# Data, Decisions, and Drinking Water Safety

## An interdisciplinary analysis of the complex adaptive response to monitoring in rural Kenya

*A thesis submitted for the degree of Doctor of Philosophy*

Saskia Josephine Nowicki

School of Geography and the Environment
St Catherine's College
University of Oxford
Trinity Term 2021

# Abstract

For decades, international and national development efforts have endeavoured to improve rural drinking-water safety in Sub-Saharan Africa by focusing on infrastructure provision, devolving responsibility for operations and maintenance to the community level. Rural areas continue, however, to have severely limited access to both safe water and to water quality information for operational decision-making. This thesis argues that sustained provision of safe water is an emergent function of a complex adaptive system, and that information-response feedback mechanisms must be positioned to support decision-making at the local level if this function is to be realised. Through empirical research situated in rural Kenya, it explores how a systems-based understanding of the links between data and decision-making can elucidate leverage points for establishing an information feedback that improves water safety and thereby mitigates health risk.

Guided by a structurationist systems framing and questions that align with normative, descriptive, and prescriptive modes of decision analysis, the research described in this thesis intersects with both natural and social science disciplines. Pragmatically, it draws on a diverse range of literature and methods. The empirical work is structured in three parts:

**Data uncertainty has implications for normative conceptions of risk management.** Research demonstrating growth of *E. coli* in the environment challenges interpretations of microbial water quality based on *E. coli* test results. Characterising strains using whole genome sequencing offered insight into the utility of *E. coli* as an indicator of microbial contamination in rural water supplies. The difficulty of interpreting health risk from grab samples, especially at the household level, is highlighted. Monitoring can

be an effective feedback mechanism at supply level, informing more reliable understandings of hazard dynamics, by accounting for sanitary conditions and temporal variability in indicator concentrations.

**Data-informed understandings of risk interact with other drivers of decision-making.** An integrated fear appeal framing, which responds to key weaknesses in the behaviour change literature, is applied a) to assess user perceptions of drinking-water safety and b) to evaluate an information intervention through which monitoring data were shared with local lay water managers. The findings emphasise that data should be reported with sensitivity to self-efficacy limitations and the threatscapes that decision-makers navigate. Specific, contextualised, and repeated messaging can reinforce engagement with water safety precautions at supply level – especially if lay water manager self-efficacy is supported through infrastructure design, training, and ongoing resourcing.

**Institutional structure enables and constrains monitoring activity and data flows.** Dilemma analysis is used to synthesise views from stakeholders in bureaucratic, market-based, and community domains. The findings challenge the common practice of conceptualising water quality versus quantity as dichotomous objectives. They advance the literature on pluralistic water governance by explicitly considering quality risks, which have received less coverage than other service dimensions. Progress on securing safe water is inhibited by unclear divisions of responsibility and risks associated with not being able to respond to data, particularly at the local level.

This thesis concludes that, although the health of water users is the ultimate concern, monitoring activity should focus at supply level – with research and policy developments needed to establish technical and institutional structures that support the efficacy of lay management. A structurationist systems framing was instrumental in guiding the research to evidence a range of stock and flow, feedback, and structural leverage points for implementing effective monitoring. This framing, which links international policy and local practice by recognising the interaction of agency and structure in stakeholder responses to hazards, could be applied broadly to problems of health risk management. It is useful for research that aims to contribute prescriptive decision analysis to bridge the gap between normative models and decision-making in practice.

# Acknowledgements

I am immeasurably grateful for the extensive and varied support that I received in working towards this thesis. I have many people to wholeheartedly thank.

To everyone who participated in the interviews and surveys that inform this thesis, and to those who gave access to their water for sampling, thank you. Your contribution underpins all the value of this work.

To my supervisors, Katrina Charles and David Bradley, it has been a privilege to learn from you. Thank you for your guidance and support in the conception and completion of this thesis, and through all the messy iteration in between. To Katrina, thank you for helping me to access resources and navigate collaborations, and for encouraging me to challenge my assumptions and think critically and expansively. Your passion for research, breadth of knowledge, and the genuine care and pragmatism that you bring to your work, are inspiring. And David, your teaching ignited my interest to work on water and health, and throughout the journey your perspective and guidance have been invaluable. Thank you for sharing your exceptional insight and for encouraging me to engage with the enduring complexity of challenges in this space.

I am grateful also to my interim assessors and examiners, Danny Dorling, Susan Elliott, Rob Hope, and Jamie Lorimer. And to the anonymous peer-reviewers of my papers. Thank you for taking time to engage in-depth with my work and for your thoughtful, constructive feedback.

To everyone who worked with me in Kenya, I am grateful for your guidance and collaboration. Cliff Nyaga and Jacob Katuva, thank you for your insight and feedback and for your pivotal and ongoing support on logistics. To the FundiFix team in Kyuso, especially Annastacia Kalee, Peter Musili, and Peter Mugo, thank you for supporting the water safety monitoring work and for assisting and welcoming me in Kyuso. Annah Kavata, Grace Muisyo, and Lucy Wambua, thank you for the excellent work that you did on the water diaries and beyond. And special thanks to my stellar research assistants, Mary Musenya Sammy and Martin Mbogo Mwaniki, for your hours of diligent work, your patience with my many questions, and your support when I was in Kyuso – and through all the messages and calls when I have been away. The time I spent with you in the field was a highlight of these past few years.

I am also immensely grateful for the support and input I received from the County Government of Kitui, both in Kitui town and in Mwingi North sub-county. And to Pauline Kiamba, thank you for supporting my engagement with stakeholders in Kitui and for your insightful feedback in discussing my research. Further, to Rural Focus Ltd., especially Tom Traexler, Agnes Masila, and Boniface Mutua, thank you for enabling the water quality monitoring programme, for your effort and patience on contracting and logistics, and for the many hours spent getting me and so many supplies safely between Nairobi and Kyuso.

To the team at the KEMRI hub in Kilifi, Martin Rono, James Nokes, Charles Agoti, Everlyn Kamau, and especially Zaydah deLaurent, George Githinji, and Etienne de Villiers, thank you for supporting me during my time in Kilifi and for all of your input to my *E. coli* sequencing endeavour. To the Aquaya Institute, especially Clara Macleod and Kara Stuart, thank you for your input in preparing, conducting, and discussing our interviews in Nairobi. And from the University of Nairobi, Dan Olago and Florence Tanui, thank you for sharing insight into the geology of Kitui County and for discussing and exchanging groundwater quality data with me. Further, to Salome Bukachi, Dalmas Ochieng Omia, Mercy Mbithe Musyoka, and Faith Wambua, thank you for sharing insight and transcripts from your exploring inequalities project, and for providing feedback on my understanding and representation of household water management.

I am also grateful to have benefited from many forms of support and enriching exchange in Oxford. To Joanne Keenan, Geis Simmons, Alice Chautard, Alex Black, and Ruth Saxton, thank you for all of the contracting, budgeting, administrative, and communications support. To my fellow water and health enthusiasts, Nameerah Khan, Li Ann Ong, May Sule, Nassim El Achi, and Patrick Thomson thank you for your energy and passion, and for helping me to expand and clarify my thinking. Thank you also to Ellen Dyer, Alex Fischer, Nancy Gladstone, Catherine Grasham, Marina Korzenevica-Proud, and especially Johanna Koehler and Sonia Hoque, for engaging with me in exploring crossovers between our work. I have learned so much from you all. I am also grateful to the SOGE Geolabs and IT teams, especially Mona Edwards, Hong Zhang, Jack Longman, and David Ford, and to the online R community, for enabling the analysis that went into this thesis. And I thank the Oxford Water Network, particularly Kathryn Pharr and Louise Slater, for providing exposure to a broad set of perspectives and some key ideas that have informed my work. To Matilda Becker, Tess Doeffinger, Safa Fanaian, Sabrina Li, Shona Loong, Caitlyn McGeer, Amelie Paszkowski, Rebecca Peters, and Jade Ward. Thank you for being with me on this academic journey, and for helping me to be self-reflective, critical, and resilient.

Thank you to my family and friends who encouraged and helped to balance me through the ups and downs of the last few years. For the meals we shared, socially distanced and otherwise, for the laughs, celebrations, and consolation, I am grateful. To Heather Bond and Elias Post, this last strange year would have been much heavier without you – thanks for the house plants, the book chats, the bonfires, and the best pizza. And Murray McGregor and Anouchka, Tom, and Janek Nowicki – you mean the world to me. Thank you for your constant love, for all the ways you have helped me grow, and for supporting me in my work even when it takes me away from you.

Finally, I recognise with gratitude that this research was funded through the REACH programme by UK Aid from the UK Foreign, Commonwealth and Development Office (FCDO). Further, I was supported in undertaking this work by the Commonwealth Scholarship Commission in the UK. And I am grateful for additional support for travel and equipment acquisition from St Catherine's College and the School of Geography and the Environment.

# Format and Publications

This thesis is structured in book format to allow better integration of the empirical work. The following peer-reviewed papers containing content from the empirical chapters as well as the introduction, framing, and methodology chapters have been published or submitted. Publication co-authorship statements for each paper are provided in Appendix A.

- Nowicki, S., Koehler, J. and Charles, K. J. (2020). "Including water quality monitoring in rural water service provision: why safe water requires challenging the quantity versus quality dichotomy". In: *npj Clean Water* 3.14.
- Nowicki, S. et al. (2021). "The utility of *Escherichia coli* as a contamination indicator for rural drinking water: Evidence from whole genome sequencing". In: *PLoS ONE* 16.1.
- Nowicki et al. (under review). "Fear, efficacy, and environmental health risk reporting: complex responses to water quality test results in low-income communities".

Ideas in the introduction, framing, methodology, and discussion of this thesis are also reflected in and influenced by publications that I led or co-authored since the beginning of my DPhil studies including:

- Nowicki, S. et al. (2019). "Tryptophan-like fluorescence as a measure of microbial contamination risk in groundwater". In: *Science of the Total Environment* 646, pp.782–791.
- Charles, K. J., Nowicki, S. and Bartram, J. K. (2020). "A framework for monitoring the safety of water services: from measurements to security". In: *npj Clean Water* 3.36.
- Charles, K. J. et al. (2020). "Water and Health: A Dynamic, Enduring Challenge". In: Dadson, S. J. et al. (eds) *Water Science, Policy, and Management: A Global Challenge*. John Wiley and Sons Ltd., pp. 97–116.

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# Acronyms

AMR ........ antimicrobial resistance
CA ........ correspondence analysis
CBM ........ community-based management
CDOM ........ coloured dissolved organic matter
DHIS ........ District Health Information System
DNA ........ deoxyribonucleic acid
EED ........ environmental enteric dysfunction
EHL ........ environmental health literacy
FIB ........ faecal indicator bacteria
FWSP ........ formal water service provider
HHWT ........ household water treatment
IC ........ ion chromatography
ICP-MS ........ inductively coupled plasma mass spectrometry
IMF ........ International Monetary Fund
KEMRI ........ Kenya Medical Research Institute
KIHBS ........ Kenya Integrated Household Budget Survey
KIMWASCO ........ Kiambere-Mwingi Water and Sanitation Company
KITWASCO ........ Kitui Water and Sanitation Company
KNBS ........ Kenya National Bureau of Statistics

LWM ........ lay water manager
MDG ........ Millennium Development Goal
MLST ........ multi-locus sequence type
MPN ........ most probable number
NGO ........ non-governmental organisation
NPM ........ New Public Management
PCS ........ post-construction support
PoC ........ point of collection
PoU ........ point of use
RWSP ........ rural water service provider
SDG ........ Sustainable Development Goal
SI ........ sanitary inspection
SOGE ........ School of Geography and the Environment
TC ........ total coliform
TLF ........ tryptophan-like fluorescence
TTC ........ thermotolerant coliform
WASH ........ water, sanitation, and hygiene
WASREB ........ Water Services Regulatory Board
WGS ........ whole genome sequencing
WRA ........ Water Resources Authority
WSP ........ Water Safety Planning

*The international community is well aware that it has the obligation,*
*both moral and legal,*
*to ensure access to safe drinking water and to sanitation*
*for all, without discrimination.*

— Léo Heller, Statement by the Special Rapporteur on the human right to safe water, 2020

*Hierarchies evolve from the lowest level up*
*- from the pieces to the whole,*
*from cell to organ to organism,*
*from individual to team,*
*from actual production to management of production...*
*The original purpose of a hierarchy is always*
*to help its originating subsystems do their jobs better.*

— Donella Meadows, Thinking in Systems, 2008

# 1 Introduction

In rural Sub-Saharan Africa, safely managed drinking-water is the exception not the norm. Despite decades of national and international efforts to improve water supplies, less than a fifth of the population have access to water that is free from contamination (JMP, 2020). A human right to water has existed in different forms and spaces for centuries (Larson et al., 2020), and the United Nations adopted Resolution 64/292 more than ten years ago, marking international recognition that clean drinking-water is essential to the realisation of all human rights. Nevertheless, best estimates indicate that one in four people globally do not have sustained access to safe water, progress is not on track for universal access to basic water services by 2030, and strong inequalities persist along rural-urban and income divides (JMP, 2017, 2019). The challenge is particularly acute in Sub-Saharan Africa, where much of the population are dispersed in rural communities, relying on water they manage themselves with limited means (JMP, 2017; Sutton & Butterworth, 2021).

Formally established rights and targets serve as foils against inequitable policy, as beacons signalling priority, and as tools to advance accountability (Larson, 2013), but implementation – making universal access to safe water a reality – is a wicked challenge (Neely, 2019a; Rittel & Webber, 1973). Wicked in that it entails many dynamic elements, large costs, incomplete information, and myriad interconnections. Framing water safety as an intended outcome of a complex adaptive system, this thesis is founded on an understanding that progress towards the global-level ambition of safe water for all depends on improving local-level water management practices. Recognising that hierarchical systems evolve from the bottom-up and are interconnected by information flows (Meadows, 2008), it focuses on the potential for monitoring data to influence local-level decision-making towards securing safe water supplies in rural Sub-Saharan Africa,

There are eight chapters. In this introductory chapter, I establish the rationale for the research (1.1), explain my interdisciplinary systems-based approach (1.2), set out my main research questions (1.3), outline the structure of this document (1.4), and explain how my work relied on multiple collaborations and is linked to a wider programme of research (1.5). Chapter 2 reviews the foundational literature that informs the conceptual frameworks and analytical approaches used to address each research question. Chapter 3 covers methodology. It explains the study location context, provides method details, and discusses research ethics and positionality. The next four chapters, spanning Chapters 4 to 7, present my empirical results. The findings converge in Chapter 8, with discussion of cross-cutting themes and key findings, a summary of contributions, and reflections on limitations and future research directions.

## 1.1 Research Rationale

Water-related disease is an important public health challenge in rural Sub-Saharan Africa. As of 2017, it was estimated that only 19% of the rural population had access to water free from microbial and chemical contamination (JMP, 2020). Although measuring health impacts is complicated by interactions of many variables, diarrhoeal disease is a key health outcome of microbial infections. For Sub-Saharan Africa, the Global Burden of Disease (GBD) study[1] estimated that 8.2% (6.6 – 9.8%) of disability adjusted life years (DALYs[2]) were due to diarrhoeal disease in 2019, and 86% (71 – 94%) of those DALYs are attributed to unsafe water sources (IHME, 2020)[3]. Other estimates attribute a lower proportion of diarrhoeal disease to unsafe water but draw attention to chronic and more varied health impacts (Prüss-Ustün et al., 2019). Prolonged consumption of water containing microbial and chemical hazards is linked to environmental enteropathy[4] (Korpe & Petri, 2012) and chronic conditions including cognitive impairment, metabolic dysfunction, and cancers (Prüss-Ustün et al., 2011; Villanueva et al., 2014).

Measures to address the health problems arising from consumption of unsafe water in rural Sub-Saharan Africa remain insufficient despite decades of effort to improve water supply. The drinking-water Millennium Development Goal (MDG) was achieved by 2010. In the preceding decade, more than two

[1]The Global Burden of Disease study, led by the Institute for Health Metrics and Evaluation (IHME), is a comprehensive observational epidemiological study that reports deaths and disability-adjusted life years (DALYs) for all major categories of communicable and non-communicable disease and injuries. See https://www.thelancet.com/gbd

[2]The disability-adjusted life year, DALY, is a common health indicator that reflects loss of life as well as the severity and duration of a health problem.

[3]For comparison, diarrhoeal disease was estimated to account for 3.2% (2.6 – 4.0%) of global DALYs in 2019, with 80% (65 – 90%) attribution to unsafe water sources.

