2 weeks?*
- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

    Conditional: if yes
    Alipokuwa na ugonjwa wa kukohoa je, alikuwa akipumua karaka kuliko au kupata ugumu wa kupumua? *Did he/she breath faster than usual with sport, rapid breaths or have difficulty breathing?*
    - ✓ Ndio [*yes*]
    - ✓ La [*no*]
    - ✓ Sijui [*don't know*]
    - ✓ NR [*no response*]

Je, ana ugonjwa wowote wa ngozi? *Does he/she have any skin infections?*
- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Ndani ya kipindi cha wiki mbili zilizopita je alikuwa na madhara katika macho yake? *Has he/she had eye infection in the last 2 weeks?*
- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Je, ameugua malaria mwaka uliopita? *Has he/she had malaria in the last 12 months?*
- ✓ Ndio [*yes*]

- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Are there other household members? If so, now ask about the next oldest person in the household.

Income and Employment

Sasa ningependa kukuuliza maswali kuhusu kuajiriwa au mapato yako.
"Now I'm going to ask you about your income/employment"

Je, unafanya kazi gani? *What kind of job are you doing?*

- ✓ Ameajiriwa [*hired*]
- ✓ Kibarua [*laborer*]
- ✓ Amejiajiri mwenyewe [*self-employed*]
- ✓ Anasoma *[studying]*
- ✓ Hana kazi [*does not work*]
- ✓ Zinginezo *[doesn't know]*
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi? *Specify if other___*

Conditional: if self-employed or does not work
Mhusika anajipatia mapato kwa nija gani? *What work?*

- ✓ Ukulima [farming]
- ✓ Uvuvi [fishing]
- ✓ Biashara ndogo ndogo [small business]
- ✓ Usaidizi kutoka kwa jamaa [
- ✓ Nyenginezo [*other*]
- ✓ NR [*no response*]

Conditional: if self-employed or does not work
Je, alipata au kupokea malipo au fedha kwa siku, kwa wiki au kwa mwezi? *Did you receive money or get paid per day, per week or per month?*

- ✓ Kwa siku [*per day*]
- ✓ Kwa wiki [*per week*]
- ✓ Kwa mwezi [*per month*]
- ✓ Other
- ✓ NR [*no response*]
- ✓ Sijui [*don't know*]

Conditional: if per day/week/month
Fedha alizopokea au kulipwa kwa siku? *Money received or paid per day/week/month?___*

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi? *Specify if 'other'?___*

Conditional: if other

Fedha alizopokea au kulipwa kama ni nyinginezo? *Payment per other time period?___*

Health

Je, watu katika nyumba yako wakiwa wogonjwa huenda kliniki aghalabu mara ngapi?
How often do members of your household go to a medical facility when they are sick?

- ✓ Kawaida [*common*]
- ✓ Mara kwa mara [*regularly*]
- ✓ Si sana [*not common*]
- ✓ Wakati wamezidiwa sana [*rare*]
- ✓ Hawaendi kliniki/hospitali [*do not go to clinic / hospital*]
- ✓ Wanaendelea na matibabu [*undergoing treatment*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Ni kliniki/hospitali gani wao huenda? *Which medical facility do they go to?___*

Kuna nyakati ambazo afya ya watu wazima na watoto zaidi ya miaka 5 katika familia yako hudhoofika kwa sababu ya magonjwa yafuatayo? *Are there times when the health of adults and children over 5 years in your family is weakened due to the following diseases?*

	Malaria	Diarrhea	Respiratory problems	Skin/eye disease	Schistosomiasis
Msimu wa mvua *Wet season*					
Msimu wa kiangazi *Dry season*					
Mwisho wa kiangazi *End of dry season*					
Wakati bomba la maji limeharibika *When HP breaks*					
Nyinginezo *Other time*					

Kuna nyakati ambazo afya ya watoto chini ya miaka 5 katika familia yako hudhoofika kwa sababu ya magonjwa? *Are there times when the health of children under 5 years of age in your family is weakened due to the following diseases?*

	Malaria	Diarrhea	Respiratory problems	Skin/eye disease	Schistosomiasis
Msimu wa mvua *Wet season*					
Msimu wa kiangazi *Dry season*					
Mwisho wa kiangazi *End of dry season*					

Wakati bomba la maji limeharibika *When HP breaks*					
Nyinginezo *Other time*					

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi? *Specify if other___*

Ni mabadiliko gani mazuri yamechangia kuboresha afya yako katika mda wa miezi 12 iliyopita?
What has changed positively to improve your family's health in the last 12 months? *Tick ALL that apply.*

- ✓ Hakuna mabadiliko [*no change*]
- ✓ Mafunzo katika elimu ya afya [*training/education about health*]
- ✓ Kuongezeka kwa fedha ninazopata [*increased earnings*]
- ✓ Umbali wa kliniki kupungua [*shorter distance to a clinic*]
- ✓ Kuboreka kwa huduma za kliniki [*improved clinical services*]
- ✓ Kuboreka kwa upatikanaji wa vifaa vya usafi [*improved access to sanitaty facilities*]
- ✓ Kuboreka kwa upatikanaji wa maji ya matumizi nyumbani [*improved access to water for household use*]
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if training/education about health
Nani aliwaelimisha juu ya fya? *Who provided the education/training on health practices?*

- ✓ Serikali kuu [*central government*]
- ✓ Serikali ya Kaunti [*county government*]
- ✓ Shirika lisilo la Kiserikali [*NGO*]
- ✓ Jamaa wa vijijini [*indigenous rural people*]
- ✓ Nyinginezo [*other*]
- ✓ DK [*don't know*]
- ✓ NR [*no response*]

Conditional: if increased earnings
Je, kuongezeka kwa fedha unazopata kumewasaidia aje? *How has more household income helped?* *Tick all that apply.*

- ✓ Serikali kuu [*central government*]
- ✓ Serikali ya Kaunti [*county government*]
- ✓ Shirika lisilo la Kiserikali [*NGO*]
- ✓ Jamaa wa vijijini [*indigenous rural people*]
- ✓ Nyinginezo [*other*]
- ✓ DK [*don't know*]
- ✓ NR [*no response*]

Conditional: if shorter distance to a clinic or improved clinical services
Nani alichangia katika ujenzi/uboreshaji wa kliniki? *Who funded the building/improvement of the clinic?*

- ✓ Serikali [*government*]
- ✓ Base Titanium

- ✓ KISCOL
- ✓ Nyinginezo [*other*]
- ✓ NR [*no response*]

Conditional: if improved clinical services

Ni sababu gani zimechangia kuimarika kwa kliniki? *Which factors contribute to improved clinic conditions?* *Tick all that apply.*

- ✓ Daktari na wauguzi kuongezeka [*increase in number of doctors and nurses*]
- ✓ Dawa kuongezeka [*pharmaceuticals increase*]
- ✓ Mda wa kingojea kutibiwa kliniki umepungua [*waiting times for treatment have decreased*]
- ✓ Nyinginezo [*other*]
- ✓ NR [*no response*]