[4]Environmental enteropathy is a sub-clinical condition that is associated with long-term exposure to faecal pathogens. It involves harmful positive feedbacks between structural changes in the intestines, reductions in immune and gut function, malabsorption of nutrients and stunting and other health complications.

billion people had gained access to 'improved' sources of drinking water[1], leaving only 780 million with supplies that were considered unsafe (JMP, 2012). Although this achievement was celebrated, progress reports immediately acknowledged that Sub-Saharan Africa was lagging behind, with only 61% coverage of improved sources (JMP, 2012). Additionally, the focus on increasing access to improved infrastructure had allowed the underlying concern of water quality to become secondary (Bartram et al., 2014). In 2012, research into the quality of water supplied by improved sources emphasised that they remain susceptible to microbial and chemical contamination. Many rely on direct access to groundwater, which accounts for a third of global water supply, with regional estimates of contamination ranging from 10 to 41% of boreholes and 78 to 97% of shallower, less secure water points like dug wells (Bain et al., 2014). When water quality was explicitly considered, estimates of the number of people at risk from unsafe drinking water rose from 780 million to around two billion (Bain et al., 2014; Bain, Gundry, et al., 2012; Onda et al., 2012; Wolf et al., 2013).

When the Sustainable Development Goals (SDGs) superseded the MDGs, the importance of measuring water quality was more widely recognised. SDG target 6.1[2] seeks to secure safe, affordable water for all people. Progress towards it is being measured by a newly defined category of water services, 'safely managed', which goes beyond considerations of infrastructure design to include compliance with microbial and priority chemical standards[3]. The challenge is immense: baseline data for the SDGs estimated that a quarter of the global pop-

[1]Improved sources are those that protect against human and animal faecal contamination by nature of their design and construction, they include piped schemes, boreholes, protected wells, protected springs, rainwater catchment systems, and packaged or vended water. The drinking-water MDG was measured by counting improved sources, using them as an infrastructure-based proxy for water safety.

[2]SDG target 6.1 is: "By 2030, achieve universal and equitable access to safe and affordable drinking water for all." The indicator for monitoring progress towards this target (indicator 6.1.1) is the proportion of the population using safely managed drinking water services.

[3]As defined by the World Health Organisation and UNICEF Joint Monitoring Programme, safely managed drinking water comes from an improved water source that is located on premises, available when needed, and free from faecal and priority chemical contamination. See the full drinking water service ladder here: https://washdata.org/monitoring/drinking-water

ulation lacks drinking water that is free from faecal and priority chemical (arsenic and fluoride) contamination (JMP, 2017) and highlighted a stark divide between urban and rural access to safely managed sources (JMP, 2019). In Sub-Saharan Africa, as of 2017, 54% of urban dwellers were using water that tested clear for microbial or chemical contamination, compared to only 19% of rural dwellers (JMP, 2020). Additionally, water quality monitoring in rural Sub-Saharan Africa is often minimal or absent (Marks & Schwab, 2015; Peletz et al., 2016), so the inequality is two-fold: rural areas have less access both to safe water and to water quality information.

Globally, there are four main scenarios under which drinking-water quality information is currently generated: operational monitoring by formal water providers; compliance monitoring by regulators; target tracking by governments and international agencies[1]; and research (JMP, 2021; Peletz et al., 2016; Rouse, 2013; WHO, 2017a). Each serves an important purpose, but these scenarios are not well-aligned with the institutional context of water supply in rural Sub-Saharan Africa (Chapter 2). An assessment of operational and compliance monitoring across 72 institutions from ten Sub-Saharan African countries found that more than 95% of water quality testing was done for operational monitoring of urban piped networks, with minimal compliance monitoring and negligible testing of rural and non-piped sources (Peletz et al., 2016). Consequently, the main source of information on the quality of rural water supplies is from household survey campaigns that are designed to inform national and international estimates of living conditions but have no operational value[2].

[1]Progress towards SDG 6.1 is being tracked by the WHO and UNICEF Joint Monitoring Programme using nationally representative household surveys, population and housing censuses, national regulatory data, and water service provider data. See https://washdata.org/monitoring/methods/data-sources

[2]These include UNICEF Multiple Indicator Cluster Surveys, Demographic and Health Surveys, and Living Standards Measurement Studies. The water quality test results from household survey campaigns are not returned to survey respondents or local water managers. Even if results were reported locally, they are designed to support large-scale estimates and the sampling is too infrequent to usefully inform near-term management decision-making.

In Sub-Saharan Africa, daily rural water management responsibilities usually rest with non-specialists who have neither professional qualifications nor expert scientific knowledge (Section 2.3). These lay water managers (LWMs) rarely have the training or access to equipment that is needed for water quality assessment and control. Additionally, the rural water sector is characterised by multiple source use such that the safety of drinking water is partly a function of user choice (M. Elliott et al., 2019; Hoque & Hope, 2018; Kelly et al., 2018). Thus, LWMs and users have a role in securing safe drinking water – which they generally fulfil without the technical means to reliably assess water quality.

Monitoring is a fundamental component of drinking-water management, one that is necessary for sustaining water safety and assessing the reality of provision against expectations established by standards (WHO, 2017a), and it is necessary for making and measuring progress towards SDG 6.1. Considering the human right to water and the "leave no one behind" rhetoric of the sustainable development agenda, the lack of local access to water quality information in rural Sub-Saharan Africa is increasingly contrary to international and national norms and standards (Moriarty et al., 2013). This thesis advances a framing of rural water safety management that links international policy to local practice. As explained in the next section, this framing recognizes the interaction of agency and structure in stakeholder decision-making around water quality hazards.

The main aim of this thesis is to explore how rural drinking-water safety can be improved through monitoring activity that prioritizes water users and LWMs as information recipients. In this endeavour, beneficence is recognised as a key ethical principal (NCPHS, 1979) that is relevant to the sharing of environmental health risk information with people who may not be positioned to protect themselves. The link between knowledge and empowerment is a key theme throughout this thesis. It is reflected in the research design and is an important focus of the results (Chapters 6 and 7) and concluding discussion (Chapter 8).

## 1.2 Interdisciplinary Systems-based Approach

The research described in this thesis approaches drinking-water safety not as a fixed outcome nor an end-point of a linear process, but rather as the intended function of a complex adaptive system. A systems-thinking perspective informs both the questions that direct the research and the choice of methods used to address them. In this introductory section, I summarise this perspective with reference to its philosophical and epistemological aspects and key concepts (1.2.1) and then I explain how I apply it to the problem of securing rural drinking-water safety to guide my research (1.2.2).

### 1.2.1 Philosophy, Epistemology, and Systems Thinking

In working with a systems-based perspective, I take a pragmatic[1] stance, employing a structurationist mode of explanation, and using a range of quantitative and qualitative methods from different disciplines. As explained in Section 1.1, in seeking to understand how monitoring can lead to safer rural water supplies, I am interested in the actions of water users and lay water managers (LWMs). In framing their actions as part of a complex adaptive system, this thesis aligns with a key axiom of pragmatism as a research philosophy: recognising that "actions cannot be separated from the situations and contexts in which they occur" (Morgan, 2014, p26). This approach – based in systems thinking and drawing on multiple disciplines – has precedent in health geography (Gatrell & Elliott, 2015) and in water-related health research specifically (S. J. Elliott, 2011).

[1] As a research paradigm, pragmatism has philosophical foundations that discourage positioning realism and constructivism as incompatible approaches to research (Maxcy, 2003; Morgan, 2014). Pragmatic research recognises reality that "exists apart from human experience" but maintains that we only encounter reality through our individual and shared experiences and, therefore, our knowledge of the world is indeed socially constructed (Morgan, 2014, p39). Pragmatism encourages researchers to be flexible in choosing methods that suit their research problem and it is well-suited to mixed-methods research that aims to produce insights for addressing problems in practice (Creswell & Clark, 2011).

Systems thinking has developed in many different fields of inquiry through efforts to understand complexity and effect change in structures that form through the interconnected behaviour of heterogeneous components (Bertalanffy, 1968; Ison, 2008). In contrast to a reductionist approach, systems thinking upholds the importance of context and emergent dynamics for understanding behaviour and function in societal, ecological, cognitive, technological, or other types of systems. In his seminal work on general systems theory, Bertalanffy, 1968, traced a long history of systems concepts in scholarship and noted their pervasiveness in different fields of science. He wrote that despite the ever-increasing specialization of siloed scientific disciplines, "we encounter a surprising phenomenon. Independently of each other, similar problems and conceptions have evolved in widely different fields" (p29). Not all systems are complex and adaptive, but there are common concepts through which all complex adaptive systems can be framed. Although it may not be necessary for readers who are already familiar with systems terminology, I summarise the key concepts in the subsequent paragraphs to explain what characterises these types of systems.

Stocks, flows, variables, and feedbacks are the basic components of complex adaptive systems (Meadows, 2008; Neely, 2019b). **Stocks** are reservoirs of something that can be either material - like water and bacteria - or abstract - like knowledge and emotion. **Flows** refer to movement in or out of stocks that change the level of the stock over time. Inflows and outflows are decoupled by stock characteristics and, therefore, often have disjointed behaviour. **Variables** determine the rates of flows and the constraints on stocks; they are the limiting factors that exist in all systems. And **feedbacks** occur when system outputs become inputs, creating cause-effect loops through signals and information flows or other mechanisms, like rules. Loops can strengthen the initial direction of change (positive/reinforcing feedback) or they can oppose it (negative/balancing feedback). The behaviours of a system through the interaction of these component parts over time are often referred to as system **dynamics**.

Complex adaptive systems are also conceptualised through higher-order concepts including, most importantly: complexity, adaptation, and emergence (Meadows, 2008; Neely, 2019b). **Complexity** describes the state of a system which has dynamics that are observably structured but limited in their specific predictability. Complex systems are neither completely ordered (stable and predictable) nor completely disordered (chaotic and unpredictable). **Adaptation** in systems is characterised by the interdependence of system components. The closer the connections between system components, the greater the capacity for reciprocal evolution. Finally, **emergence** refers to structures or dynamics in a system that are not predicted by the known behaviour of individual components. This is the idea, often traced to Aristotle, that "the whole is something besides the parts"[1]. It is a relative concept in that it is strongly influenced by the observer's knowledge of a system at a point in time. This concept is neatly illustrated with a Sufi teaching story as quoted in (Meadows, 2008, p.12): "You think that because you understand 'one' that you must therefore understand 'two' because one and one make two. But you forget that you must also understand 'and'."

Thus, a complex adaptive system is a set of interconnected stocks, flows, variables, and feedbacks the function of which emerges from the dynamic interplay between agency and structure. Systems vary in their complexity and their components are defined by the spatiotemporal scale at which they are observed. They are subject to path dependency in that adaptation is sensitive to initial conditions (Capra, 2007). Inquiry into systems is generally an endeavour to understand their component parts and interconnections, their structure and dynamics, to model them conceptually and to understand them at different scales in order to predict or modify their behaviour and ultimate functions (R. Arnold & Wade, 2015). In epistemological terms, the systems-based approach used in this thesis is consis-

[1]As translated by W. D. Ross and J. A. Smith in 1908, Aristotle wrote in Metaphysics: "In the case of all things which have several parts and in which the totality is not, as it were, a mere heap, but the whole is something beside the parts, there is a cause [of their unity]" in his discussion of the difficulty of bounding definitions.

tent with a structurationist[1] mode of explanation (Giddens, 1984), which upholds that structure enables and constrains agency and is also transformed by it. This interplay[2] progresses "through space and time connections" (Aitken & Valentine, 2015, p18), which are integral to understandings of complex adaptive systems.

A structurationist view of systems differs from a functionalist view in that it does not rely on purely physical or biological analogies; it recognises social systems as being hierarchically and laterally organised such that the totality of any system is understood to be "constituted by the intersection of multiple [other] systems" (Giddens, 1984, p164). In research, therefore, the boundaries drawn around systems necessarily but artificially interrupt a continuum and are informed by the purpose of the research.

### 1.2.2 Framing Rural Drinking-water Safety

The subject of this thesis, drinking-water safety in rural Sub-Saharan Africa, is here conceptualised as an intended function of a system that has dynamics (and sub-systems) at different scales, from local to global (Figure 1.1). My objective, to investigate how monitoring can lead to safer rural drinking-water, can be considered in systems terms. At the level of rapid local interaction, water quality hazards and knowledge of them are key stocks. The research task is to understand how monitoring can act as a feedback mechanism that leads to reduced human exposure to water quality hazards. Furthermore, recognising that slower-changing higher-level structures enable and constrain, but are also transformed

[1] Structuration theory has influenced thought in philosophy, sociology, psychology, and in multiple sub-fields of human geography (Dyck & Kearns, 2015; Giddens, 1983). In health geography specifically, structurationism is a prominent mode of explanation (Gatrell & Elliott, 2015), manifesting either explicitly in research frameworks or as an "internalised" perspective widely held by contemporary health geographers (Dyck & Kearns, 2015, p87).

[2] Structuration theory conceptualises structure as dynamic and comprised of rules and resources that constitute both physical environments and the social relations within them. It uses the term 'human agency' to express the idea that individuals knowledgeably perpetuate events by routinely and reflexively exercising choice (Dyck & Kearns, 2015; Giddens, 1984)

by, local-level activities, the aim is to understand how higher-level structures influence and are potentially transformed by monitoring.

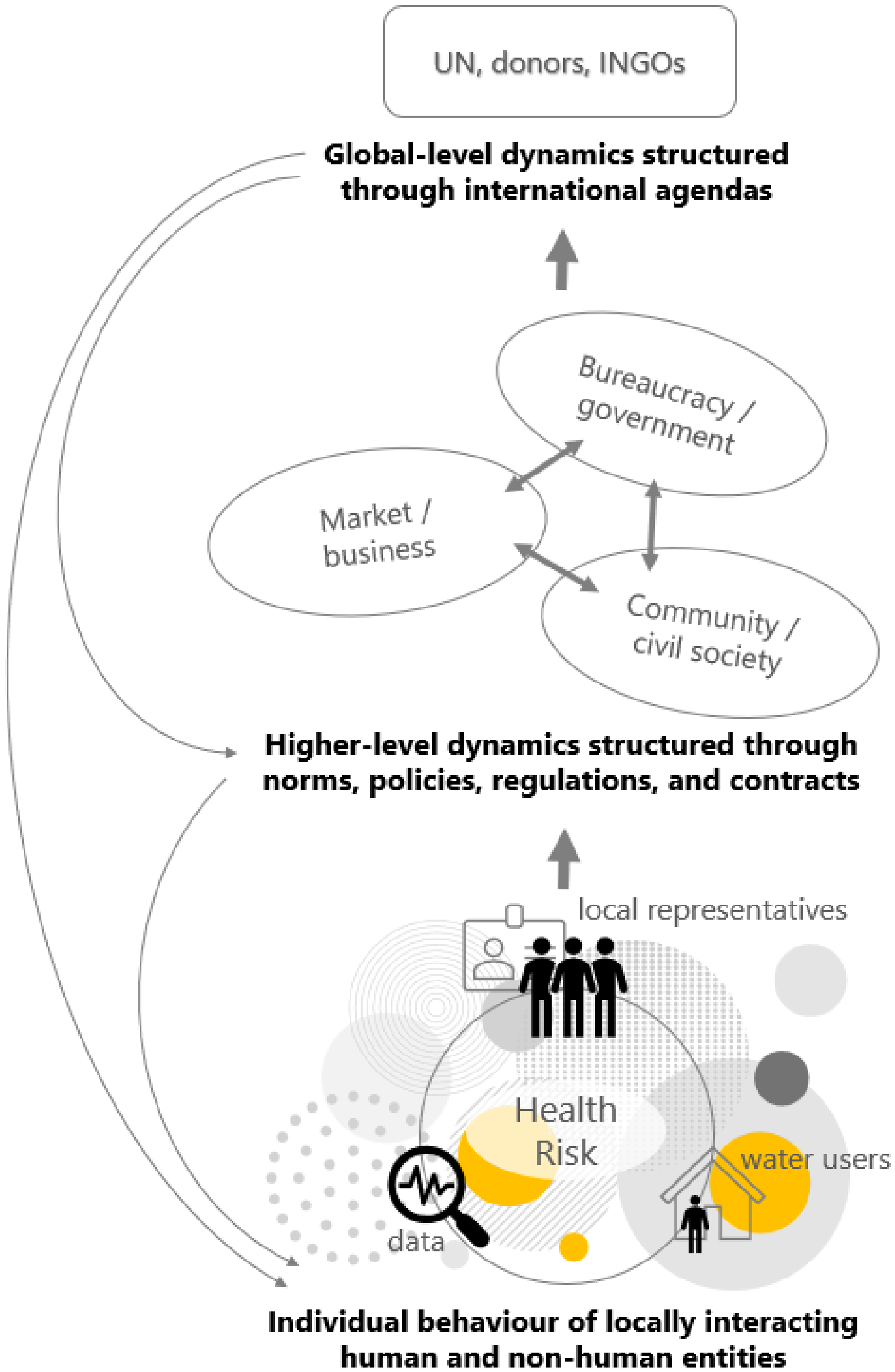



**Figure 1.1:** Organisational hierarchy of drinking-water supply based on the general hierarchy of complex adaptive systems presented by Parrott, 2002. *Higher-level dynamics reflect pluralistic institutional arrangements for drinking-water governance as reviewed in Section 2.3. Local-level dynamics highlight interactions between monitoring data, water users, and local representatives (in community, market, and government domains). Lay water managers (LWMs) are conceptualised as local community representatives.*

As formally recognised by the Human Right to Water and SDG 6.1, universal consumption of safe drinking water is an intended global-level function of water management at the local scale. The qualifier “intended” is important. A key principle of systems thinking is that the actual functions of a system are derived from their component structures and dynamics and, therefore, may differ from stated or intended functions (Dyck & Kearns, 2015; Meadows, 2008). Efforts to mobilise a complex system towards an intended function contend with forces of signification (conveyance of meaning), legitimation (norms and values), and domination (distribution of power), and must recognise that actions often have restricted or unintended consequences (Giddens, 1984). Although securing safe water supply may appear, superficially, as a straightforward technical problem, a structurationist systems-based framing reveals deep complexity and makes crucial governance dimensions evident.