Conditional: if other

Kama ni nyenginezo, tafadhali fafanua kwenye nafasi? *Specify if other___*

Conditional: if improved access to water

Nini iliboresha upatikanaji wa maji? *What improved your water supply access?* *Tick all that apply.*

- ✓ Bomba la maji kuwa karibu [*water tap is now available*]
- ✓ Urekebishaji wa bomba la maji uko haraka [fast repair of pipeline]
- ✓ Upatikanaji wa maji safi katika sehemu zingine mpya [new access to clean water]
- ✓ Fundifix Kwale / Kwale Handpump Services Ltd.
- ✓ Nyinginezo [*other*]
- ✓ NR [*no response*]

Conditional: if other

Kama ni nyenginezo, tafadhali fafanua kwenye nafasi? *Specify if other___*

Ni changa moto gani za ki afya nyumba yako hupata? *What health-related challenges does your household face?* *Tick ALL that apply*

- ✓ Kliniki ziko mbali [*clinics are far away*]
- ✓ Bei ya matibabu iko juu [*the price of treatment*]
- ✓ Bei ya dawa iko ghali sana [*the price of medicine*]
- ✓ Huduma za kliniki zimedhoofika [*worsened clinical services*]
- ✓ hamna [*none*]
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other

Kama ni nyenginezo, tafadhali fafanua kwenye nafasi? *Specify if other___*

Household Assets

Je, nyumba yako ina vitu vifuatavyo? *Does your home have the following items?*

	Ndio [*yes*]	La [*no*]	NR [*no response*]
Umeme [*electricity connection*]			
Sola [*solar panel*]			

Televisheni / Runinga [*television*]			
Kompyuta / Tarakilishi [*computer*]			
Redio [*radio*]			
Baiskeli [*bicycle*]			
Pikipiki [*motorcycle*]			
Dhow [*dhow*]			
Simu ya mkononi / rununu [*mobile phone*]			

Je, nyumba yako ina vitu na vyakula vifuatavyo? *Does your home have the following food items?*

	Ndio [*yes*]	La [*no*]	NR [*no response*]
Mafuta ya kupikia [*cooking oil*]			
Sukari [*sugar*]			
Unga [*flour*]			
Majani chai [*tea leaves*]			
Sabuni [*soap*]			

Conditional: if have mobile phone

Je, kuna mtu yeyote wa nyumba hii amewahi tuma au kupokesa pesa kutumia simu ya mkononi kwa mwaka uliopita? *Has anyone in the household sent or received money by mobile phone for the past year?*

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ NR [*no response*]

Conditional: if have cooking oil

Unatumia nini kupikia? *Type of fuel used for cooking?*

- ✓ Umeme [*lightning*]
- ✓ Gesi [*gas*]
- ✓ Mafuta ya taa [*kerosene*]
- ✓ Makaa [*hearth*]
- ✓ Kuni [*wood*]
- ✓ Nyasi [*grass*]
- ✓ Mahunzi (Maguguta)
- ✓ Mavi ya ngombe [*cattle dung*]
- ✓ Hatupiki *[not used]*
- ✓ Nyinginezo [*other*]
- ✓ NR [*no response*]

Mnatumia choo cha aina gani? *Type of toilet facility used?*

- ✓ Choo cha kusukuma kwa kupitia bomba [toilet to piped system]
- ✓ Choo cha kusukuma kwa kupitia tangi [*toilet to tank*]
- ✓ Choo cha kusukuma hadi kwenye shimo [*toilet to pit*]
- ✓ Shimo la choo lenye hewa nzuri [*pit latrine with good air*]
- ✓ Choo cha shimo kilichojengewa [*built pit latrine*]
- ✓ Choo cha ndoo [*toilet bucket*]
- ✓ Choo cha kuhifadhi mbolea
- ✓ Choo kando kando ya maji
- ✓ Hakuna choo/ Choo cha msituni/uwanjani [*no toilet, use bush*]
- ✓ Nyinginezo [*other*]
- ✓ NR [*no response*]

Conditional: if other

Kama ni nyenginezo, tafadhali fafanua kwenye nafasi? *Specify if other___*

Je, mnatumia hiki choo pamoja na watu wengine? *Share toilet with other households?*

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ NR [*no response*]

Conditional: if share toilet

Kama ndio, mbali na nyumba yako, ni ngapi zingine zinatumia choo hiki? *How many other households share the facility?___*

Je, mnamiliki ardhi ya nyumba hii? *Does the household own the land on which the dwelling sits?*

- ✓ Tunamiliki [*we own it*]
- ✓ Tumekodi ardhi [*don't own or have consent, just living on it*]
- ✓ Hatukukodi-tumepewa kwa ridhaa
- ✓ Hatukukodi-ni maskwata [we don't own it but we have consent to live]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Mnamiliki hekari ngapi za shamba? *How many acres of land are owned by the household?___*

Kuna yeyote anaelima? *Does the household grow any crops?*

- ✓ Ndio, mimea hukuzwa kwa ajili ya matumizi ya nyumbani [*yes, plants are grown for home use*]
- ✓ Ndio, mimea hukuzwa kwa ajili ya kuuza [*yes, plants are grown for sale*]
- ✓ Ndio, mimea hukuzwa kwa ajili ya matumizi ya nyumbani na pia kuuza [*yes, plants are grown for home use and sale*]
- ✓ La [*no*]
- ✓ NR [*no response*]

Conditional: if plants grown for sale

Je mnakuza miwa kwa ajili ya KISCOL? *Does household grow sugarcane for KISCOL?*

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ NR [*no response*]

Conditional: if yes

Ni hekari ngapi zilizopandwa miwa kwa ajili ya KISCOL? *How many acres under sugarcane for KISCOL?___*

Je, mnamiliki mifugo wa aina yoyote? *Does the household own any kind of livestock/herd?*

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ NR [*no response*]

Conditional: if yes

Mna ng'ombe wa kienyeji wangapi? *Number of indigenous cattle?___*

Conditional: if yes
Mna ng'ombe wa maziwa wangapi? *Number of dairy cattle?*___

Conditional: if yes
Mna ng'ombe wa kulima wangapi? *Number of oxen?*___

Conditional: if yes
Kuku wangapi? *Number of chickens?*___

Wealth and Expenditure

Sasa ningependa kujua kiwango cha pesa nyumba yako inatumia kwa vitu kadha wa kadha.
"Now I would like to know how much money you spend on different things"
Matumizi ya nyumbani kwa wiki/mwezi uliopita. Kama hakuna matumizi, andika 0 (sufuri).
Spending for home use per week/month. If no use, write 0.