In this thesis, I evaluate how water quality monitoring data may influence the emergence of safer drinking-water supplies by considering both the agency of local water managers and the higher-level structures that limit and enable their actions. I focus first on monitoring data itself, evaluating its utility and key limitations for understanding water quality. I then focus on decision-making in response to data-based understandings of water quality, considering both cognitive and contextual determinants of choice. Accordingly, the set of research questions specified in the next section intersects domains of both natural and social science research and, pragmatically (Bryman, 2006; Teddlie & Tashakkori, 2003), informs a varied selection of methods. The resulting interdisciplinary investigation draws on literature, research instruments, and analytical approaches from diverse fields including micro- and molecular biology, aqueous chemistry, health geography, public governance, and action research.

## 1.3 Research Questions

This thesis explores how monitoring activity that recognises water users and lay water managers (LWMs) as key decision-makers can influence improvements in rural drinking-water safety (Section 1.1). In doing so, it advances a framing of rural water safety management that links international policy to local practice and directs research to account for the interaction of agency and structure in stakeholder decision-making around water quality hazards. Thus framed, the main question that this thesis addresses is:

How can systemic links between data and decision-making be elucidated to identify leverage points for implementing monitoring as an effective feedback to mitigate health risk?

In this introductory section, I explain how my approach to this main question is guided by three sub-questions. Development of these questions was influenced by the systems-based problem framing depicted previously in Figure 1.1. The first two questions focus on local-level decision-making dynamics and the third broadens the scope to more explicitly consider the influence of higher levels of organisation. Given the main focus on decision-making, each question aligns with a different approach for decision analysis. This alignment reflects an overlap between my problem framing and decision theory.

Decision theory has a history of use in research that aims to understand choice under conditions of uncertainty. Normative analysis forms the oldest branch and is concerned with what decisions ought to be made. It can be traced as far back as $17^{th}$ century mathematics and the advent of probability theory. The normative approach relies on logic and probabilistic risk assessment that aims to quantify and account for uncertainty (Peterson, 2017). It is not concerned with deviation between ideal and real behaviour, it is focused on determining what is ideal behaviour. Insofar as monitoring programmes are designed to determine ideal management decision-making, they are intended to inform decision-makers of what 'should' be done. 'Should', however, is a highly contextual verb, heavily laden with trade-offs and value judgements. And for reasons that will become clearer in Section 2.1, information on water quality and associated health risks is often characterised by high levels of uncertainty, which further complicates the determination of ideal behaviour. Thus, my first guiding research question engages a crucial step before 'should' by directing focus to uncertainty in interpretations of monitoring data. It asks:

1. How do uncertainties in understandings of hazard flows based on monitoring data influence the potential effectiveness of monitoring as a feedback mechanism?

This question is concerned with hazards (contaminants) that change in time, as opposed to hazard presence as a static factor, and the focus on hazard rather than risk is intentional. Measurement data from monitoring activities are multiple-steps removed from health risk, for which the significance of hazards is determined by exposure and susceptibility factors (as discussed, for example, by McFadyen & Robertson, 2015, in their introduction to water-related hazards). Exposure and susceptibility are key considerations in my work responding to guiding questions two and three, but the first is more narrowly concerned with how well data represent hazards.

In contrast to the normative alignment of question one, my second question is better aligned with descriptive decision theory, which focuses on how and why people make choices. This is a younger realm of decision theory that began with examining bounded rationality (Simon, 1947) and systematic deviations between actual and expected behaviour (Allais, 1953; Ellsberg, 1961). It has developed prominently through an economic lens (e.g., Thaler, 2015; Tversky & Kahneman, 1974) and also, in health behaviour research, through focus on psychosocial determinants of decision making (Section 2.2.3). As with the normative view, descriptive analysis considers uncertainty to be an important element in decision-making. Going beyond the limitations of determining ideal or optimal decisions, however, the descriptive view in health research extends the analysis of uncertainty by considering how it influences human behaviour, recognising that "virtually all diseases and conditions that can be attributed to environmental causes are highly contested" (Kroll-Smith et al., 2000, p9). Thus, my second guiding research question invites a descriptive analytical approach to decision-making, it asks:

2. How do understandings of data interact with other drivers of decision-making to influence the actions of individuals?

This question inquires how individuals in rural communities engage with monitoring as a feedback mechanism. As elaborated in Section 2.2, it directs focus to cognitive and affective processing of information but maintains the importance of local context for understanding behaviour (acknowledging the duality of agency and structure). From a systems perspective, communities are emergent organisational units comprised of people and the varied components of their environments interacting locally (Figure 1.1). Recognising both the heterogeneity of communities and the necessity of conceptual models that simplify reality, I have disaggregate water management within communities into two key levels to focus on supply-level management and household-level management:

- Supply-level management by LWMs: Whether in a community-based management, facility administration, or self-supply scenario, the caretakers of water supplies in Sub-Saharan Africa rarely have the training or access to equipment that is needed for water quality assessment (as elaborated in my literature review, Section 2.3).

- Household-level management by water users: In the context of decentralised and multiple water point use, choices are made on a daily basis about where to source water and how to transport, treat, store, and use it (e.g. Hoque & Hope, 2018). In making these decisions a person takes on a management role that distinguishes them from users who are reliant on centralised systems in more urban and / or higher-income settings.

Moving beyond local context, my third and final guiding research question engages with system dynamics at higher organisation levels. A key motivation for this research is built around the role of lay water management and user choices in determining drinking-water safety in rural Sub-Saharan Africa (Section 1.1). In asking how rural water management can be supported by monitoring, this thesis seeks to understand the strengths and limitations of water quality hazard assessment capabilities, to evaluate responses to monitoring over time, and then to generate insight that looks to "bridge the gap between the normative ideal [what 'should' be done to secure safe water] and the descriptive reality [what is done]" (Fischhoff & Kadvany, 2011, p6). This is a move into the domain of prescriptive decision analysis, which directs one to be "mindful of the findings of descriptive decision studies" when applying normative ideas "to guide real decision making" (French, 1995, p242).

Prescriptive analysis takes varying forms but is generally conceptualised as an effort to reconcile the differences between 'rational' models of behaviour – developed through normative analysis – and actual behaviour – understood through descriptive analysis (Fischhoff & Kadvany, 2011; French et al., 2009; J. Smith & Von Winterfeldt, 2004); it rarely engages with institutional structure (da Silva et al., 2020). However, while normative and descriptive models are judged on their correctness and empirical validity, respectively, prescriptive analysis is judged by its pragmatism (Keeney, 1992). A structurationist systems perspective clarifies, therefore, that prescriptive methodologies should account for structure (system rules and resources) beyond the immediate determinants of individual behaviour if they are to be useful. Thus, in endeavouring to respond to my main research question, I have designed this thesis to focus on data uncertainty (question one), data-user behaviour (question two), and structural determinants of stakeholder decision-making – specifically, higher-level institutional dynamics. My third guiding research question asks:

3. What are the key institutional enablers of and constraints on monitoring activity and data use?

In systems terms, it queries both how higher-level structures influence monitoring activity and data use and, simultaneously, how data use may influence change in those structures. As elaborated in the literature review and methodology chapters that follow, this question requires my research to be embedded within a real institutional context – with stakeholder groups at national, sub-national, and local levels included as important units of analysis.

## 1.4 Thesis Structure

Here I explain how this thesis is structured to respond to my research questions. I ordered the sub-questions to focus first on the details of monitoring data, then on local level decision-making, and finally on higher-level dynamics (Section 1.3). This does not mean that my research in response to each question builds on itself in that sequence. Rather, the three parts are nested and mutually informing. My work is informed by a systems-based framing and writing about systems requires engaging with non-linear phenomena in a necessarily linear format. The overall structure of this thesis maps onto the order of my questions (Figure 1.2), but this is not intended to imply a chronological order in the sequencing of the research, all three parts were developed concurrently.

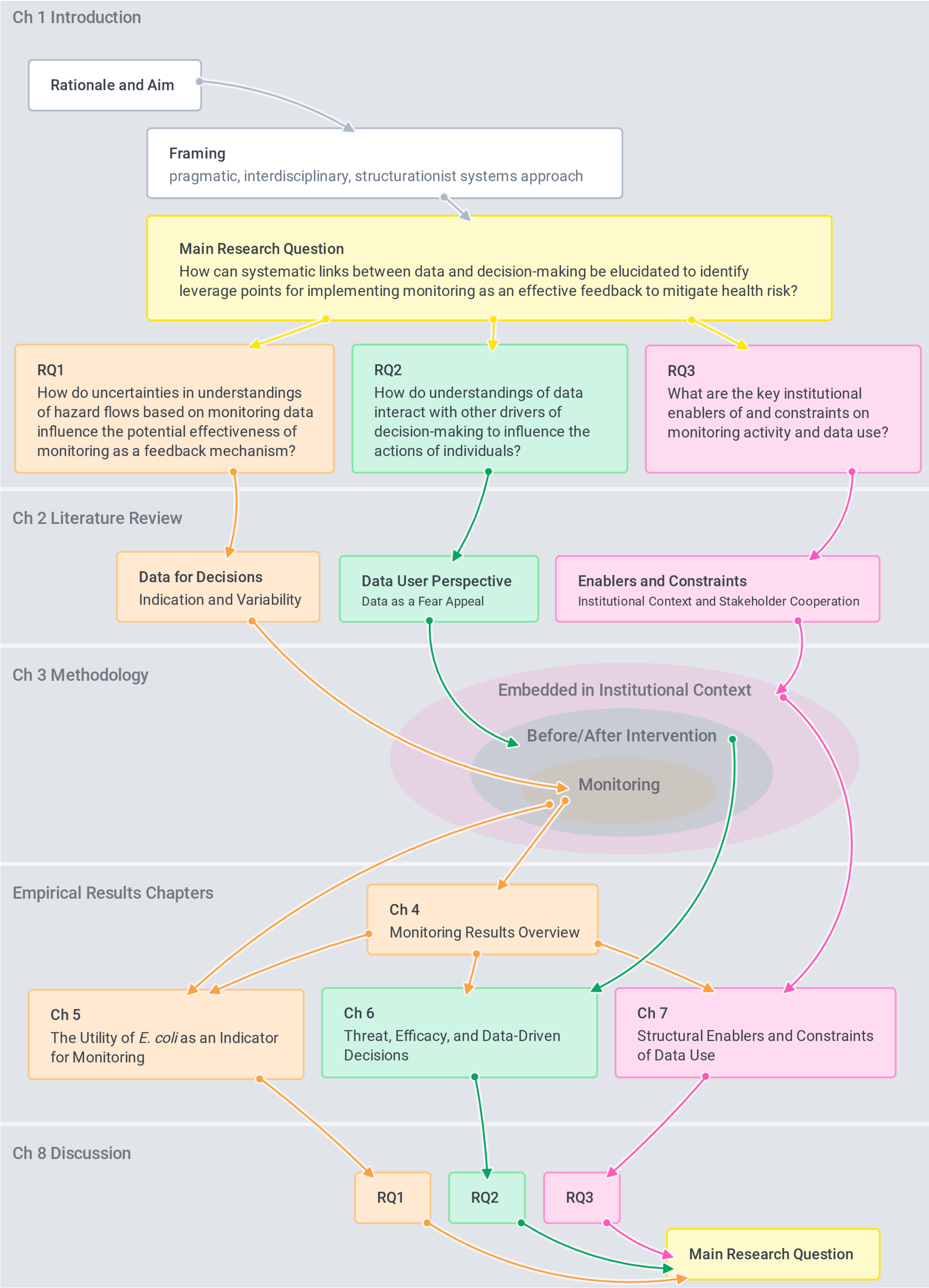



**Figure 1.2:** Thesis structure overview. *The aim of this thesis is pursued through literature review and empirical research that address three guiding sub-questions, the responses to which were developed concurrently.*

Following this introduction, Chapter 2 reviews key literatures to form a foundation for the empirical work that responds to each of my guiding research questions. It identifies knowledge gaps and analytical approaches, drawing on a wide range of literature. The literature review is presented in three parts:

- In Section 2.1, I focus on the process of generating data for decision-making through monitoring activities. I draw on literature to define what is meant by 'safe' water, explaining why this thesis focuses on microbial water quality with chemical and organoleptic aspects included for context. I explore water quality data utility, identifying indicator-pathogen relationships and temporal variability as key areas of uncertainty. Then I discuss pathways for research that may help advance the utility of water safety monitoring data.

- In Section 2.2, I focus on the data user perspective. I review literature that explores the advantages and disadvantages of reporting water quality data to decision-makers in rural communities who may utilise the information for daily management purposes. Drawing on the literature, I establish that the data-user's perspective is critical to the effectiveness of monitoring as a feedback mechanism for improving water safety; I identify key weaknesses in the evidence base regarding behaviour change in response to sharing of water quality data; and I explain my choice and development of a conceptual framing to guide empirical work that responds to those weaknesses.

- In Section 2.3, I focus on structural enablers and constraints of data use. The review presented in this section supports a response to my third research subquestion by outlining the institutional context within which my empirical work is situated. However, it is not a comprehensive review of water governance models. I present a brief historical overview of key governance policy that has informed contemporary institutional arrangements for rural water service provision in Sub-Saharan Africa, in particular I focus on the community-based management model and discuss tripartite configurations of pluralistic water governance. I then discuss water quality governance in particular – highlighting a key research gap – and identify an analytical approach to guide my empirical work in responding to that gap.

Building from the literature review, Chapter 3 explains the research methodology. This includes descriptions of the empirical research setting in northern Kitui County, Kenya – including geographic, demographic, and institutional context (Section 3.1). This chapter also provides details of the methods used in the empirical research, which includes a water quality monitoring programme (Section 3.2), an *E. coli* whole genome sequencing study (Section 3.3), a baseline assessment of water user decision-making (Section 3.4), an evaluation of an information intervention with LWMs (Section 3.5), and a dilemma analysis engaging stakeholders from bureaucratic, market, and community domains (Section 3.6). The chapter concludes with discussion of the ethics (Section 3.7) and positionality (Section 3.8) of the research.

The empirical research method details are presented in one main methodology chapter (rather than separately in the subsequent chapters that discuss the research findings) to avoid excessive repetition – because there is overlap in the design and methods used for each piece of work. Subsequently, the first results-focused chapter presents an overview of the water quality monitoring programme results (Chapter 4), which provides context for the chapters that follow. The findings of my genome-level study of *E. coli* isolates are then presented in Chapter 5. They provide insight into the utility of *E. coli* as a microbial contamination indicator. In Chapter 6, I discuss the baseline assessment and information intervention findings, with data sharing conceptualised as a form of fear appeal. Chapter 7 then explores the potential for monitoring information to induce action within the wider institutional context of the rural water sector.

To conclude the thesis, Chapter 8 discusses the cross-cutting themes from the preceding chapters, highlights key findings, and responds to the main research question by outlining a prescriptive set of potential leverage points for influencing system change. It also summarises the key contributions and limitations of the research and points to directions for further research.

## 1.5 Research Collaboration

The research presented in this thesis was designed to contribute insight towards the ongoing challenge of securing access to safe drinking water in rural Sub-Saharan Africa. In this endeavour it engages, and is intended to be useful to, diverse stakeholders including academics, policy-makers, service providers in the rural water space, and water users themselves, albeit indirectly. Consequently, collaboration[1] has been important in my research journey. I have led the design, development, execution, analysis, and presentation of the work in this thesis, with the support of key collaborators.

The funding and network of connections that have enabled this thesis were made possible by the REACH Programme (2015-2024). REACH is a research consortium[2] led by the University of Oxford with partner institutions in Kenya, Bangladesh, and Ethiopia. It is funded by UK Aid through the Foreign and Commonwealth Development Office (FCDO), formerly the Department for International Development (DFID). It aims to generate evidence; foster science, practitioner and enterprise partnerships; and build capacity to improve water security for people living in poverty. REACH research is guided by the conviction that policy and practice, including institutional and infrastructure investments, require better guiding evidence to unlock opportunities and influence improved water security outcomes. The programme activities largely center around 'water security observatories' in the three focal countries, including one in northern Kitui County, Kenya, where the empirical research for this thesis was based.

Through REACH, and with the particular help of my supervisor, Katrina

[1]Recognising that there are many degrees and forms of collaboration, I note that my work is interdisciplinary but not transdisciplinary. The requirement of demonstrating academic leadership in a DPhil degree is not readily compatible with fully collaborative or action research based approaches, which aim to flatten hierarchies in research partnerships to enable better co-development of research aims and to align with ideas of cognitive justice (de Sousa Santos, 2014; People's Knowledge Editorial Collective, 2016).
[2]https://reachwater.org.uk/

Charles, and the research manager for the Kitui Observatory, Cliff Nyaga, I was able to develop key collaborations with people from FundiFix[1]; the Kenya Medical Research Institute (KEMRI) Wellcome Trust Research Programme[2]; and the University of Nairobi; and to access pivotal connections within Rural Focus[3], the County Government of Kitui[4], the Kenyan Water Services Regulatory Board (WASREB)[5], and the Aquaya Institute[6]. Details of these collaborations and connections, and how they informed the research for this thesis, are elaborated in Chapter 3. As a result of these collaborations, the core academic papers produced from this thesis recognise co-authorship. As detailed in the co-authorship agreement forms in Appendix A, I led the preparation and writing of these papers but they were enriched by input from contributors based at the KEMRI Kilifi hub, FundiFix, the University of Nairobi, and the University of Oxford.

Additionally, dissemination of research findings through blogs, memorandums, policy-facing reports, and spoken presentations is important for the practical aims of this research. My plans for sharing results with stakeholders were substantially derailed by the COVID-19 pandemic. In particular, stakeholder meetings organised around a REACH conference in Kenya in March and April 2020 were cancelled, I have not returned to Kenya since 2019, and stakeholder priorities have necessarily shifted to focus on immediate concerns related to COVID-19 and its widespread consequences. Despite the difficulties of this period, however, through REACH and the collaborations it has facilitated, I have had valuable opportunities to contribute to blogs, memorandums, and reports, and have shared results with academics and wider audiences through teaching, presentations, and conference events. These activities are briefly discussed in Section 8.2.1 and are listed in Appendix B.

[1]https://fundifix.co.ke/
[2]https://kemri-wellcome.org/about-us/
[3]https://www.ruralfocus.com/
[4]https://www.kitui.go.ke/
[5]https://wasreb.go.ke/
[6]https://aquaya.org/

*neither does any thing preserve Water from corrupting,*
*and acquiring the most mischievous Qualities,*
*so well as a brisk and rapid Motion,*
*which is so essentially necessary to this End,*
*as to be constantly enumerated amongst the distinguishing Characters*
*of a wholesome Water.*
— Clifton Wintringham, A Treatise of Endemic Diseases, 1718

*It was found that users rarely were willing to sacrifice health for convenience.*
*They widely misjudged factors affecting health,*
*but they gave them heavy weight as perceived.*
— White, Bradley & White, Drawers of Water, 1972

# 2

# Literature Review

This chapter reviews the key literatures that form a foundation for the empirical research that follows. Expanding on the research rationale introduced in Section 1.1, the review identifies knowledge gaps and methodological approaches that correspond with my guiding questions (Section 1.3). As established, an interdisciplinary systems-based approach suits the aim of this thesis (Section 1.2). Accordingly, the literature reviewed in this chapter spans a wide range of disciplines. The obvious trade-off of this diverse scope is that less space and attention is allocated to any one topic, none of which can be explored in their totality. The systems continuum is necessarily simplified and focus is directed to key concepts and knowledge gaps. Recognising this trade-off, I begin by reflecting on an example that emphasises the value of an interdisciplinary systems-based approach to water and health research.

The role of the Broad Street water pump in spreading cholera during the 1854 outbreak in London is one of the oldest and most famous discoveries in health geography. The innovative early epidemiological work that led John Snow to his theory of cholera as waterborne is now widely applauded, but the near-term impacts of his findings were less widespread than might be expected. Snow shared his information with the local parish and said that "the handle of the pump was removed on the following day" because of the evidence that he had provided them (Snow, 1855, p40). But beyond this local-level response, change evolved more slowly. Understanding water management as a complex adaptive system, it's interesting to note that it took longer for Snow's theory to be widely accepted than it did for "the most advanced and elaborate sewage system in the entire world", Bazalgette's sewer system, to be implemented in London (Johnson, 2006, p208).

Recognition that 'wholesome' water is linked to health predated Snow's work (e.g. Wintringham, 1718, p.87), enough so that prior to 1850 a water filtration system had been installed for London's Chelsea residents and extensive water-works had been undertaken in Scotland and British industrial towns to combat shortages of clean water (Soloman, 2010). Higher-level structures, particularly pertaining to the role of government, were the key enablers and constraints for action to improve water safety management in London in the $19^{th}$ century. Before Bazalgette's sewers, London was experiencing a sanitary crisis that manifested largely through social inequalities. For example, commentary in a medical journal from that period opined that a "real panic" in response to the first cholera outbreak in England was avoided when it was quickly evident that most victims were "the poorest of the poor" (Inglis, 1971, p272). Then the infamous 'Great Stink' that overwhelmed London in 1858 brought the issue into parliament, literally (Collinson, 2019). The stench coupled with changing ideas about the role of government[1] created the conditions for improving water-related health outcomes.


*John Snow's discovery commemorated outside his namesake pub in Soho, London.*

The story of cholera in $19^{th}$ century London illustrates how knowledge of the link between water quality and disease is a necessary but not sufficient driver of water safety improvements (hence the design of this thesis to account for the perspective of decision-makers and the structures they operate within). Thus, exploring how rural drinking-water safety can be improved through monitoring is served by engagement with a wide range of literature. This chapter is structured in three parts, corresponding to my three guiding research questions (Section 1.3). First, I focus on the process of generating data for decision-making (Section 2.1),

[1]As industry developed in England, an increasingly prominent administrative class began to influence debates about the role of government away from aristocratic ideals towards more socially conscious ideals of civic pride (Plumb, 1963).

with particular attention to: defining 'safe' water; exploring water quality data utility; and identifying pathways for research to inform better monitoring design and data interpretation. Second, I focus on the data user perspective (Section 2.2), with particular attention to knowledge gaps regarding the influence of data on decision-making. This section also identifies a conceptual framing to guide research in responding to those gaps. Finally, I focus on structural enablers and constraints of data use (Section 2.3). This section includes a brief review of relevant governance policy, discusses water quality governance in particular, and identifies an analytical approach to advance research in this space. Finally, Section 2.4 concludes with a summary of the literature review.

## 2.1 Generating Data for Decision-Making

My first guiding research question asks: How do uncertainties in understandings of hazard flows based on monitoring data influence the potential effectiveness of monitoring as a feedback mechanism? Investigating how accurately hazard flows can be monitored through rural water safety assessment methods begins with defining the hazards of interest (Section 2.1.1), reviewing the strengths and limitations of the methods and data used to assess them (Section 2.1.2), and identifying avenues for research that may generate insight for improving data utility (Section 2.1.3).

### 2.1.1 Defining 'Safe' Water

To appreciate the totality of drinking-water health risk and the user and lay water manager (LWM) perspective of water safety, it is important to understand water quality as a compound property. This understanding gives rise to notions of water as 'wholesome,' as have appeared in written record since before the germ theory of disease or John Snow's work on cholera (for example Wintringham, 1718, p87). But as understandings of water quality advanced, it became increasingly useful to divide the compound property into measurable parts that can be separately engaged and discussed. Interestingly, as aspects of water quality have increasingly been measured and assessed against standards, the use of 'wholesome water' in written English-language texts has increasingly been replaced with the more defensive phrasing of 'safe water' (Figure 2.1).

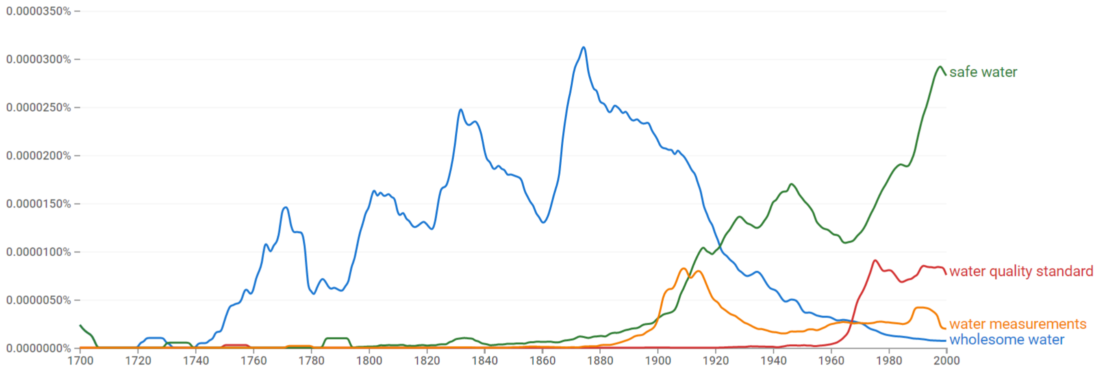



**Figure 2.1:** Use of "safe water", "wholesome water", "water measurements" and "water quality standard" in English language books between 1700 and 2000 (Google Books, 2020). *The y-axis shows the percentage of bigrams or trigrams in the Google Books database that are the search terms of interest.*

The reductionist approach that focuses on aspects of water quality individually has obvious advantages for manageability and for in-depth study of specific hazards; accordingly, the majority of published water quality research focuses on one or a few hazards. From a systems perspective, however, the totality of hazards matters – particularly for exploring stakeholder perceptions and use of water quality information.

In this thesis, I consider different aspects of water quality in three broad categories – microbial, chemical, and organoleptic. Although my investigation of data utility necessarily focuses on specific parameters[1] as explained in Section 2.1.2,

[1]Parameter is used here in the sense of a measureable factor that helps the observer characterise or understand some aspect of the behaviour of a larger system. This differs from the common use of the word in modelling applications, where parameters are specified boundaries of a process or activity.

the overall design of my research appreciates the decision-making implications of interactions and trade-offs between different aspects of quality. Thus, although much of this thesis focuses on microbial contamination of water, chemical and organoleptic quality are also included in the research scope. Microbial quality is prioritised, firstly, because faecal pathogens are recognised to be the most significant cause of drinking-water quality related health problems globally (Bartram & Baum, 2015; JMP, 2017; WHO, 2017a). And secondly, because there are key uncertainties inherent in the methods used to assess microbial water safety, as elaborated in the subsequent section (2.1.2).

Faecal pathogens are linked to acute health outcomes, which are the main driver of drinking-water safety management efforts historically and currently (Charles, Nowicki, Thomson, et al., 2020; G. F. White et al., 1972; WHO, 2017a). The acute nature of infectious disease garners substantial attention, but prioritising microbial water quality is further supported by recognising the chronic health problems that arise from long-term exposure to infectious agents. In particular, environmental enteric dysfunction (EED), chronic gut inflammation from repeated exposure to pathogens, is linked to malabsorption of nutrients and a cycle of malnutrition that increases susceptibility to further infection and can lead to stunted development especially in young children (Korpe & Petri, 2012). Stunting has lifelong and inter-generational consequences (Prendergast & Humphrey, 2014). It increases mortality and morbidity, being associated with reduced cognitive development and increased risk of adult obesity and associated comorbidities like type 2 diabetes and cardiovascular disease (Guerrant et al., 2013).

Chemical water quality is also associated with chronic health problems that develop through prolonged periods of exposure. In contrast to microbial contamination, however, chemical aspects are associated with considerably different causes and management options. In rural areas with lower population densities, minimal industrial activity, and low use of agrochemicals, the main chemical contaminants of concern derive from natural geogenic sources or water supply infrastructure (e.g. pipes and solder). Key health issues related to these contaminants, as presented in the international drinking-water guidance (WHO, 2017a) and discussed by Charles, Nowicki, Thomson, et al., 2020, are summarised below:

- **Visible physical damage to skin, teeth, or bones,** is linked most prominently to arsenic and fluoride, both of which are readily absorbed in the gastrointestinal tract and cause chronic health conditions (arsenicosis and dental and skeletal fluorosis) that have visible and potentially debilitating effects. High intake of selenium is also associated with visible symptoms including skin discolouration, dental decay, and hair or nail loss (as well as gastrointestinal disturbance and changes to peripheral nerves) (WHO, 2017a).

- **Hypertension**, which is linked to cardiovascular and renal disease and preeclampsia, is strongly associated with dietary sodium intake. Significant intake through drinking water is assumed to be preempted by taste-based acceptability limits, but this assumption may not hold for water-insecure populations in coastal and dryland areas and an evidence base is in development as researchers respond to this knowledge gap (e.g. Scheelbeek et al., 2017). Studies have also reported links between hypertension and arsenic, cadmium, mercury, and lead (Martins Jr et al., 2018; USEPA, 2013).

- **Cancer** is linked to arsenic, radon, and industrial or pharmaceutical chemicals (endocrine disruptors) (WHO, 2017a). Arsenic is the prominent geogenic concern: cancers of the skin, lungs, bladder and kidneys have been causally related to elevated arsenic in drinking-water. Cancer may also be causally related to intake of uranium (due to its chemical not radiological properties) and fluoride (bone cancer), but there is insufficient evidence for a substantial evaluation of their carcinogenicity in humans.

- **Cognitive impairment** is prominently linked to lead exposure (USEPA, 2013), and there is growing evidence of links to long-term arsenic and manganese exposure as well, with children most severely impacted (e.g. Bryant et al., 2011; Khan et al., 2011; G. A. Wasserman et al., 2004).

- **Psychosocial distress** resulting from the experience and consequences of the health problems above is also an important area of health research. Studies have linked psychosocial consequences to multiple dimensions of drinking-water insecurity including microbial aspects linked to sanitary conditions (Bisung & Elliott, 2016) and chemical aspects, like arsenic exposure (Brinkel et al., 2009).

There is strong evidence of the health significance of exposure to certain chemicals, like arsenic and fluoride, through drinking-water (WHO, 2017a). Evidence is less well-established, however, for other potential hazards where organoleptic factors are assumed to preempt hazardous intake levels (e.g. sodium); concentrations in drinking-water are assumed to be low (e.g. molybdenum); opportunities to study long-term health impacts of intake in human populations have been scarce (e.g. uranium); and research is complicated by complex contextual factors like host susceptibility (e.g. opportunistic pathogens), intake from multiple sources besides water (e.g. selenium), dietary and other modifiers of absorption from water (e.g. aluminium), and interaction effects between multiple hazards (WHO, 2017a).

Manganese provides an interesting example for discussion because water quality guidance initially focused on its aesthetic properties (due to acceptability issues of taste and discolouration). Some epidemiological studies suggested an association between soluble manganese and cognitive impairment in children but the evidence base to establish causality was weak, presumably in part due to research on manganese in drinking-water being dissuaded by assumptions that food is a more important exposure route and manganese is "not of health concern at levels normally causing acceptability problems in drinking-water" (WHO, 2017a, p387). Over time, however, the evidence base has grown with increasing recognition that in some contexts, particularly where drinking-water is sourced from acidic or anaerobic groundwaters, a health-based guideline for manganese in drinking-water is warranted (a background document for developing this guideline recently came under public review: WHO, 2020).