Kitu [*item*]	Kiasi cha pesa [*Amount Kshs*]	Per day/week/month
Chakula [*food*]		
Usafiri [*transport*]		
Matibabu / Dawa [*health / medicine*]		
Karo ya Shule [*school fees*]		
Maji [*water*]		
Matumizi kwa umeme na nguvu ya kupikia (kuni, makaa n.k) [*energy*]		
Matumizi kwa simu [*mobile phone*]		

Kwa ujumla, utasema familia yako ni tajiri, inajiweza au ni maskini? *Does household think they are well-off, average or not well-off in terms of assets and income?*

- ✓ Tajiri [*rich*]
- ✓ Inajiweza [*average*]
- ✓ Maskini [*poor*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Je hali ya maisha ya nyumba yako ni bora Zaidi, hamna mabadiliko mbaya zaidi ikilinganishwa na mwaka jana? *Does household think they are better-off, the same or worse-off than last year?*

- ✓ Better-off
- ✓ Same
- ✓ Worse-off

Conditional: if better-off or worse-off
"Sasa ningependa tuzumzie kuhusu sababu ya kuboreka au kudhoofika kwa familia yako tukilinganisha na mwaka jana. Ni sababu gani mabadiliko hayo yametokea?" *"Now I would like to know about the cause of the improving or worsening of your household compared to last year. What is the reason for this change?"*

Je, kumekuwa na kifo, magonjwa, au watoto kuzaliwa? *Have there been deaths, diseases or births?*

	Male adult	Female adult	Male child	Female child	No change
Vifo [*Deaths*]					
Ugonjwa mkuu [*Serious illness*]					
Watoto kuzaliwa [*Births*]					

Je, nyumba yako ina kiasi cha mali sawa na ya mwaka jana? *Does your house have the same amount of assets last year?*

	More	Less	No Change
Shamba [*land*]			
Mifugo [*livestock*]			
Uvuvi [*fishing*]			
Biashara ya usafiri [*transport*]			
Ukulima [*farming*]			

Je, kuna mabadiliko yoyote makubwa katika mapato au matumizi ya nyumbani kulingana na mwaka jana? *Is there any major change in income or home use compared to last year?*

	More	Less	No Change
Pesa kutoka kwa wanafamilia [*remittances*]			
Pesa kutoka kwa serikali/shirika lisilo la kiserikali [*cash transfers*]			
Mabadiliko katika aijira [*change in employment*]			
Malipo ya shule [*school fees*]			
Bei ya chakula [*food prices*]			

Je, kumekua na mabadiliko yoyote kwa huduma nyumba yako hupokea? *Has there been any change in the services your home receives?*

	Better	Worse	No Change
Huduma ya maji ya kunywa [*drinking water services*]			
Huduma ya afya [*health services*]			
Huduma ya elimu [*education services*]			
Huduma ya usafi wa vyoo [*sanitation services*]			
Huduma ya usafiri wa barabara [*road/transport*]			
Huduma ya umeme/stima [*energy services*]			
Huduma za ulinzi [*political stability/security*]			

Mabadiliko mengine amabayo hatujayazungumzia? *Specify any other changes.*___

Water Sources

"Sasa nitakuuliza njia unazotumia kupata maji ya KUNYWA."
"Now I will ask you about how you get drinking water."

Wakati wa kiangazi, mnapata maji ya kunywa wapi? *Main source of drinking water in the dry season?*

- ✓ Reference handpump
- ✓ Handpump nyengine [*other handpump*]

- ✓ Mashine ya kupamp maji (ya umma) [*public submersible pump*]
- ✓ Mashine ya kupamp maji (ya binafsi) [*personal submersible pump*]
- ✓ Kisima kilichofunikwa (cha umma) [*public protected well*]
- ✓ Kisima kilichofunikwa (cha binafsi) [*personal protected well*]
- ✓ Kisima kilichowazi (cha umma) [*public unprotected well*]
- ✓ Kisima kilichowazi (cha binafsi) [*private unprotected well*]
- ✓ Maji ya ardhini (mito, ziwa, kidimbwi, mito midogo, kishimo) [*surface water (rivers, lakes, dams, small rivers)*]
- ✓ Maji ya mfereji nyumbani [*canal water at home*]
- ✓ Maji ya mfereji kwa jirani [*canal water for the neighbourhood*]
- ✓ Mfereji wa umma [*public canal*]
- ✓ Gari la maji [*truck vendor*]
- ✓ Mkokoteni/baiskeli iliyo na madebe/ mitungi [*bicycle vendor*]
- ✓ Maji ya mvua [*rainwater*]
- ✓ Maji ya chupa [*bottled water*]
- ✓ Nyenginezo [*other*]

> *Conditional*: if surface water
> **Ni mto gani unaotumia? *Which river to you use?***
> - ✓ Mkurumudzi
> - ✓ Ramisi
> - ✓ N'Gade
> - ✓ Pongwe Kidimu
> - ✓ Mwena
> - ✓ Mwakwembe
> - ✓ Nyinginezo [*other*]
>
> *Conditional*: if other
> **Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___**

Ni sababu gani zinazofanya uchague kupata maji ya kunywa kwa njia hiyo wakati wa kiangazi?
What factors make you choose to use this source in the dry season?
Usimuelekeze mhusika. Chagua yote yatakayotajwa. *Do not prompt. Tick ALL that apply.*

- ✓ Iko karibu na nyumba [*it is near the house*]
- ✓ Ladha ya maji [*the taste of the water*]
- ✓ Harufu ya maji [*the smell of the water*]
- ✓ Rangi ya maji [*the colour of the water*]
- ✓ Usalama wa kunywa [*safety of water]*
- ✓ Yananulika kwa bei nafuu [##]
- ✓ Ni bure [*it's free*]
- ✓ Yanategemeeka [##]
- ✓ Ndio njia ya pekee [*it's the only option*]
- ✓ Nyenginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

> *Conditional*: if other
> **Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___**
>
> *Conditional*: if any source other than reference handpump

Wakati wa kiangazi, maji haya ni salama kwa kunywa? *Is water source safe to drink in dry season?*
- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if any source other than reference handpump
Unalipa pesa ngapi kutumia maji haya wakati wa kiangazi?

Kiasi cha pesa (Amount Kshs)	Jinsi ya malipo (Frequency)

Wakati wa masika, mnapata maji ya kunywa wapi? *Main drinking water source in the wet season?*
- ✓ Reference handpump
- ✓ Handpump nyengine [*other handpump*]
- ✓ Mashine ya kupamp maji (ya umma) [*public submersible pump*]
- ✓ Mashine ya kupamp maji (ya binafsi) [*personal submersible pump*]
- ✓ Kisima kilichofunikwa (cha umma) [*public protected well*]
- ✓ Kisima kilichofunikwa (cha binafsi) [*personal protected well*]
- ✓ Kisima kilichowazi (cha umma) [*public unprotected well*]
- ✓ Kisima kilichowazi (cha binafsi) [*private unprotected well*]
- ✓ Maji ya ardhini (mito, ziwa, kidimbwi, mito midogo, kishimo) [*surface water (rivers, lakes, dams, small rivers)*]
- ✓ Maji ya mfereji nyumbani [*canal water at home*]
- ✓ Maji ya mfereji kwa jirani [*canal water for the neighbourhood*]
- ✓ Mfereji wa umma [*public canal*]
- ✓ Gari la maji [*truck vendor*]
- ✓ Mkokoteni/baiskeli iliyo na madebe/ mitungi [*bicycle vendor*]
- ✓ Maji ya mvua [*rainwater*]
- ✓ Maji ya chupa [*bottled water*]
- ✓ Nyenginezo [*other*]