Considering the constraints on the evidence linking water quality properties to health, internationally and nationally legitimated guidance may not sufficiently direct monitoring priorities in all contexts. This thesis focuses on microbial water quality and includes chemical and organoleptic aspects because they constitute integral context (both because of their links to chronic health conditions and because their influence on user and LWM decision-making also has consequences for microbial risk management). The selection of water quality testing methods (specified in Chapter 3) was designed to track chemical hazards that are recognised concerns in the study area (primarily fluoride and salinity as explained in Section 3.1.2) and to scan more broadly for additional potential geogenic hazards that are not often prioritised in rural water quality sampling efforts (e.g. selenium, uranium, and manganese).

Additionally, the scope of research includes parameters that capture organoleptic properties of water quality. Organoleptic aspects of quality are those detected using the sense organs: taste (e.g. saline, metallic), odour (e.g. sulfurous smell from bacterial activity), appearance (e.g. cloudiness, colour) and to a lesser extent touch (e.g. soft water with low magnesium and calcium content is preferred for washing because it lathers better than hard water). This dimension is included for its relevance to lay management decision-making, being the only dimension of water quality that is perceivable by non-technical means. This is not to imply that LWMs and water users understand water safety only through organoleptic perception[1], but rather that they have limited access to technical means of assessment.

Whilst organoleptic judgement is subjective, these properties can also be tracked with physicochemical parameters including, for example, measurements of turbidity, iron, or hardness (calcium and magnesium ions). The next section focuses more closely on the parameters that are measured to monitor microbial, chemical, and organoleptic aspects of water quality.

[1]In rural Tanzania for example, Drangert, 1993, described differentiated terminology for referring to 'maji safi' meaning clear or clean water and 'maji salama' which translates more closely to 'safe' water "that cannot be judged only by eye inspection" (p108).

### 2.1.2 Exploring Data Utility

Water quality monitoring is at the center of the World Health Organisation's framework for safe drinking-water (WHO, 2017a, p1). It is integral to the process of water safety planning, which has been internationally legitimated since 2004 and for which guidance is widely disseminated (Bartram et al., 2009; WHO & IWA, 2010), including for small-scale rural water supplies (Greaves & Simmons, 2011; Mudaliar et al., n.d.; MWIE, 2015; Rickert et al., 2014; WHO, 2012b). The intended purpose of monitoring is to create a feedback that helps secure and maintain water safety. It is useful to frame it as a process with nested stages: monitoring begins with measurement of a parameter of interest and progresses through use of measurements to interpret water quality, tracking quality over time to understand the safety of the water system, and at the highest level ensuring safe services are sustained in the long-term (Charles, Nowicki, & Bartram, 2020). Thus, the monitoring process is strongly influenced by measurement priorities and capabilities.

The strength of evidence linking potential hazards to health impacts is a key driver of water quality guideline development (for example see the background document for development of a WHO drinking-water quality guideline for fluoride: WHO, 2004). And regional and national water quality standards are based closely on international guidance, often including most chemical parameters for which WHO guidelines are specified (e.g. EAC, 2014; ESA, 2013; KEBS, 2015). In practice, however, not all parameters with set standards receive equal attention. A review[1] of hydrogeological research and regulatory monitoring in Kenya and Ethiopia found that fluoride is overwhelmingly prioritised whilst other potential geogenic hazards with less strongly evidenced links to health are rarely measured. Prioritisation is also related to testing capacities within national in-

[1]This review was a collaborative undertaking of the REACH research programme led by Florence Tanui and Behailu Birhanu and we are preparing it for publication at the time of writing.

stitutions. In Ethiopia, for example, uranium has been identified as a potential contaminant of concern in water supplies particularly in the Rift Valley region, but it is infrequently tested and in-county laboratories lack suitable equipment for uranium analysis (ACEWM & AECOM, 2020). Thus, the accessibility of measurement methods is important.

Beyond access, monitoring design is also influenced by characteristics of measurement methods, including how accurately they represent hazards of interest. Understanding method limitations is central to the research presented in Chapters 4 and 5, which respond to my first research question: how do uncertainties in understandings of hazard flows based on monitoring data influence the potential effectiveness of monitoring as a feedback mechanism? The measurement methods that generate monitoring data are either direct (the measured parameter is the hazard of interest) or indirect (the measured parameter is indicative of the hazard of interest).

Chemical hazards are often measured separately and directly. Although electrical conductivity, for example, is a useful parameter that indirectly informs on chemical water quality more broadly. Microbial water quality, in contrast, is typically assessed through an indicator-based approach that does not differentiate between pathogens (WHO, 2017a). In using this indirect approach, interpretations of measurements are substantially challenged by uncertainty around the relationships between pathogens and indicators and the extent to which discrete samples represent water safety over time. These challenges are discussed in the three sub-sections that follow.

#### ***The Relationship Between Pathogens and E. coli***

There are many types of microbial pathogens so sampling for each directly is impractical: the WHO drinking-water guidelines include fact sheets for 40 different varieties including groups of bacterial (18), viral (7), protozoan (11), and helminth (4) pathogens (WHO, 2017a). Besides their variety, sampling for pathogens directly is additionally difficult because they frequently occur in low concentrations, are generally only detectable with costly analyses, and differentiating between infectious and non-viable organisms is challenging (Cangelosi & Meschke, 2014; Leclerc et al., 2001). As a result, a risk-based approach relying on bacterial indicator organisms (commonly referred to as faecal indicator bacteria: FIB) has been used for the last century. Desirable indicator characteristics have long been contemplated for drinking-water and other mediums like food or recreational waters (e.g. Mossel, 1982), and there is broad agreement around five key criteria (WHO, 2017a). Ideally, FIB should:

1. be universally present in faecal matter at higher concentrations than pathogens.
2. not be pathogenic.
3. be simply and inexpensively detected.
4. persist and respond to treatment in a similar manner to pathogens.
5. not multiply in natural waters.

The gram-negative thermotolerant coliform bacterial species[1], *Escherichia coli*, is considered to be the best matched, although not entirely matched, to these criteria (Charles, Nowicki, & Bartram, 2020). It is well-matched to the **first** criteria – as reported by Tenaillon et al., 2010, *E. coli* are highly prevalent in humans (>90%) and many animals (10-55%) at high concentrations (between $10^7$ and $10^9$ colony forming units per gram of human faeces and between $10^4$ and

[1]The *Escherichia* genus also includes *Escherichia fergusonnii* and *albertii*. It belongs to a broad group of coliform bacteria, the 'total coliforms', that also includes *Klebsiella*, *Enterobacter*, *Serratia* and *Citrobacter*. Thermotolerant coliforms (TTCs), sometimes misleadingly referred to as faecal coliforms, are differentiated from total coliform bacteria by their ability to reproduce at higher temperatures, typically 44.5°C. TTCs are often used as a proxy for *E. coli* in water quality sampling under the assumption that the majority are *E. coli*. However, ratios of *E. coli* to TTCs are highly variable (Garcia-Armisen et al., 2007; Hamilton et al., 2005; WHO, 2012a) because other coliforms, like *Klebsiella pneumoniae* for example, are also thermotolerant and are found abundantly in the environment – that is they have diverse non-faecal sources.

$10^6$ per gram of domestic animal faeces). They are less well-matched, however, to the **second** criteria since although most strains of *E. coli* are commensals[1], a significant subset are pathogenic (Donnenberg, 2013).

With reference to the **third** criteria, views are more mixed. Particularly in low-income settings, there are significant time, money, and capacity challenges for *E. coli* testing and although many methods have been developed (Bain, Bartram, et al., 2012), it can be argued that none of them are inexpensive enough to meet the intent of criteria three (Medema et al., 2003) particularly in African and other 'developing' countries (Crocker & Bartram, 2014; Delaire et al., 2017). On the other hand, there are no established alternative indicators that are both easier to measure and easier to interpret than *E. coli* (WHO, 2017a), for which detection methods have been advanced through considerable research over the decades and for which method development continues to receive considerable focus (UNICEF, 2019).

The **fourth** and **fifth** criteria are most concerned with the co-occurrence of *E. coli* and faecal pathogens in water supply. Due to the difficulty of sampling for pathogens, direct comparisons between the presence of *E. coli* and of pathogens are relatively rare and the indicative relationship between them is subject to much uncertainty (Ferguson et al., 2012; Leclerc et al., 2001). Some research has shown, however, that concentrations of *E. coli* in water do not correlate well with concentrations of pathogens (e.g. Payment & Locas, 2011). This is attributed in part to differences in their respective behaviours. *E. coli* mimics physiologically similar pathogens, but viruses and protozoa are typically more robust to environmental conditions and disinfection methods (Leclerc et al., 2001; Murphy, 2017; Osborn et al., 2004; WHO, 2017a). Compared to viruses, *E. coli* are also more efficiently filtered by soil and artificial matrices because of their size and surface charge characteristics (R. Taylor et al., 2004). Thus the absence of *E.*

[1] Commensals are organisms that gain from a long-term interaction with an organism of another species that is neither harmed not advantaged by the interaction.

*coli* cannot be interpreted as confirmation of the absence of pathogens (Osborn et al., 2004).

Neither, though, can the presence of *E. coli* be interpreted as confirmation of faecal contamination. As explored in the next sub-section, understandings of the population dynamics of *E. coli* in water and the environment more generally have evolved substantially over time, but the implications for the utility of *E. coli* as an indicator in different contexts are still being established.

### *Evolving Understandings of E. coli in the Environment*

*E. coli* bacteria were discovered in 1885 during an investigation of the microbial life of the human gastrointestinal tract (Chaudhuri & Henderson, 2012) and their use as indicators of microbial contamination risk in water has been recommended since 1892 (Leclerc et al., 2001). For decades, they were studied primarily in lab and clinical settings that further emphasised their association with the gastrointestinal tract and, therefore, the faeces of humans and other vertebrates. The ecological niche of *E. coli* is much broader than initially realised, however, and the species is now recognised as 'hardy generalist' rather than gastrointestinal tract specialist (Alm et al., 2011).

*E. coli* occupy two habitats: the primary (gastrointestinal tract) and secondary (water, sediment, soil, flora). Initially, they were thought to have a net negative growth rate in the secondary habitat, implying short-term extra-host persistence (Savageau, 1983). But since the early 2000s, the assumption of negative growth rate in secondary habitats has increasingly been challenged by recognition of naturalised *E. coli* populations. *E. coli* have a core genome of about 2,000 genes, but roughly half the genes in any *E. coli* bacterium are contained in the 'accessory genome' – which exhibits large genotypic and phenotypic diversity across strains, allowing for diverse adaptive paths (Rasko et al., 2008; Touchon et al., 2009). This adaptability enables *E. coli* to contend with many stresses in environmental habitats (Bergholz et al., 2011; Tenaillon et al., 2010), which could include nutrient deprivation; sub-optimal temperature, salinity, moisture, and substrate texture ranges; exposure to solar radiation; competition with other microbes; and predation by protozoans (Berthe et al., 2013; Ishii & Sadowsky, 2008). *E. coli* have been found to grow in solutions of pH ranging from 4.5 to 9 (Luby et al., 2015). They are able to acquire energy in versatile ways and grow in both anaerobic and aerobic conditions with temperatures ranging from 7.5 to 49°C (Ishii & Sadowsky, 2008).

Studies have demonstrated *E. coli* persisting on algae and in soils, sediment, and sand in tropical, subtropical and temperate environments (Ishii & Sadowsky, 2008), as well as in handpumps removed from boreholes (Ferguson et al., 2011). Furthermore, long-term growth of *E. coli* has been demonstrated in a diverse array of source environments including lakes, rivers, sediments, beaches, soils, and aquatic plants and animals (Devane et al., 2020). Few studies have investigated the genetic background of *E. coli* in drinking water supplies specifically, but a characterisation of 28 isolates from chlorinated water supplies in Australia suggested that 9 isolates were naturalised *E. coli* that were unlikely to represent human health risk (Blyton & Gordon, 2017). Furthermore, several investigations have described genetically distinct populations of naturalised *E. coli* (Byappanahalli et al., 2006; Gordon et al., 2002; Nandakafle et al., 2020; Power et al., 2005; Texier et al., 2008; Whittam, 1989; Zhi et al., 2019), including environmentally associated cryptic clade phylogroups (Devane et al., 2020). And a recent meta-analysis representing the phylogenetic diversity of more than 5000 (mostly) non-clinical isolates from Australia associated genetic backgrounds with specific habitats, including freshwater environments (Touchon et al., 2020).

Thus, the utility of *E. coli* as a faecal contamination indicator in water systems is challenged by the existence of naturalised *E. coli* populations (Jang et al., 2017). So while the absence of *E. coli* cannot confirm the absence of pathogens, neither does its presence guarantee contamination. It can be difficult, therefore, to interpret *E. coli* sampling results, particularly when water system safety controls have not been validated and when sampling is infrequent (Charles, Nowicki, & Bartram, 2020). The severity and immediacy of the potential threat indicated by an *E. coli* positive sample is unclear. Despite this uncertainty, *E. coli* remains the preferred indicator of microbial water safety, including for rural community managed supplies (WHO, 2017a). The WHO drinking-water quality guidelines do not account for naturalised *E. coli* populations in source waters or distribution systems; they continue to assure that "the presence of *E. coli* should be considered as evidence of recent faecal contamination" (WHO, 2017a, p.57).

*E. coli* is widely used to monitor microbial water quality. In tracking progress towards SDG 6.1, for example, *E. coli* is used to assess whether water is free from faecal contamination, a prerequisite of being considered 'safely managed'. As a result, *E. coli* testing is increasingly included in large-scale household survey programmes[1] that aim to assess progress towards universal safe water provision. These programmes are testing water both at point of collection (PoC) and household-level point of use (PoU). This approach recognises that where water is not supplied on-premises, the PoC and PoU are both key stages where water safety must be ensured. PoC water quality reflects safety of the source and, where applicable, the distribution system, whereas PoU water quality reflects PoC quality as well as the sanitary conditions of transport and storage to/within the household. Recommendations to sample at PoC and PoU have also been included in the draft of updated WHO *Guidelines for Small Drinking-water Supplies*, which are set to replace the WHO, 1997, guidance in the fourth quarter of 2021 (a preview of the new guidance was shared in a survey in December 2020 that solicited input from researchers and practitioners with experience of regulating or monitoring small drinking-water systems).

[1] https://washdata.org/monitoring/methods/data-sources

That concentrations of *E. coli* often increase between PoC and PoU is well-established in the literature, evinced by studies from both urban and rural areas in Africa, South-East Asia, South and Central America, and the Caribbean (Machdar et al., 2013; Oswald et al., 2007; Shields et al., 2015; Sobsey, 2002; Wright et al., 2004). However, the health implications of this increase are debated, as are the implications for where water quality monitoring and treatment efforts should focus (Shields et al., 2015). Increases in *E. coli* concentration between PoC and PoU may result from contamination introduced during transport and household storage, which is influenced by sanitation, hygiene, and water handling practices; however, it may also result from growth of *E. coli* that was in the water supply, or from sloughing of biofilms in storage containers – neither of which would normally represent an increased health hazard (Trevett et al., 2004, 2005).

Thus, use of *E. coli* in rural water quality monitoring involves two key uncertainties. First, to what extent is *E. coli* at PoC linked to recent faecal contamination? Second, what are the health hazard implications of changes in *E. coli* concentration between PoC and PoU?

#### ***Temporal Variability of Hazard***

Compounding the difficulties of understanding how indicators like *E. coli* relate to hazards at any given point in time, temporal variability further complicates interpretations of monitoring results. Due to expense and logistical demands, water quality sampling is usually infrequent. The household survey campaigns mentioned in the preceding sub-section, for example, happen only once every few years. The WHO recommendation for small-scale piped supplies (serving $<$5000 people) is that faecal indicators be sampled at least monthly, but the minimum sampling frequency for point sources is once every 3 to 5 years (WHO, 2017a) or vaguely “once initially, thereafter as the situation demands” (WHO, 1997, p54).

Research has demonstrated that these recommended frequencies generate inadequate information to understand contamination prevalence or trends in water supplies (e.g. D. D. Taylor et al., 2018). In December 2020, the WHO released a call for input towards updated *Guidelines for Small Drinking-water Supplies*. In the draft guidance, the recommended sampling frequencies were differentiated by management type with minimum frequency set at monthly for utility or community managed piped systems, biannually for community managed non-piped systems, and once every three to five years for self-supply systems. A long list of 'key considerations' accompanying these recommendations highlighted that more frequent sampling may be needed to understand microbial contamination variability.