Conditional: if surface water
Ni mto gani unaotumia? *Which river to you use?*
- ✓ Mkurumudzi
- ✓ Ramisi
- ✓ N'Gade
- ✓ Pongwe Kidimu
- ✓ Mwena
- ✓ Mwakwembe
- ✓ Nyinginezo [*other*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___

Ni sababu gani zinazofanya uchague kupata maji ya kunywa kwa njia hiyo wakati wa masika? *What factors make you choose to use this source in the dry season?*
- ✓ Iko karibu na nyumba [*it is near the house*]
- ✓ Ladha ya maji [*the taste of the water*]
- ✓ Harufu ya maji [*the smell of the water*]
- ✓ Rangi ya maji [*the colour of the water*]

- ✓ Usalama wa kunywa [*safety of water]*
- ✓ Yananulika kwa bei nafuu [##]
- ✓ Ni bure [*it's free*]
- ✓ Yanategemeeka [##]
- ✓ Ndio njia ya pekee [*it's the only option*]
- ✓ Nyenginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___

Conditional: if any source other than reference handpump
Wakati wa masika, maji haya ni salama kwa kunywa? *Is water source safe to drink in dry season?*
- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if any source other than reference handpump
Unalipa pesa ngapi kutumia maji haya wakati wa masika?

Kiasi cha pesa (Amount Kshs)	Jinsi ya malipo (Frequency)

Kwa mwaka uliopita, ni njia gani mbadala munayotumia kupata maji ya kunywa wakati wa kiangazi na wakati wa masika? *For the past year, what alternatives did you use for drinking water during the dry season and wet season?*

	Dry season	Wet season
Handpump nyengine [*other handpump*]		
Mashine ya kupamp maji (ya umma) [*Submersible pump (public)*]		
Mashine ya kupamp maji (ya binafsi) [*Submersible pump (private)*]		
Kisima kilichofunikwa (cha umma) [*Protected well (public)*]		
Kisima kilichofunikwa (cha binafsi) [*Protected well (private)*]		
Kisima kilichowazi (cha umma) [*Unprotected well (public)*]		
Kisima kilichowazi (cha binafsi) [*Unprotected well (private)*]		
Maji ya ardhini (mito, ziwa, kidimbwi, mito midogo, kishimo) [*Surface water*]		
Maji ya mfereji nyumbani [*Piped to yard/dwelling*]		
Maji ya mfereji kwa jirani [*Piped to neighbour's yard/dwelling*]		
Mfereji wa umma [*Public tap / kiosk*]		
Gari la maji [*Tanker truck*]		
Mkokoteni/baiskeli iliyo na madebe/ mitungi [*cart/bicycle vendor*]		
Maji ya mvua [*Rainwater collection*]		
Maji ya chupa [*Bottled water*]		
Nyenginezo [*other*]		

Conditional: if surface water
Ni mto gani unaotumia? *Which river to you use?*
- ✓ Mkurumudzi
- ✓ Ramisi
- ✓ N'Gade

- ✓ Pongwe Kidimu
- ✓ Mwena
- ✓ Mwakwembe
- ✓ Nyinginezo [*other*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.__*

Je, huwa mnatibu maji kabla ya kunywa? *Does household treat water before drinking?*

- ✓ La [*no*]
- ✓ Ndio - wakati wa kiangazi [*yes – during the dry season*]
- ✓ Ndio - wakati wa masika [*yes – during the wet season*]
- ✓ Ndio - nyakati zote [*yes – always*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if yes
Ni nija gani mnayotumia kuyatibu maji ya kunywa? *Methods used to treat drinking water?* *Tick all that apply.*

- ✓ Kuchemsha [*boiling*]
- ✓ Kuongeza dawa
- ✓ Kuchuja na nguo [*filter with cloth*]
- ✓ Kutumia kichungio cha maji
- ✓ Kutumia miale ya jua
- ✓ Kuyaacha yatulie
- ✓ Nyenginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if boiling
Je, unatumia nija gani kuchemsha maji ya kunywa*? What fuel do you use to boil water for drinking?*

- ✓ Umeme [*electricity*]
- ✓ Gesi [*gas*]
- ✓ Mafuta ya taa [*lamp oil*]
- ✓ Makaa [*coal*]
- ✓ Kuni [##]
- ✓ Nyasi [##]
- ✓ Mahunzi (Maguguta) [##]
- ✓ Mavi ya ngombe [##]
- ✓ Hatupiki [##]
- ✓ Nyenginezo [*other*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.___*

Je, mbali na kunywa, una matumizi yapi mengine ya maji kutoka kwenye handpump? *Other than drinking, do you use the handpump water for other uses?*

	Dry season	Wet season	NR

Kupika, kufua na kuonga [*cooking, washing, bathing*]			
Kunyunyizia mimea [*irrigation*]			
Kunywesha mifugo [*livestock watering*]			

Nani mwenye bomba la maji? *Who owns the reference handpump?*
Usimuelekeze mhusika. *Do NOT prompt.*

- ✓ Nyumba fulani [*a certain house*]
- ✓ Kikundi cha maji pamoja na kamitii [*water committee*]
- ✓ Jamii ya kijiji [*village community*]
- ✓ Shirika la kidini [*religious organization*]
- ✓ Shule [*school*]
- ✓ Kliniki [*clinic*]
- ✓ Chifu [*chief*]
- ✓ Serikali ya Kaunti [*County government*]
- ✓ Serikali kuu/Wizara/WRMA [*Central Government / Ministry / WRMA*]
- ✓ Coast Water Services Board
- ✓ KWAWASCO
- ✓ Shiriki lisilo la Kiserikali [*NGO*]
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___

Nani mwenye shamba lenye bomba la maji? *Who owns the land where the reference handpump is located?* Usimuelekeze mhusika. *Do NOT prompt.*

- ✓ Nyumba fulani [*a certain house*]
- ✓ Kikundi cha maji pamoja na kamitii [*water committee*]
- ✓ Jamii ya kijiji [*village community*]
- ✓ Shirika la kidini [*religious organization*]
- ✓ Shule [*school*]
- ✓ Kliniki [*clinic*]
- ✓ Chifu [*chief*]
- ✓ Serikali ya Kaunti [*County government*]
- ✓ Serikali kuu/Wizara/WRMA [*Central Government / Ministry / WRMA*]
- ✓ Coast Water Services Board
- ✓ KWAWASCO
- ✓ Shiriki lisilo la Kiserikali [*NGO*]
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___

Nani mwenye maji yanayopigwa kutoka kwa bomba la maji? *Who owns the water drawn from the reference handpump?* Usimuelekeze mhusika. Do NOT prompt.

- ✓ Nyumba fulani [*a certain house*]
- ✓ Kikundi cha maji pamoja na kamitii [*water committee*]
- ✓ Jamii ya kijiji [*village community*]

- ✓ Shirika la kidini [*religious organization*]
- ✓ Shule [*school*]
- ✓ Kliniki [*clinic*]
- ✓ Chifu [*chief*]
- ✓ Serikali ya Kaunti [*County government*]
- ✓ Serikali kuu/Wizara/WRMA [*Central Government / Ministry / WRMA*]
- ✓ Coast Water Services Board
- ✓ KWAWASCO
- ✓ Shiriki lisilo la Kiserikali [*NGO*]
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___

Nani anasimamia na kudumisha bomba la maji? *Who manages and maintains your drinking water supply infrastructure?*

- ✓ Mtu binafsi kutoka kwa kaya [*individuals from the household*]
- ✓ Kamitii ya bomba la maji [*water committee*]
- ✓ Kampuni ya kibinafsi (FundiFix, Kwale Handpump Services Ltd.) [*private company*]
- ✓ Serikali ya Kaunti [*County government*]
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___

Kwa maoni yako, ni nani unadhani anafaa kudumisha shina la maji ya kunywa? *Who do you think would be best placed to maintain your drinking water supply infrastructure?*

- ✓ Serikali ya kaunti/huduma za uma/kampuni ya kutoa huduma ya maji
- ✓ Muungano wa uma-na kampuni za kibinafsi [*the County government / service provider*]
- ✓ Kampuni za kibinafsi [*private companies*]
- ✓ Wana vijiji [*the villages*]
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___

Unadhani sahii ni msimu wa kiangazi au wa mvua. *Right now, would you consider this to be dry season or wet season?*

- ✓ Msimu wa kiangazi [*seasonal*]
- ✓ Msimu wa mvua [*rainfall*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Reference Handpump

NOTE: All the following questions relate to the reference handpump.

Je, unaamini kuwa wale wenye maisha magumu katika jamii wanafaa kupewa maji bila kulipia katika handpump? ***Do you think that the most vulnerable households (old, poor etc) of your community should have free access to water at the handpump?***

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Je, kuna amri/kanuni katika handpump hii inayo waruhusu msilipie maji wakati wa Ramadhan? ***Is there a specific rule that you do not have to pay handpump user fees during Ramadhan?***

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Je, handpump imerekebishwa kwa mwaka mmoja uliopita? ***Has handpump been repaired in the last 12 months?***

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if yes

Mara ya mwisho iliporekebishwa, ilikaa siku ngapi bila kuhudumu? ***Last time handpump was repaired, for how many days was it broken?___***

Conditional: if yes

Malichanga pesa ngapi kwa ajili ya urekebishaji wa handpump? ***How much money did your household contribute for these repairs?*** *If no contribution enter '0'.* ___

Nani alirekebisha hand pump? ***Who carried out the repairs?***

- ✓ Mmoja wa jamii ya Kijiji [*someone from the village*]
- ✓ FundiFix/Kwale Handpump Services Ltd. (Idd Mwaropia, Okoti Omayo)
- ✓ Mafundi wengine kutoka inje [*other technicians*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]
- ✓ Other

Conditional: if other

Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. ***Specify if other.___***

Je, umeridhika na mpangilio unaotumika kwa urekebishaji wa handpump? ***Currently how satisfied are you with handpump repair arrangements?***

- ✓ Nimeridhika sana [*very satisfied*]
- ✓ Nimeridhika [*satisfied*]
- ✓ Naona kawaida [neiter satisfied nor dissatisfied]
- ✓ Sijaridhika [*dissatisfied*]
- ✓ Sijaridhika kabisa [*very dissatisfied*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if satisfied

Mbona umeridhika? *Why are you satisfied?*

Chagua yote yatakayotajwa. Tick all that apply.

- ✓ Urekebishaji unafanyika haraka [*repair is quick*]
- ✓ Handpump haiharibiki kila wakati [*handpump is not often damaged*]
- ✓ Maekebisho sio ghali [*not expensive*]
- ✓ Nyenginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other

Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___

Conditional: if dissatisfied

Mbona umeridhika? *Why are you satisfied?*

Chagua yote yatakayotajwa. Tick all that apply.

- ✓ Urekebishaji unafanyika polepole [*repair is slow*]
- ✓ Handpump inaharibika mara kwa mara [*handpump is often damaged*]
- ✓ Maekebisho ni ghali [*expensive*]
- ✓ Nyenginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other

Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___

Je, ungependa handpump irekebishwe? *Would you like the handpump to be repaired?*

- ✓ Ndio [*yes*]
- ✓ Sijiali [*don't care*]
- ✓ La [*no*]
- ✓ NR [*no response*]

Conditional: if yes or don't care

Nyumba yako iko tayari kulipia pesa kiasi gani kwa ajili ya marekebisho ya handpump? *How much would you be willing to contribute to have the handpump repaired? (Kshs)*___

Water Storage

Familia yako inahifadhi maji ya kunywa? *Does household store drinking water in the house?*

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ NR [*no response*]

Conditional: if yes

Unahifadhi kiasi cha maji yanayotosha matumizi ya siku ngapi wakati wa msimu wa kiangazi? *How many days' worth of water do you store at home in the dry season?*___

Conditional: if yes

Unahifadhi kiasi cha maji yanayotosha matumizi ya siku ngapi wakati wa msimu wa mvua? ***How many days' worth of water do you store at home in the wet season?___***

Water Resources Management

Ni nani ana jukumu la kutunza na kusimamia maji kwenye mito, visima na chemichemi? ***Who is responsible for managing water in rivers, wells and springs?***

Usimuelekeze mhusika. *Do NOT prompt*.

- ✓ Mzee wa kijiji [##]
- ✓ Kamati ya maji [*water committee*]
- ✓ Water Resources Management Authority (WRMA)
- ✓ Water Resources Users Association (WRUA)
- ✓ Serikali ya kaunti [*County government*]
- ✓ Chifu [*chief*]
- ✓ KWAWASCO
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other

Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. ***Specify if other.___***

Ni mashirika au tahasisi gani yananufaisha watumizi wa maji sehemu hii? (serikali, shirika la kibinafsi, shirika lisilo la kiserikali) ***Which institutions (government, private, NGO) benefit water users in this area?***

Usimuelekeze muhusika, Jaza zaidi ya majo. *Do NOT prompt. Tick ALL that apply*.