Low frequency sampling struggles to characterise seasonality differences, which have demonstrated significance for water quality (Carlton et al., 2014; Cronin et al., 2006; Guzman Herrador et al., 2015; Kostyla et al., 2015; Kumpel et al., 2017; Pujari et al., 2007). Seasonal changes in rainfall and temperature have been found to complicate year to year comparisons of water quality test results (Government of Bangladesh et al., 2021). And beyond seasonality, evidence suggests that shorter-term variability driven by rainfall and other factors is also important. Despite efforts to protect sources and treat water, "water quality can vary rapidly, and all systems are at risk of occasional failure" (WHO, 2017a, p26). Rainfall is identified as a key driver of short-term variability (Stukel et al., 1990), even for shallow groundwater (Howard et al., 2003). And the threat of waterborne outbreaks is often elevated following rainfall events (WHO, 2017a), even in high-income settings (Setty et al., 2018).

Many supplies source from groundwaters, which have longer residence times and, as a result, are generally less temporally variable than surface water. Nevertheless, the assumption that short-term variability is not a concern for groundwater supplies fails to account for geological differences in aquifer structure and localised contamination pathways, "fast horizontal pathways to the supply", that often occur as a result of well or borehole construction (Lawrence et al., 2001, p36). An investigation of urban shallow boreholes, for example, found that high short-term water quality variability could cause routine monitoring to miss hazard spikes (Roser & Ashbolt, 2007).

Another study of *E. coli* in surface-sourced drinking water described high short-term variability and concluded that most sampling is too infrequent to transcend this variability, making data interpretation challenging (Levy et al., 2009). This study, and a second study that examined microbial indicator concentrations in marine coastal waters (Boehm, 2007), proposed that geometric means calculated from multiple samples (even if taken only minutes apart) would be more useful than single samples. This is due in part to the aggregation behaviour of bacteria, which are non-randomly distribution in water (Kirchman et al., 1982; Tillett, 1993), and may also relate to method-induced variability as explained by Nowicki et al., 2019.

Even short-term, infrequent, exposure to faecal pathogens can cause significant health problems (J. Brown & Clasen, 2012; Enger et al., 2013; P. R. Hunter et al., 2009; WHO, 2017a). For example, P. R. Hunter et al., 2009, provided compelling evidence to this point when they modelled that drinking untreated water for a single day increases the annual probability of microbial infection by more than ten percent (the probabilities of infection by enteropathogenic *E. coli*, *Cryptosporidium*, or rotaviruses increased by 13%, 18%, and 12%, respectively). Thus, the consistency of safe water supply is important and water quality information may only be useful to decision-makers if it is at a high enough resolution to understand changes in hazard flows.

This idea has been promoted by researchers who, in reporting on the daily variability of water quality at household level in Bangwe, Malawi, have called for increased temporal resolution of water quality sampling at the household level (H.

Price et al., 2021). But the marginal cost, monetary and otherwise, of additional sampling is not negligible and tests to confirm the presence of viable indicator organisms like *E. coli* require a culturing step that delays results, usually 18 to 24 hours, and thereby reduces their value for reactive management (Bain, Bartram, et al., 2012; J. Brown & Grammer, 2015). Thus, the challenge is to find a balance between cost and insight. As noted in the draft update of WHO guidance for sampling small-scale water supplies, and elaborated in the subsequent section, this may be approached in two contrasting but complementary ways: by reducing sampling costs so that temporal resolution may be increased, or by decoupling hazard assessment from short-term variability.

### 2.1.3 Pathways to Advanced Data Utility

Improved understanding of the behavior of indicators relative to hazards may provide insight for better using and interpreting measures of indicators in monitoring efforts. In particular, this literature review has identified that links between faecal contamination and occurrence of *E. coli*, in the environment generally, and in water supplies specifically, may be obscured to an unknown extent by naturalised *E. coli* populations. This introduces important uncertainty into the use of *E. coli* in rural drinking-water monitoring, particularly where systems are loosely controlled and not subjected to a validation step[1]. Advancements in DNA sequencing capabilities present an opportunity for sub-species, strain-level, characterisation of *E. coli* isolated from water supply systems. This detailed characterisation may provide useful insight into the origins and behaviours of *E. coli*, advancing hazard assessment that would otherwise be based only on presence/absence or concentration measurements. In my methodology chapter, Section 3.3 details how I

[1]In Water Safety Planning, as recommended by the WHO, validation processes during the establishment of a water system or introduction of water safety management confirm whether a water system can meet water quality standards under varying conditions when it is operating as intended (WHO, 2017a, section 4.1.7).

undertook this task.

Additionally, development of methods to either increase temporal resolution of sampling or conversely decouple hazard assessment from short-term variability, present further opportunities to advance microbial water quality monitoring.

***Increasing Sampling Frequency***

The marginal cost of additional sampling is a key determinant of feasible sampling frequency. *E. coli* sampling has relatively high costs because of the need for consumables and the time spent processing and culturing samples. For example, Bain, Bartram, et al., 2012, reviewed forty-four test methods for faecal indicator bacteria (FIB; including *E. coli*, thermotolerant coliforms, or total coliforms) and found costs per test ranged from USD 0.5 to USD 7.5 before considering additional costs for import, delivery, time, labour, training, etc.

In contrast to FIB testing, sensor-based on site measurement involves negligible consumable costs per sample and the results are immediate, so time-associated costs are substantially reduced (and reactive management is more closely linked to real-time water quality). Turbidity and chlorine residual (where chlorine disinfection is used) are common monitoring parameters (often referred to as 'process indicators') that are better suited than FIB to higher frequency sampling (WHO, 1997, 2017a). In rural systems in low-income regions, however, routine chlorination is uncommon and turbidity is not a sensitive enough parameter to reliably interpret water safety without complementary testing of more specific indicators. An alternative, more sensitive parameter, tryptophan-like fluorescence (TLF) may represent an opportunity to advance sensor-based monitoring efforts (Baker et al., 2015; Nowicki et al., 2019; Sorensen, Vivanco, et al., 2018).

As a method of measuring physical phenomena, fluorimetry is not new. In recent years, however, it has been increasingly applied to investigate microbial contamination in drinking water supplies (Baker et al., 2015; Bridgeman et al., 2015; Carstea et al., 2016; Cumberland et al., 2012; Khamis & Stevens, 2013; Sorensen et al., 2015; Sorensen et al., 2016). Fluorimetry is a departure from conventional methods of microbial risk assessment because it does not capture *E. coli* concentrations, it does not measure any specific bacterial indicator. Instead, it enables measurement of TLF, which reflects concentrations of compounds that have similar fluorescence characteristics as the amino acid, tryptophan. These compounds are associated with breakdown of organic carbon by microbes (S. Elliott et al., 2006; Fox et al., 2017; Hudson et al., 2008). Studies have shown that faecally contaminated water can be distinguished from unpolluted water by strong TLF peaks that are notably higher than background levels (Hudson et al., 2007).

TLF is a promising parameter for monitoring because it has a lower marginal cost of additional sampling than *E. coli*, doesn't rely on water supplies being routinely chlorinated, and is more sensitive than turbidity to bacterial concentrations in water. It can be difficult, however, to interpret the relationship between TLF and faecal contamination, especially where water contains humic compounds or turbidity that is highly variable or frequently exceeding 50 NTU (Nowicki et al., 2019; J. S. Ward et al., 2020). In my methodology chapter, Section 3.2 explains how I included TLF measurement in a monitoring programme that underpinned much of the research for this thesis. The discussion of results in Chapter 4 elaborates on the challenges of interpreting TLF data in terms of microbial contamination hazard flows.

#### *Decoupling Hazard Assessment from Short-term Variability*

In addition to TLF, I also included sanitary inspections in the aforementioned monitoring programme design. WHO guidance recommends sanitary inspections as tools that water users and LWMs can use to monitor water sources (WHO, 1997, 2017a). The purpose of the inspections is to inform proactive management by identifying flaws in water supplies that increase the likelihood of faecal contamination. In theory, sanitary inspection helps address the problem of temporal variability by decoupling hazard assessment from short-term variability of hazard flows. But the absence of research linking sanitary inspection results to pathogen presence has generated debate about the the reliability of this approach.

In 2018 when I was designing the research for this thesis, the debate about sanitary inspection utility had more emphasis than it does today on the ability of inspection scores to predict FIB (*E. coli* or TTCs) sampling results (e.g. Ercumen et al., 2017; Snoad et al., 2017). Research attempted to prioritise sanitary inspection factors by evaluating which of them explained more variation in FIB results (e.g. Cronin et al., 2006). In the intervening years, understandings have been shifted by a) increasing recognition of the limitations of FIB to track contamination as discussed in Section 2.1.2 and b) renewed emphasis on the proactive purpose of sanitary inspections (Kelly et al., 2020). Although comparison with FIB results is still the main mode of assessing the success of sanitary inspection methods (Daniel, Gaicugi, et al., 2020; Kelly et al., 2021), the interpretations of these comparisons are more nuanced with recognition that inspections serve a different and complementary purpose to FIB sampling. Insights from qualitative and quantitative research are being incorporated in updated guidance from the WHO, which will aim to clarify the tools for and purpose of sanitary inspection (Pond et al., 2020). For my research purposes, I note that researchers have highlighted two key issues:

- poor correlation between inspection scores and FIB results are likely influenced by the inadequacy of single FIB measurements to represent microbial water quality over time (Kelly et al., 2021), and

- many studies do not adequately adapt the WHO recommended sanitary inspection protocols to reflect the complexities of local context (Kelly et al., 2020).

Thus, research to-date has compared sanitary inspection scores (often from generic protocols) with same-day FIB results, but not with summary statistics that represent FIB result variability over time. In my methodology chapter, Section 3.2.4 explains how I used an adapted inspection protocol to respond to this gap.

## 2.2 The Data User Perspective

The preceding section of this literature review focused on defining 'safe' water and evaluating the uncertainties associated with the parameters and methods used to monitor it. This section shifts focus to consider monitoring data use. Since systems evolve with lower and higher levels of organisation (Section 1.2), it is important to develop an understanding of the advantages and disadvantages of reporting water quality results to decision-makers who may utilize the information for daily management as opposed to regulatory or policy-making purposes. As introduced in Chapter 1 and elaborated in Section 2.3, in rural Sub-Saharan Africa, water management decisions are made primarily by water users and lay water managers (LWMs). Thus, my second guiding research question asks: how do water user and LWM understandings of water quality data interact with other drivers of decision-making to influence their actions?

In answering this question, I explore whether, and under what conditions, water quality data can be useful for improving water management in rural communities. Towards this aim, I first establish that the effectiveness of monitoring as a feedback mechanism to improve water safety depends on the data-user's perspective (Section 2.2.1). Subsequently, I review the literature that discusses water user and LWM behaviour change in response to water quality data and highlight key knowledge gaps (Section 2.2.2). I then identify an approach and specific conceptual framing to guide my research in response to those gaps (Section 2.2.3).

In undertaking this literature review, at the outset I recognised that any attempts to engage with user perspectives on water quality data "should be based on willingness to understand and deal with different mind-frames" (Timmerman et al., 2010, p1231). Furthermore, my review is informed by an awareness that water-related health outcomes are not only driven by exposure to hazards through consumption of unsafe drinking-water. Local-level decision makers also contend with exposures to pathogens and chemical elements through other pathways (WHO, 2017a; Wolf et al., 2019) and with the consequences of dehydration and poor hygiene from inadequate access to sufficient quantities of water (Howard et al., 2020; G. F. White et al., 1972).

### 2.2.1 The 'Data-Rich, Information-Poor Syndrome'

As outlined in the introduction (Chapter 1), unsafe drinking-water is an important public health challenge in rural Sub-Saharan Africa, where the population faces less access both to safe water and water quality information. Substantial progress towards the global-level ambition of safe water for all will require a systemic shift that must, at a fundamental level, be driven by local water management practices (Section 1.2). The potential public health benefit of monitoring on a scale that informs near-term decision-making has been noted (Bradley & Bartram, 2013) and research outputs have highlighted the need for higher frequency data to inform understandings and decision-making around water safety in low-income areas in Sub-Saharan Africa (e.g. Kumpel et al., 2016; H. Price et al., 2021; D. D. Taylor et al., 2018).

Of course the links between data and decision-making – between evidence and action – are notoriously complex. The literature recognises that water quality monitoring programmes should be designed to generate data that are meaningful for the intended data users (e.g. Behmel et al., 2016; Timmerman et al., 2010; Timmerman et al., 2000; R. Ward, 1996) to avoid what has been coined as a 'data-rich but information-poor syndrome' (R. Ward et al., 1986). Nevertheless, despite long-standing recognition that water management information needs and data user perspectives should drive data collection strategies in a cyclical manner (Figure 2.2; MacDonald, 1994; Timmerman et al., 2000), recent research in Sub-Saharan Africa finds that "those who would use information to make water management decisions are often not involved in the design and evaluation of monitoring networks" (Kumpel et al., 2020, p1).

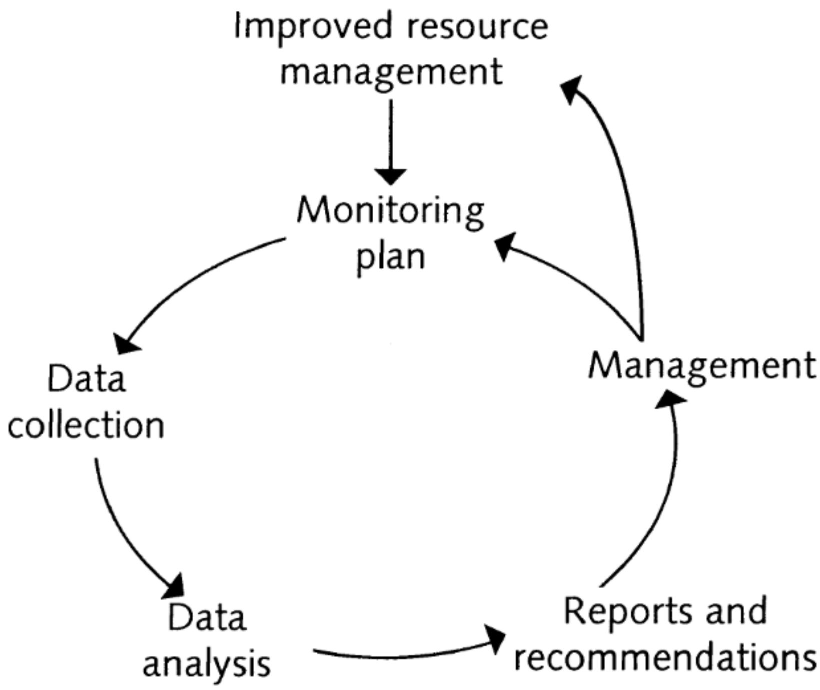



**Figure 2.2:** Conceptualising monitoring as a feedback loop (MacDonald, 1994; Timmerman et al., 2000).

This finding comes from the Aquaya Institute's Monitoring for Safe Water (MfSW) programme, which ran from 2012-16 and provided financial incentives to encourage water quality monitoring activity by twenty-six institutions (water suppliers in higher-density areas and surveillance agencies in rural areas) from six countries in Sub-Saharan Africa (Ethiopia, Guinea, Kenya, Senegal, Uganda, and Zambia). The research found that in responding to water quality test results, the actions reported by surveillance agencies involved passing responsibility for controlling hazards to water users (or occasionally LWMs). As detailed by Kumpel et al., 2016, actions taken by surveillance agencies included reporting to operators or health authorities (5% of actions) and implementing education efforts around general hygiene (11%) or specifically around household water treatment (68%), safe storage (2%), or water source protection (12%).

Through a REACH partnership-funded project, the Kenyan institutions that participated in the MfSW programme were revisited in 2019 and further analysis was conducted to explore how they use and share water quality data (Kumpel et al., 2020)[1]. The conclusions from this analysis focus on practicalities of data sharing and point in particular to potential for improving data use by increasing digitization to make data sharing more efficient; by increasing data literacy to improve analysis and information generation from data; and by taking advantage of efficiencies from combining water quality data collection with efforts to collect other types of data (Kumpel et al., 2020). The data flow diagrams used in the analysis conceptualise sharing water quality results with water users and LWMs as an action on the part of the surveillance agency. But an examination of the subsequent response from users and LWMs was outside the scope of the study.