- ✓ Kamati ya chama cha watumizi wa maji [*Water Resources User Association*]
- ✓ Chama cha watumizi wa maji [*Water Supply Association*]
- ✓ Wizara ya maji ya Kaunti [*County Water Ministry*]
- ✓ Baraza la Kaunti [*County Council*]
- ✓ Kwale Handpump Services Limited
- ✓ KWAWASCO
- ✓ Shirika kuu la kiserikali la kudhibitisha usmbazaji wa maji [*central government agency with water supply mandate*]
- ✓ Shirika kuu la kiserikali lenye mamlaka ya Kumudu 'RasiliMaji' [*central government agency with rural development mandate*]
- ✓ Wizara ya maji, mazingira, na rasilimali [*Ministry of Water, Environment and Resources*]
- ✓ Shirika kuu la kiserikali la mazingira [*central governmental organization with environment mandate*]
- ✓ South Coast Development Agency
- ✓ Base Titanium Ltd
- ✓ KISCOL
- ✓ Team & Team International
- ✓ Rural Focus Limited
- ✓ World Wildlife Fund
- ✓ Nyenginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other

Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. ***Specify if other.___***

Je, unadhani mito/visima/chemichemi zimedumishwa vizuri na Serikali ya Kaunti iliyo chaguliwa kulingana na hoja zifuatazo? ***Do you think the rivers/wells are well cared for by the County Government according to the following arguments?***

	Negative change	No change	Positive change	DK
Ubora wa maji [*water quality*]				
Wingi wa maji [*water quantity*]				
Jamii ya vijiji kuhusika katika kumudu mito [*greater community participation*]				
Rasilimali kuongezeka na kupatikana kwa matumizi ya 'Chama cha watumizi wa maji' [*more resources for WRUA (Water Resources User Association*]				
Jamii za vijiji kujua Zaidi kuhusu kumudu mito [*more awareness raising for communities*]				
Nyinginezo [*other*]				

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. ***Specify if other.*___**

Je, unajua chama cha watumizi wa maji (WRUA) kinafanya nini? ***Do you know what the Association of Water Users (WRUA) does?***
To confirm, ask respondent to explain what they believe the local WRUA does.

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ NR [*no response*]

Conditional: if yes
Je, unajua mwanachama yeyote wa WRUA? ***Do you know any members of the local WRUA?***

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ NR [*no response*]

Conditional: if yes
Umewahi kuhudhuria mkutano wa WRUA? ***Have you ever attended a WRUA meeting?***

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ NR [*no response*]

Conditional: if yes
Umeridhika na utendakazi wa WRUA? ***Are you satisfied with the performance of the WRUA?***

- ✓ Nimeridhika sana [*very satisfied*]
- ✓ Nimeridhika [*satisfied*]
- ✓ Naona kawaida *[neither satisfied nor dissatisfied]*
- ✓ Sijaridhika [*dissatisfied*]
- ✓ Sijaridhika kabisa [*very dissatisfied*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Kwa maoni yako, ni nani mtumizi mkuu wa maji sehemu hii? *Who would you identify as the major water users in the area?* Usimuelekeze mhusika. *Do NOT prompt. Tick all that apply.*

- ✓ Base Titanium Ltd (Kampuni ya madini)
- ✓ KISCOL
- ✓ Utalii/mahoteli [*tourism/hotel*]
- ✓ Miji mikuu [*big cities*]
- ✓ Jamii za vijijini [*rural communities*]
- ✓ Mashule [*schools*]
- ✓ Kliniki/Hospitali [*clinic / hospital*]
- ✓ Misikiti / Makanisa [*mosques/churches*]
- ✓ Mazingira [*environment*]
- ✓ Nyenginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___

Una wasiwasi wowote kuhusu matumizi ya maji sehemu hii? *Do you have any major concerns about water use in the area?*

- ✓ Ndio [*yes*]
- ✓ La [*no*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if yes
Ni hoja/mada gani tatu kuu zinakutia wasiwasi kuhusu matumizi ya maji sehemu hii? *What three main topics about water do you worry about?*
Usimuelekeze mhusika. [*Do not prompt.*]
___*Concern 1 options:*

- o Kuchafuka wa maji
- o Upungufu wa maji/shina kukauka [*water shortage*]
- o Mafuriko [*floods*]
- o Watu kutolipa ada/karo [*people do not pay fees*]
- o Ufisadi
- o Hatari ya kuharibu mazingira
- o Matumizi haramu [*illegal use*]
- o Nyenginezo [*other*]
- o Sijui [*don't know*]
- o NR [*no response*]

___*Concern 2*
___*Concern 3*

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.*___

Conditional: if yes
Kati ya hizi, ni gani KUU zaidi? *Of these concerns, which is your greatest concern?*

- ✓ Kuchafuka wa maji

- ✓ Upungufu wa maji/shina kukauka [*water shortage*]
- ✓ Mafuriko [*floods*]
- ✓ Watu kutolipa ada/karo [*people do not pay fees*]
- ✓ Ufisadi
- ✓ Hatari ya kuharibu mazingira
- ✓ Matumizi haramu [*illegal use*]
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other*.___

Conditional: if yes
Ni nani anayechangia kwa hoja/mada hii inayokutia wasiwasi mkuu*? Who do you think is responsible for causing the problem about which you are most concerned?*
Usimeulekeze mhusika. *Do NOT prompt.*
- ✓ Watu binafsi [*individuals*]
- ✓ Jamii za vijiji [*village communities*]
- ✓ Shirika za kidini [*religious organizations*]
- ✓ Kampuni [*company*]
- ✓ Serikali [*government*]
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other*.___

Conditional: if village communities
Ni jamii gani unadhani zinahusika? *Which community do you think is responsible?*
- ✓ Jamii yetu [*our community*]
- ✓ Jamii jirani [*neighbouring community*]
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other*.___

Conditional: if company
Ni kampuni gani unadhani inahusika*? Which company do you think is responsible?*
- ✓ Base Titanium Ltd. (Kampuni ya madini)
- ✓ KISCOL
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.___*

Conditional: if government
Ni Serikali gani inahusika? *Which level of government do you think is responsible?*
- ✓ Serikali ya Kaunti
- ✓ Serikali kuu
- ✓ Nyinginezo [*other*]
- ✓ Sijui [*don't know*]
- ✓ NR [*no response*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.___*

About the Dwelling

Vifaa husika kwa ajili ya sakafu. *MAIN MATERIAL OF FLOOR (record observation)*
- ✓ Mchanga [*sandy*]
- ✓ Mavi ya ng'ombe [*cow patties*]
- ✓ Mbao [*wood*]
- ✓ Bamboo
- ✓ Mbao zilizopakwa rangi [*painted wooden*]
- ✓ Vinyl or asphalt strips
- ✓ Vigae
- ✓ Simiti
- ✓ Mpira
- ✓ Nyenginezo [*other*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.___*

Vifaa husika vya paa. *MAIN MATERIAL OF ROOF - Record observation*
- ✓ Makuti [*coconut*]
- ✓ Mabati
- ✓ Vikebe, Matope
- ✓ Mavi ya ng'ombe
- ✓ Asbestos
- ✓ Zege
- ✓ Vigae
- ✓ Nyenginezo [*other*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other.___*

Vifaa husika vya ukuta. *MAIN MATERIAL OF WALLS - Record observation*
- ✓ Mawe na udongo [*stone and clay*]
- ✓ Mawe na simiti [*stones and stems*]
- ✓ Matofali ya zege [*concrete bricks*]

- ✓ Mbao na udongo [*wood and clay*]
- ✓ Mabati
- ✓ Mbao za mtumba [*wooden boards*]
- ✓ Makuti [*coconut*]
- ✓ Simiti
- ✓ Vipande vya miti
- ✓ Matofali [*bricks*]
- ✓ Matofali ya udongo [*clay bricks*]
- ✓ Plaiwudi [*plywood*]
- ✓ Cardboard
- ✓ Fito
- ✓ Takataka [*waste*]
- ✓ Hakuna kuta [*no walls*]
- ✓ Nyenginezo [*other*]

Conditional: if other
Kama ni nyenginezo, tafadhali fafanua kwenye nafasi. *Specify if other*.___

Conditional: if stone and clay, stone and stems, concrete bricks, wood and clay, bricks, clay bricks
Are the walls rendered?
- ✓ *Rendered*
- ✓ *Unrendered*

Chukua picha ya nyumba | *take a picture of a house*
Only take photo if existing photo is inadequate or dwelling has changed since first photo was taken.