Recognising the systems logic that data collection efforts will be more useful if they are informed by the perspectives of the intended data users (MacDonald, 1994; Timmerman et al., 2000), it is important to ask under what conditions water quality data can be useful to rural water users and LWMs in low-income settings. Some studies have specifically recommended sharing data at household level to motivate the implementation of drinking-water safety practices (e.g. Madajewicz et al., 2007; Trent et al., 2018). These studies support the view held by the surveillance agencies in the MfSW study, and by many other organisations in

[1]My supervisor, Katrina Charles, and I initiated this project with the idea that examining information flows with the MfSW institutions in Kenya could provide valuable insight into the wider context in which my thesis research resides.

the water sector, that increasing access to water quality data can lead to water safety improvements by addressing low awareness of water quality hazards among rural populations. For example, UNICEF Sudan has developed a water quality testing kit that is intended to be a "practical solution to address...glaring gaps, especially in the management of rural water facilities" by fostering "a culture of water quality testing and response" that would "set in motion demands for water disinfectants and also support from Local Authorities" (UNICEF, 2021, p1-2). As explored in the next subsection, however, there are key knowledge gaps that cast doubt on the validity of the assumption that water quality test results will sustainably and effectively motivate behaviour change among water users and LWMs.

### 2.2.2 Data-Driven Behaviour Change

From a public health point of view, there is clear interest in disseminating information as a catalyst of health-protective behaviours. Reflecting on what they learned from a participant in their study of domestic water use in East Africa, the authors of the original *Drawers of Water* book said that:

> "Her perception of the available sources of water seems to emphasise their purity by her standards. Considerations of direct cost enter heavily into her discrimination among those sources which are perceived as healthful...It would be a mistake to regard water users in rural areas as heavily bound by traditional views of water quality and source...choices, in many instances, may be traced to views of cleanliness, practicality, and interpersonal consequences which represent discerning choice on her part rather than blind conformity to the customary procedures of her cultural group. To the extent that this is true, a change in choice of source is not a matter of breaking habit or the hard cake of custom but involves cultivating new perceptions of health, convenience, and cost." – G. F. White et al., 1972, p262.

Access to information has an important influence on perceptions – it has been identified as a key dimension of empowerment for water, sanitation and hygiene (WASH) programme interventions (Dery et al., 2020). And research has demonstrated that limited access to information in households in lower-income areas impacts perceptions of environmental health risks, including from drinking-water (for example see the review by Figueroa and Kincaid, 2010).

These findings coupled with recognition that uptake and sustainability of household water treatment technologies is complex (for example B. Arnold et al., 2009; Luby et al., 2008; Makutsa et al., 2001; Null et al., 2012), have prompted researchers to ask whether information can increase 'willingness to pay' and motivate household water treatment behaviour change. This idea, of course, also extends to other health-related behaviours and research has evaluated the impact of information on diverse issues from preventing contraction of malaria (Dupas, 2009) or human immunodeficiency virus (Duflo et al., 2015) to reducing neurotoxin producing cyanobacterial blooms in recreational water bodies (P. Hunter et al., 2012). Here, I focus on studies that investigated the impact of sharing drinking-water quality test results.

Several years ago, Lucas et al., 2011, published a systematic review of studies on behavioural responses to dissemination of household-specific drinking water quality information. Although they conducted a wide initial search, screening more than 14,000 documents and accepting any research design and different water quality hazards, only six studies met their criteria of using water quality test results in an information intervention for which outcomes were evaluated. Four of these studies focused on arsenic in Bangladesh and the remaining two engaged with microbial contamination in urban India and rural Kenya.

The four large cohort studies[1] from Bangladesh found that people were more likely to switch to using an alternative water point if informed about arsenic

[1] These were the Arsenic Support Unity programme, the Health Effects of Arsenic Longitudinal Study, the Planning Alternatives for Change study, and a fourth study by Tarrozi et al., which each have multiple associated publications as summarised by Lucas et al., 2011.

contamination. As summarised in the review paper, all four studies included well testing and some combination of handpump labeling and provision of advice directly to households or through public education campaigns. Lucas et al., 2011, highlighted that the evidence base provided by these studies is limited by a lack of robust control group comparisons.

They were also critical of the microbial studies, concluding that neither provided strong evidence that household water treatment increases in response to receiving information about contamination from household water samples. The research from India linked test results showing faecal indicator bacteria (FIB) presence to an 11% increase in household water treatment in the following two months (Jalan & Somanathan, 2008), but Lucas et al., 2011, were concerned about bias in the study. The research in Kenya found household water test results did not significantly increase household treatment activity but source water quality test results did (Luoto et al., 2011).

Ultimately, the 2011 review concluded that evidence on the impacts of disseminating water quality test results is ambiguous and that "rigorous studies on this topic are needed" (Lucas et al., 2011, p8). Since then, studies have continued to focus on either arsenic or microbial contamination and have reported variable findings.

***Responding to Microbial Water Quality Test Results***

In rural Andhra Pradesh, India, microbial water quality testing and guidance was delivered at household-level to an intervention group, whilst a control group received neither. The intervention group responded by "purchasing more of their water from commercial sources but not by making more time-intensive adjustments" (Hamoudi et al., 2012, p18). An information intervention in peri-urban Tanzania, on the other hand, found that provision of household water test results was associated with increased self-reported safe behaviour, but no associated improvement in water quality measured one or two months later (Davis et al., 2011). The researchers concluded that "additional work is needed to elucidate the conditions under which such testing represents a cost-effective strategy to motivate improved household water management and hand hygiene" (p184).

In contrast, a later study in rural and peri-urban villages in Uttar Pradesh, India, found that household water treatment (boiling in the last two weeks) increased significantly in the cohorts who either received water quality test results or test kits that they used to test their water themselves, but not in the cohort that received only information about safe water management without a test result (Trent et al., 2018). Whilst the concentration of *E. coli* in household water was found to increase for the messaging-only group (measured a month later), it decreased in the groups that had water quality test data.

Another study took a different approach and studied not just whether behaviour changes in response to water quality data but also what factors may explain the heterogeneity of responses across different types of households (J. Brown et al., 2017). In a peri-urban area in Cambodia, they found that:

- Water treatment increased only in households with FIB-positive test results (indicating contaminated water), but the frequency of treatment remained "substantially less" than recommended (p142).
- Change in beliefs about water safety was more likely to be observed "among households with lower than median wealth and education, households living in the less developed area, and households who received a contamination signal despite having been initially optimistic about the safety of their water" (p142).
- But the average effect of the test result signal on health risk beliefs reduced over the six-week study period, particularly for households that were initially optimistic. Households that were initially pessimistic about their water safety and that received a contamination signal "were significantly more likely to remain pessimistic over time and to be using Aquatabs and engaging in alternative hygiene-improving behaviors six weeks later" (p143).

• Additionally, despite changes in beliefs and water treatment behaviours, observing a contamination signal was not associated with improved water quality or reduced incidence of diarrheal disease six weeks after the intervention.

From these findings they concluded that intervention to provide water quality information could be beneficial, but that "important questions remain about how and when households decide to engage in health risk management" (J. Brown et al., 2017, p143). Their study suggests that education, wealth, baseline perceptions of water safety, and time are key factors.

In agreement with J. Brown et al., 2017, another study from the greater Accra region in Ghana also suggested that previous perception / historical knowledge of water quality is an important determinant of response to test results (Okyere et al., 2017). This study used a novel approach that considered intra-household decision making by focusing on the impact of sharing water quality test results with school children versus with adult household members. The researchers reported that the information intervention, particularly with the children, increased selection of improved water sources and motivated other safe water behaviours. They concluded that water quality testing could be part of a social marketing strategy to promote safe water practices and that school children can be effective 'agents of change'.

***Responding to Arsenic Test Results***

In contrast to the microbial studies, the arsenic research in Bangladesh continues to focus on source switching as the key behavioural outcome. Two studies that provide particularly useful insights are highlighted here. Balasubramanya et al., 2014, offered a long-term perspective not provided by the microbial studies, they reported that household decisions to switch sources based on test results in and before 2005 were largely persistent and that by 2008 additional switching had "doubled the share of households [initially] at unsafe wells who had switched" (p631). On the other hand, however, they also reported that by 2008 almost a quarter of households did not recall the arsenic tests and decisions to switch away from safe wells among these households were attributed in part to their low recall.

In another arsenic-focused publication, Bennear et al., 2013, explored how different emphasis in messaging influenced choice of sources. They found that richer / more detailed messaging had an insignificant impact on well switching rates and concluded that "a one-time oral message conveying richer information on arsenic risks, while inexpensive and easily scalable, is unlikely to be successful in reducing exposure relative to the status-quo policy" of encouraging households to use water from wells that meet the Bangladesh national standard for arsenic[1].

Other research on arsenic aversion from the USA, took a different approach and considered the importance of the source of information. Leidner, 2014, looked at both a household's propensity to acquire health related water quality information and their likelihood of adopting 'aversion behaviour' (in this case using a household-level filtration device) in response to information acquired from: water utilities, media, friends, or 'other'. He found that aversion behaviour was more likely when information came from friends, and that household income and the presence of children in the household were also significantly associated with household decisions to use filters.

[1] A key part of the research premise was that households should use water with the lowest arsenic concentration that they can access. The Bangladesh national standard for arsenic is 50 ppb, it is considered an interim standard that improves prioritization of interventions to address the highest risk water points (WHO & UNICEF, 2018). The WHO guideline for arsenic in drinking water is 10 ppb based on measurement capabilities and treatment efficiencies, but studies have indicated that there is no safe level of arsenic intake (WHO, 2017a)

#### ***Key Weaknesses in the Evidence-base***

Overall, the studies reviewed in this section demonstrate the complexity of the relationship between data reporting and behavioural responses. Collectively, they highlight the need for research with a greater temporal scope to understand long-term behaviour change (and the potential impact of repeated messaging which has yet to be investigated). Additionally, they indicate that contextual factors are important and under-studied. Despite their mixed findings and acknowledged limitations, overall, these studies are supportive of information sharing at household level. In my view, the evidence for the effectiveness of this approach is unconvincing. And other approaches to behaviour change strongly question the value of information for motivating change in otherwise stable behavioural settings (Curtis et al., 2019). Most research in this space has taken a quantitative approach, but some exceptions have provided important, nuanced insight that emphasises how the influence of information on behaviour is moderated by a multitude of factors. Qualitative inquiry from Levison et al., 2011, in rural Kenya, for example, found that community members "understood that there was a link between the quality of water and their health, however, perceived benefits of current contaminated sources outweigh the potential health impacts and proliferate their continued use." (p103).

Furthermore, the majority of studies use households as their unit of analysis, usually without considering intra-household or intra-community dynamics. Okyere et al., 2017 propose that school children, specifically, may be effective 'agents of change', by influencing outcomes, again, at the household-level. But the literature that evaluates behavioural response to water quality test results is so focused on water safety at the point of use (household level) that none of the reviewed studies considered the potential of LWMs to be change agents for water safety at the supply level. Robinson et al., 2018, describe a comprehensively designed water safety planning intervention in Nepal during which community-led water safety monitoring (focusing on microbial aspects) was implemented through a participatory approach with involvement of community water user committees, researchers, and an NGO. In this project, water quality test results were shared at household level and also used to inform water safety interventions at the supply-level (e.g. intake filtration, chlorination).

The result was measured improvements in water quality at points of collection and use even eight months after the intervention. Based on their findings, the researchers promote "a comprehensive approach that merges household-centered WASH promotional activities with system-scale water safety efforts" (Robinson et al., 2018, p18). Unfortunately, however, their analysis of changing water safety perceptions and behaviours is again focused on the household level rather than on the members of the management committees that were responsible for operating and maintaining the water supplies.

In summary, the literature reviewed in this section points to a need for additional research to understand how water quality data may encourage safe water practices at both household and supply levels. It also highlights the need for evaluations over longer time-periods that consider how contextual factors – like intra-community variability in socioeconomic conditions, prior knowledge of water safety, perceptions of information trustworthiness, and competing priorities – drive response heterogeneity. In the next section, I explain the different approaches that I considered in designing research to respond to these knowledge gaps.

### 2.2.3 Behaviour Change Frames and Models

In deciding what theoretical grounding would be most useful for this middle phase of my research, I considered multiple literatures from different disciplines. Stemming from the alignment of my second research questions with the descriptive mode of decision theory, behavioural economics was the first body of work that I approached. I then considered literature on public engagement in environmental risk decision-making, before exploring psychosocial and stage change models of health learning and behaviour. I decided on an integrated fear appeal conceptual framing, which I explain in detail at the end of this section.

Originating with the work of Tversky and Kahneman, 1974, on judgement under uncertainty, the main strength of behavioural economics is in addressing the bounded rationality of decision makers. As a field of study it has received a lot of attention from governments and the public, for example many behavioural economics contributions are showcased in a popular non-fiction book called *Misbehaving: The Making of Behavioural Economics* (Thaler, 2015). Grounding my research in behavioural economic theory would direct me to focus on understanding the decisions of water users and LWMs through their use of heuristics, to focus on the influence of cognitive biases on 'thinking, fast and slow' (Kahneman, 2011).

Although it is frequently extended to other contexts, much of the theory of behavioural economics has been created through research in high-income settings, often through experimental exercises under laboratory conditions. Nudge theory, which informs a 'libertarian paternalistic' choice architecture approach, in particular has found wide application (Thaler & Sunstein, 2009), including in the WASH sector (e.g. Grover et al., 2018; Neal et al., 2016). But it has also been criticised as an ineffective basis for efforts to sustainably change health behaviour in lower-income settings because it does not adequately engage with the "everyday complexity of poverty" (Ray & Smith, 2021, p1). Deciding that a different approach would align better with my research objectives and systems-based orientation, I decided not to use a design informed by a behavioural economic theory in responding to my second research question.

Returning to the question, I focused on the aspect of laypersons engaging with a conventionally technical domain. This led me to literature on public engagement in environmental risk decision-making. This is an area that draws investigation from a variety of research approaches. When I began my research, a review study had recently grouped the literature by focus on risk governance, disaster risk management, science and technology studies (including post-normal science), and public understanding of science (van der Vegt, 2017). This literature has valuable depth in examining perception of risk, but it prioritises the constructed, contingent nature of scientific information and the need for accountability in scientific processes. Where decision making is central, the focus is generally on collective action not on individuals, so I determined that this would not be a good fit for my work.

With the goal of engaging with the decision-making of water users and LWMs as individuals, while also recognising "underlying social and environmental determinants of [their] behaviour" (Nutbeam, 2000, p261), I turned next to the broad field of health literacy. This literature draws on various psychosocial models of health learning and behaviour, a selection of which are highlighted in Table 2.1. There is considerable overlap between these models, with all of them sharing at least some concepts in common with others. In exploring this literature, I realised that health literacy focuses largely on clinical conditions (Nutbeam, 2008), and the discourse in the relatively young field of environmental health literacy has engaged primarily with empirical research in the United States (Finn & O'Fallon, 2017; Hoover, 2019). Thus, I found that the literacy focused literature was not well-suited to my research aims. I looked next at the literature that focuses specifically on behaviour change in WASH programmes.