End.
Huu ni mwisho wa mahojiano, asante sana kwa kunipa muda wako, tabasamu, jibu maswali yoyote utakayoulizwa ni mhusika na uondoke ili kukamilisha maswali. Kazi nzuri! *This is the end of the interview, thank you very much for giving me your time, smile, … Good work!*

Onyesha jinsi mhusika alivyoelewa maswali? *HOW WELL WAS INTERVIEW UNDERSTOOD?*
- ✓ Ufahamu mzuri [*good understanding*]
- ✓ ufahamu wastani [*average understanding*]
- ✓ ufahamu mbaya [*bad understanding*]

Kwa maoni ya mwandishi, unadhani kwamba majibu uliyopewa na mhusika ni ya kweli na hakika? *In the opinion of the enumerator, do you think the majority of answers given by the respondent are true and correct?*
- ✓ Nakubali sana [*strongly agree*]
- ✓ Nakubali [*agree*]
- ✓ Tashwishi juu ya baadhi ya maswali - (ELEZEA kupitia njia ya sauti)

Je, mahojiano yalikuwa kwa lugha gani? *In what language was the interview?*
- ✓ Swahili
- ✓ Digo
- ✓ Duruma
- ✓ Kamba
- ✓ English
- ✓ Other

Conditional: if respondent over 18 is not available today (follow-up required)
Phone number of respondent or household member?___
Save as incomplete and record this with the Team Leader.

If you would like to add any other comments about the interview, please include them here.
Time end.

Appendix 7 – Logistic Regressions

Below are the commands and outputs from the bivariate and mixed effects logistic regression models conducted using Stata (StataCorp 2015).

Some redundant lines from the raw outputs have been removed for space/formatting purposes.

Bivariate logistic regressions

```
. logistic DiarrW2 Repairs if Include ==1 & Treatment ==1 [pweight = Fweight], vce(cluster
Zone)

Logistic regression                             Number of obs     =        840
                                                Wald chi2(1)      =       0.64
                                                Prob > chi2       =     0.4229
Log pseudolikelihood = -40.703598               Pseudo R2         =     0.0014

                                    (Std. Err. adjusted for 3 clusters in Zone)
------------------------------------------------------------------------------
     DiarrW2 | Odds Ratio   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
     Repairs |   .9542909   .0557133    -0.80   0.423     .8511106     1.06998
       _cons |   .1472846   .0169639   -16.63   0.000     .1175217    .1845853
------------------------------------------------------------------------------
```

```
. logistic DiarrW2 Repair24 if Include ==1 & Treatment ==1 [pweight = Fweight], vce(cluster
Zone)

Logistic regression                             Number of obs     =        840
                                                Wald chi2(1)      =      22.32
                                                Prob > chi2       =     0.0000
Log pseudolikelihood = -40.339348               Pseudo R2         =     0.0103

                                    (Std. Err. adjusted for 3 clusters in Zone)
------------------------------------------------------------------------------
     DiarrW2 | Odds Ratio   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
    Repair24 |   .3995959   .0775832    -4.72   0.000      .273122    .5846358
       _cons |    .143575   .0209788   -13.28   0.000      .107821    .1911853
------------------------------------------------------------------------------
```

```
. logistic DiarrW1 Repair24 if Include ==1 & Treatment ==1 & Same_HH ==1 [pweight = Fweight],
vce(cluster Zone)

Logistic regression                             Number of obs     =        751
                                                Wald chi2(1)      =       0.00
                                                Prob > chi2       =     0.9843
Log pseudolikelihood = -28.397876               Pseudo R2         =     0.0000

                                    (Std. Err. adjusted for 3 clusters in Zone)
------------------------------------------------------------------------------
     DiarrW1 | Odds Ratio   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
    Repair24 |   1.008262   .4228029     0.02   0.984     .4432331    2.293585
       _cons |   .0859878   .0125644   -16.79   0.000     .0645744    .1145021
------------------------------------------------------------------------------
```

Mixed effects logistic regression models

Model 1 (Socio-Economic factors)

```
. logistic DiarrW2 Repair24 Noincome Crops People_per_HH FemaleHead if Include ==1 & Treatment
==1 [pweight = Fweight], vce(cluster Zone)

Logistic regression                               Number of obs     =        840
Log pseudolikelihood = -39.501922                 Pseudo R2         =     0.0308

                                    (Std. Err. adjusted for 3 clusters in Zone)
--------------------------------------------------------------------------------
      DiarrW2 | Odds Ratio   Std. Err.       z    P>|z|      [95% Conf. Interval]
--------------+-----------------------------------------------------------------
     Repair24 |   .3746293    .085031     -4.33   0.000      .2401051    .5845238
     Noincome |   1.381582   .1486251      3.00   0.003      1.118942    1.705868
        Crops |   .8041661   .1281263     -1.37   0.171      .5884714     1.09892
People_per_HH |    1.11572   .0161235      7.58   0.000      1.084562    1.147774
   FemaleHead |   .6464086   .1280852     -2.20   0.028      .4383716    .9531732
        _cons |   .0921987   .0174924    -12.56   0.000      .0635669    .1337269
--------------------------------------------------------------------------------
```

Model 2 (...plus Dwelling factors)

```
. logistic DiarrW2 Repair24 Noincome Crops People_per_HH FemaleHead ImpRoof ImpWalls
rooms_sleeping ImpFloor if Include ==1 & Treatment ==1 [pweight = Fweight], vce(cluster Zone)

Logistic regression                               Number of obs     =        840
Log pseudolikelihood = -38.170203                 Pseudo R2         =     0.0635

                                    (Std. Err. adjusted for 3 clusters in Zone)
---------------------------------------------------------------------------------
       DiarrW2 | Odds Ratio   Std. Err.       z    P>|z|      [95% Conf. Interval]
---------------+-----------------------------------------------------------------
      Repair24 |   .3683819   .0764414     -4.81   0.000      .2452838    .5532579
      Noincome |   1.360852   .1371963      3.06   0.002      1.116852    1.658158
         Crops |   .7124017   .1362415     -1.77   0.076        .48971    1.036361
 People_per_HH |   1.132862   .0338593      4.17   0.000      1.068405    1.201207
    FemaleHead |   .5911308   .1434315     -2.17   0.030      .3674081     .951083
       ImpRoof |   .7913805   .1957071     -0.95   0.344      .4873989     1.28495
      ImpWalls |    .838779   .1257411     -1.17   0.241      .6252363    1.125255
rooms_sleeping |   1.011956   .0141219      0.85   0.394      .9846526    1.040016
      ImpFloor |   .4129455   .1546394     -2.36   0.018      .1982146    .8602998
         _cons |   .1358822   .0360451     -7.52   0.000      .0807917    .2285379
---------------------------------------------------------------------------------
```

Model 3 (... plus WASH factors)

```
. logistic DiarrW2 Repair24 Noincome Crops People_per_HH FemaleHead ImpRoof ImpWalls
rooms_sleeping ImpFloor ImpToilet soap JerryPP WaterTreated if Include ==1 & Treatment ==1
[pweight = Fweight], vce(cluster Zone)

Logistic regression                               Number of obs     =        840
Log pseudolikelihood = -37.771413                 Pseudo R2         =     0.0733

                                     (Std. Err. adjusted for 3 clusters in Zone)
--------------------------------------------------------------------------------
       DiarrW2 | Odds Ratio   Std. Err.      z    P>|z|     [95% Conf. Interval]
---------------+----------------------------------------------------------------
      Repair24 |   .3392025   .0600494    -6.11   0.000     .2397562    .4798972
      Noincome |   1.362114   .1244287     3.38   0.001     1.138823    1.629185
         Crops |   .7261028   .1227198    -1.89   0.058      .521357    1.011256
 People_per_HH |   1.105108   .0475743     2.32   0.020      1.01569    1.202399
    FemaleHead |   .5587386   .1276776    -2.55   0.011     .3570264    .8744139
       ImpRoof |   .9101057   .2393009    -0.36   0.720     .5435995    1.523718
      ImpWalls |   .8022425     .13941    -1.27   0.205     .5706736    1.127778
rooms_sleeping |   1.039641   .0032308    12.51   0.000     1.033328    1.045993
      ImpFloor |   .4599784   .1846144    -1.93   0.053     .2094613    1.010116
     ImpToilet |    .757116   .1983162    -1.06   0.288     .4531081    1.265095
          soap |   .6368487   .1546957    -1.86   0.063     .3956148     1.02518
       JerryPP |    .855117   .0898955    -1.49   0.137     .6958916    1.050774
  WaterTreated |   .9662483   .4676195    -0.07   0.943     .3742369    2.494772
         _cons |   .2743291   .1419671    -2.50   0.012     .0994877    .7564396
--------------------------------------------------------------------------------
```

Model 4 (inc. floor/toilet interaction term)

```
. logistic DiarrW2 Repair24 Noincome Crops People_per_HH FemaleHead ImpRoof ImpWalls
rooms_sleeping ImpFloor##ImpToilet soap JerryPP WaterTreated if Include ==1 & Treatment ==1
[pweight = Fweight], vce(cluster Zone)

Logistic regression                               Number of obs     =        840
Log pseudolikelihood = -37.632892                 Pseudo R2         =     0.0767

                                         (Std. Err. adjusted for 3 clusters in Zone)
------------------------------------------------------------------------------------
           DiarrW2 | Odds Ratio   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------------+----------------------------------------------------------------
          Repair24 |   .3295196   .0615823    -5.94   0.000     .2284569    .4752893
          Noincome |   1.352917   .1136365     3.60   0.000      1.14756    1.595022
             Crops |    .728249   .1176087    -1.96   0.050     .5306583    .9994126
     People_per_HH |    1.10463   .0473879     2.32   0.020     1.015549    1.201525
        FemaleHead |   .5612875   .1303414    -2.49   0.013     .3560578    .8848104
           ImpRoof |    .908654   .2356826    -0.37   0.712     .5465347    1.510704
          ImpWalls |   .7788585   .1317562    -1.48   0.140     .5590677    1.085058
    rooms_sleeping |   1.043461   .0026766    16.59   0.000     1.038228     1.04872
        1.ImpFloor |   .8372244    .397042    -0.37   0.708        .3305    2.120862
       1.ImpToilet |   .8778465   .1987861    -0.58   0.565     .5632046    1.368268
                   |
ImpFloor#ImpToilet |   .4182666   .1147245    -3.18   0.001     .2443323    .7160206
                   |
              soap |   .6422139   .1547338    -1.84   0.066      .400491    1.029832
           JerryPP |   .8477611   .0889468    -1.57   0.115     .6901853    1.041313
      WaterTreated |   .9757672   .4689053    -0.05   0.959     .3804529      2.5026
             _cons |    .260439   .1262555    -2.78   0.006     .1007073    .6735212
------------------------------------------------------------------------------------
```

Model 5 (inc. female head/soap interaction term)

```
. logistic DiarrW2 Repair24 Noincome Crops People_per_HH FemaleHead##soap ImpRoof ImpWalls
rooms_sleeping ImpFloor ImpToilet JerryPP WaterTreated if Include ==1 & Treatment ==1 [pweight
= Fweight], vce(cluster Zone)

Logistic regression                              Number of obs     =        840
Log pseudolikelihood = -37.647967                Pseudo R2         =     0.0763

                                      (Std. Err. adjusted for 3 clusters in Zone)
--------------------------------------------------------------------------------
       DiarrW2 | Odds Ratio   Std. Err.      z    P>|z|     [95% Conf. Interval]
---------------+----------------------------------------------------------------
      Repair24 |   .3620716   .0564078    -6.52   0.000      .266799    .4913656
      Noincome |   1.356521   .1149091     3.60   0.000     1.149006    1.601514
         Crops |   .7304556   .1244131    -1.84   0.065     .5231364    1.019936
 People_per_HH |   1.100567   .0456929     2.31   0.021     1.014557    1.193868
  1.FemaleHead |   .8568088   .1655393    -0.80   0.424     .5867161    1.251238
        1.soap |   .8238075    .227454    -0.70   0.483     .4795217    1.415283
               |
FemaleHead#soap |  .5020662   .1628747    -2.12   0.034     .2658421    .9481963
               |
       ImpRoof |   .8930174   .2527211    -0.40   0.689     .5128289    1.555061
      ImpWalls |   .8165702   .1535952    -1.08   0.281     .5647864      1.1806
rooms_sleeping |   1.038169    .003131    12.42   0.000      1.03205    1.044323
      ImpFloor |   .4575441   .1939939    -1.84   0.065     .1993115    1.050349
     ImpToilet |   .7795682    .219133    -0.89   0.376     .4493506    1.352455
       JerryPP |   .8542552   .0837474    -1.61   0.108     .7049197    1.035227
  WaterTreated |   .9731777   .4606097    -0.06   0.954     .3848703    2.460764
         _cons |   .2284008   .1251646    -2.69   0.007     .0780254    .6685895
--------------------------------------------------------------------------------
```

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