**Table 2.1:** Key attributes of selected psychosocial and stage change models of health learning and behaviour.

| Label | Origins | Attributes |
|---|---|---|
| The self-management model | (Lorig and Holman, 2003) | Self-management is applicable in situations of chronic health risk where protective behaviour is a daily consideration, often for a lifetime. The model focuses on key mechanisms including the individuals' perspective on their health situation (Corbin & Strauss, 1988); problem solving skill set (e.g. D'Zurilla, 1986); and self-efficacy (Bandura, 1977; Bandura, 1997). |
| The health action process approach | (Schwarzer, 1992) | The health action process approach (HAPA) model distinguishes between two stages of behaviour change: the motivation stage and the volition stage, in which people are grouped as either intenders or actors. It has often been used to focus on maintenance of health behaviours like exercise (Lippke et al., 2004). |
| The precaution adoption process | (Weinstein, 1988) | The precaution adoption process model (PAPM) was developed to evaluate the influence of risk messages on adoption of household radon tests. It posits seven stages of behaviour change and is discussed in more detail in the main text. |
| Social cognitive theory | (Bandura, 1986) | Social cognitive theory outlines three dimensions of behavioural change: adoption, generalized use, and maintenance. It highlights the importance of beliefs and perceived social norms (Nutbeam, 2000). Self-efficacy has a key role in this theory (Bandura, 1997). |
| Protection motivation theory | (Rogers, 1983) | Protection motivation theory builds from the health belief model with the addition of two efficacy factors: response efficacy (relating to belief in the means available to address a problem) and self-efficacy (relating to belief in one's personal ability to address a problem). |
| The trans-theoretical model | (Prochaska and Di-Clemente, 1983) | The transtheoretical model (TTM) of stages of health behaviour change developed from research on smoking cessation. It posits six stages of change (precontemplation, contemplation, preparation, action, maintenance, and termination) and several key processes of change (Prochaska et al., 2015). |
| The theory of planned behaviour | (Ajzen and Fishbein, 1980) | According to this theory, individuals' perception of health situations (specifically their 'attitude' towards them) and related social norms are central to understanding their behaviour. In keeping with the health belief model, perception of barriers to action is also considered a key factor. |
| The health belief model | (Becker, 1974; Rosenstock, 1974) | The health belief model (HBM) centres on perception, specifically of: susceptibility, severity, benefits, barriers, and action cues. It has been applied in a range of health behaviour studies including clinical and preventative contexts (Conner & Norman, 1996). |
| The parallel process model | (Leventhal, 1970) | The parallel process model represented a shift in focus from emotional to cognitive processes and is concerned with attempts to control danger or threat cognitions. It was adapted into the extended parallel process model (EPPM) by Witte, 1992. The EPPM is discussed further in the text. |
| Bloom's taxonomy | (Bloom, 1956; Krathwohl et al., 1964; Simpson, 1966) | Although considered here for application to the learning of health protective behaviours, Bloom's taxonomy describes the general process of education by way of three hierarchical domains: cognitive, affective (emotional), and psychomotor (action-based), and has been widely applied (Anderson et al., 1994). It has been proposed for use in environmental health literacy research, with a view that at the highest levels of engagement individuals "recognize their exposures and exert some manner of control over them" (Finn & O'Fallon, 2017, p498). |
| Fear-as-acquired drive | (Hovland et al., 1953) | The fear-as-acquired drive model described the relationship between fear and acceptance of a threat with a non-monotonic function, proposing that some fear motivates action but too much fear creates maladaptive defensive responses (Janis, 1967). |

WASH behaviour change research has focused extensively on determinants of safe water collection, treatment, and storage practices (see the review by Lilje & Mosler, 2017), with ongoing debate about the relative importance of cognitive versus contextual factors (e.g., Ginja et al., 2019). Concepts from the models summarised in Table 2.1 have been influential in this space, and they inform the foundation of numerous models that were developed specifically to understand and engage with WASH behaviour change. The RANAS model, for example, focuses on five types of factors as drivers of behaviour change: these are risk, attitudinal, normative, ability, and self-regulation factors (Mosler, 2012). It was developed from empirical research on WASH behaviour change and with reference to many of the theories in Table 2.1 including the theory of planned behaviour, the health action process approach, self-management theory, the health belief model, and protection motivation theory.

Another model from Dreibelbis et al., 2013, was developed through a literature review of behaviour change models and explanatory frameworks that had previously been related to WASH. The search terms for this review included the health belief model, social cognitive theory, theory of planned behaviour, and stages of change among others. The behaviour change framework that they developed from this review was iteratively refined through pilots of WASH interventions, ultimately producing a model with contextual, psychosocial, and technological dimensions and behavioral, individual, interpersonal, communal, and societal levels – the integrated behavioural model for WASH (IBM-WASH).

The RANAS and IBM-WASH models are intended to guide the design and implementation of WASH programmes that intervene on multiple levels: Mosler, 2012, speaks of concurrently applying information, persuasion, normative, infrastructural, ability, and planning interventions and Dreibelbis et al., 2013, discuss fifteen categories of design factors for interventions that introduce new technologies like chlorine dispensers or child potties. While both models are comprehensive (including cognitive and contextual factors) and compatible with the structurationist problem framing of this thesis (Section 1.2), with so many concepts incorporated they become unwieldy to operationalise and are less helpful for guiding an approach to my particular research question, which focuses singularly on water quality data sharing. Rather than designing a multifaceted intervention programme to encourage a particular set of behaviours or use of a particular technology (like a chlorine dispenser), my research aims to understand the complex response to a relatively simple intervention - sharing water quality test results.

Withdrawing from a focus on WASH behaviour change models, I then considered the literature on using information to motivate health behaviour change more generally. Communications that describe a hazard with the purpose of motivating behaviour change are often conceptualised as fear appeals. They are used extensively for public health messaging, and the fear appeals literature, which has developed over seven decades, offers varied views on the persuasiveness and optimal design of appeals around a broad set of topics including the management of domestic and wider environmental exposures (Tannenbaum et al., 2015). In the next section, I explain how conceptualising water quality data sharing as a form of fear appeal led me to develop a conceptual framing to respond to my second research question.

#### ***An Integrated Fear Appeal Conceptual Framing***

Recognising that sharing water quality results could induce negative affective responses in individuals where water is unsafe, I found that conceptualising monitoring reports as fear appeals provides a useful initial framing to guide my work. Most fear appeals research has evaluated short-term (<2 weeks) outcomes of a single message (Tannenbaum et al., 2015), so there is limited theory and empirical evidence of sustained behaviour change or the influence of repeated messaging (Shi & Smith, 2016). Consequently, I place the fear appeal process in the wider structure of a stage change model, as has been done for other applications (Cho & Salmon, 2006; Manika & Gregory-Smith, 2017), thereby employing a hybrid framework that incorporates both drivers and stages of behaviour change (Figure 2.3). My framing focuses on decision-making by individuals, but it also acknowledges that daily water management decisions are complex and embedded in household and community systems (Neely, 2019b). Accordingly, it directs my assessment of responses to drinking water quality information to focus on cognitive and affective message processing, but also to account for time (through stages of change) and individual and situational differences (using rich qualitative data).

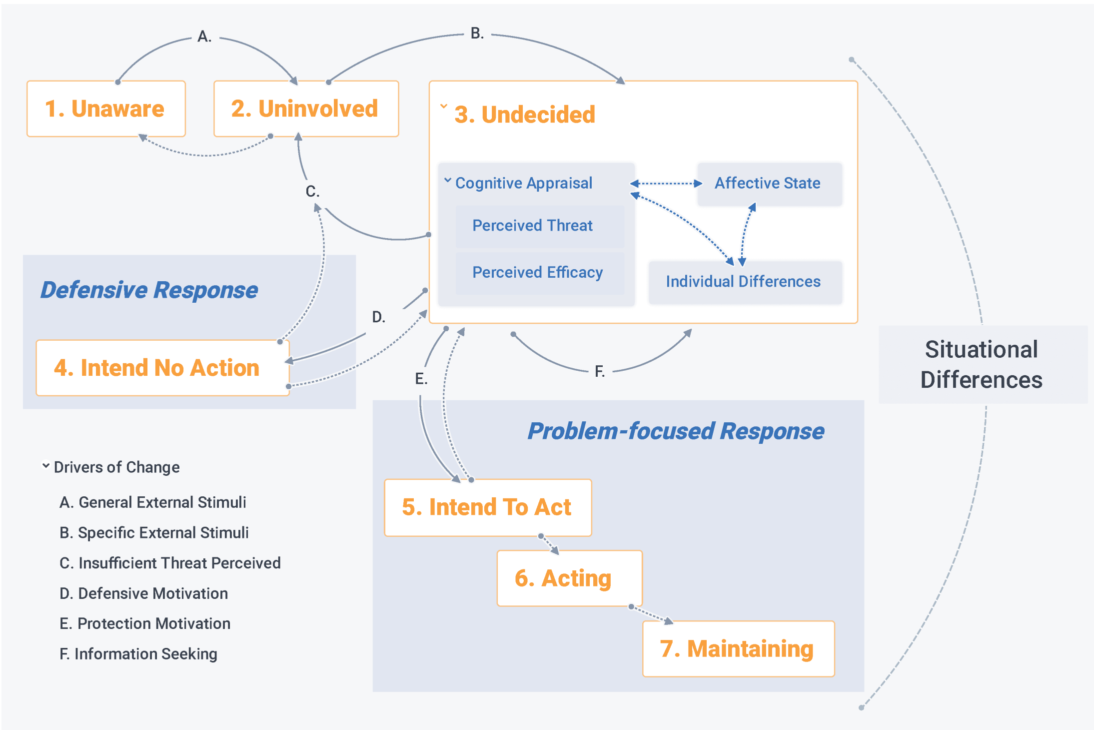



**Figure 2.3:** Integrated fear appeal framework situating the extended parallel process model (EPPM) within the precaution adoption process model (PAPM). *The numbered stages of change (in orange) are drawn from the PAPM. The message processing and outcomes concepts (in blue) are drawn from the EPPM. The drivers of change are drawn from both models as explained in the text.*

The fear appeals literature offers a rich theoretical foundation for framing the cognitive and affective processing of health risk information. In particular, the extended parallel process model (EPPM) (Witte, 1992, Figure 2.4), which consolidates concepts from protection motivation theory (Rogers, 1983), the parallel process model (Leventhal, 1970), and the fear-as-acquired drive model (Hovland et al., 1953), has been influential for health campaign design (Shi & Smith, 2016) and research in diverse areas including communication, health policy, psychology, business, and information security (Witte, 1992, had been cited 1, 500 times by the end of 2020 according to Web of Science). The genesis and concepts of the EPPM have been explained elsewhere (Popova, 2012). Briefly, the model posits that an external stimulus causing an increase in perceived threat and consequent negative affective state (fear) can motivate changes in beliefs and behaviours.

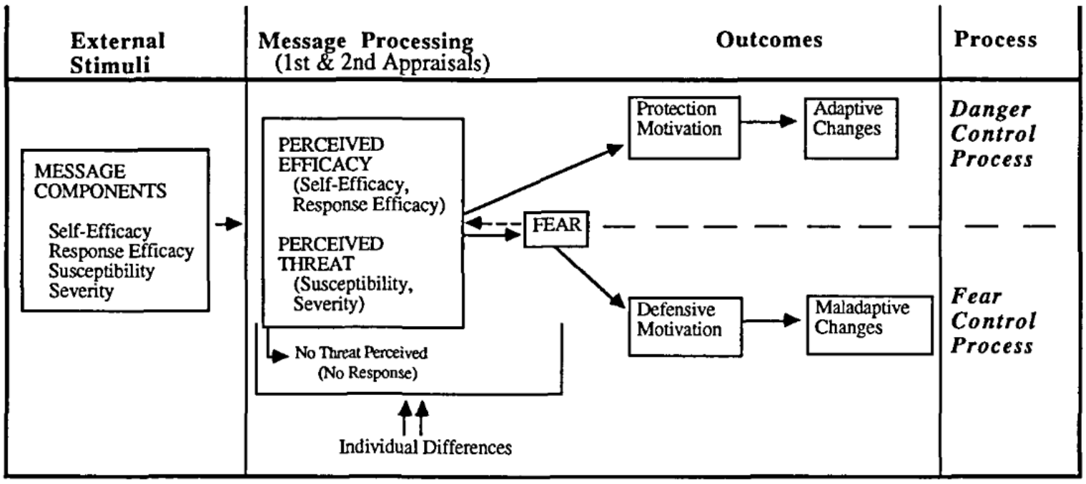



**Figure 2.4:** The extended parallel process model (EPPM) presented by Witte, 1992.

The change manifests either through problem-focused processing – when efficacy is high – or defensive processing – to reduce fear and/or cognitive dissonance when efficacy is low. Defensive processing refers to cognitive responses such as avoidance, denial, reactance, suppression, and re-appraisal, and is based in research on emotional regulation (van't Riet & Ruiter, 2013). Problem-focused processing refers to development of beliefs, intentions, and behaviours that engage with and mitigate the threat itself as opposed to the negative emotion that arises from being confronted with it. The central concepts of threat and efficacy each have two component parts: threat has dimensions of susceptibility (the likelihood of experiencing a threat) and severity (the magnitude of the consequences of a threat) and efficacy relates to both response efficacy (the effectiveness of a measure for controlling a threat) and self-efficacy (one's personal ability to take measures to control a threat). The model also includes an unspecified, catch-all parameter, 'individual differences', where contextual considerations including time and situational differences are grouped.

The EPPM is widely considered to be conceptually strong but lacking in reliable and consistent operational definitions (Popova, 2012). Empirical studies that have operationalised the model in mathematical terms, often without explicit consideration of temporal effects or context, have had inconsistent results (Maloney et al., 2011; Roberto et al., 2019). Consequently, I have used the core concepts of the EPPM to guide my study design and thematic analysis, but I do not use the model in a predictive capacity and I avoid operationalising the key concepts of threat and efficacy as continuous numeric variables. Furthermore, to better account for the influence of time and starting conditions, I draw on a second, complementary behaviour change model: the precaution adoption process model (PAPM) (Weinstein, 1988, Figure 2.5). In contrast to the EPPM, the PAPM uses stages of change to conceptualise behaviour change as a process, making time and precedent experience key considerations in understanding how individuals respond to information about threats.

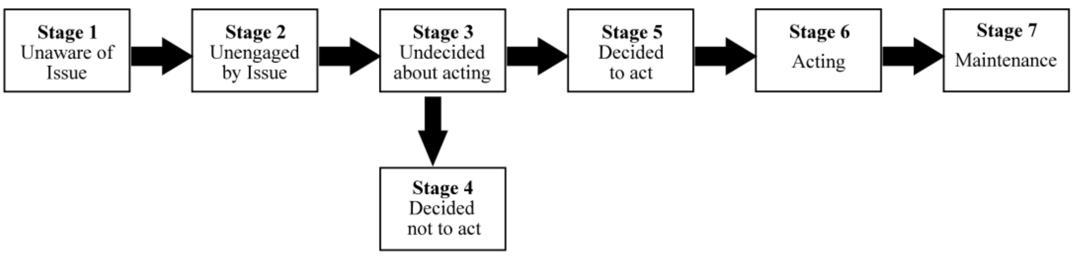



**Figure 2.5:** The precaution adoption process model (PAPM) presented by Weinstein et al., 2008.

The PAPM was developed as a theoretical framework for evaluating the influence of risk messages on adoption of household radon tests (Weinstein, 1988). It is similar to the widely used transtheoretical stages of change model (Prochaska et al., 2015), but the PAPM is more appropriate for my study context because, having been developed with reference to reducing harmful environmental exposures, it is not concerned with addiction (e.g. to unhealthy behaviours like smoking) and recognises 'unaware' as a distinct stage. The PAPM posits that when individuals receive general information about a threat, they move from being unaware (stage 1) to being aware but uninvolved in considering precaution measures (stage 2). Upon receiving information about the threat that is specific to themselves, they are prompted to consider adopting precautionary measures (stage 3, which aligns with message processing in the EPPM). If a decision is made, the stages then split with individuals either having decided not to act (stage 4, which aligns with a defensive response in the EPPM) or having developed an intention to act (stage 5, which aligns with a problem-focused response in the EPPM). For precautions to be adopted, individuals must act (stage 6) and, when relevant, maintain the adopted behaviour (stage 7).

The drivers of transitions between stages are not fully established as core concepts in the PAPM, but those that are well-supported (Weinstein et al., 2008) are included in my conceptual framework (Figure 2.3). An increase in general knowledge (driver A: general external stimuli) shifts individuals from stage 1 to 2. Increasing specificity about the relevance of the threat to an individual (driver B: specific external stimuli) prompts stage 3. The outcome of stage 3 is driven by the interaction between perceived threat and efficacy, affective state, and individual difference and, as framed by the EPPM, results in no response (driver C: insufficient threat perceived), defensive response (driver D: defensive motivation), or problem-focused response (driver E: protection motivation). Decision-making in stage 3 may be extended by driver F: information seeking (Hovick et al., 2020), which is a precursor to developing intentions around action (although it is often coded as a problem-focused response in applications of the EPPM). Neither the EPPM nor the PAPM provide well-established drivers at stages 6 and 7, for which habit formation and actual, as opposed to perceived, efficacy are expected to be important (Weinstein et al., 2008). Additionally, low information recall, defensive response outcomes, and failed problem-focused responses are logically expected to cause reversion to stages 1, 2, or 3 as indicated by the dotted lines in Figure 2.3.

By integrating the EPPM with the PAPM, I have framed behaviour change in response to a fear appeal as a process while retaining theoretical depth for conceptualising message processing. The integrated framework has several key advantages in that it distinguishes between a) individuals who are 'unaware of' versus 'uninvolved' with a threat prior to receiving a fear appeal; b) appeals that provide 'general' versus 'personally specific' threat information; and c) information seeking, intentions to act, action, and maintenance of action. Nevertheless, despite the strengths of the framework, it remains a simplified model of reality and does not explicitly account for many situational differences that impact behaviour. Recognising the insights afforded by studies that explore health-related perceptions and behaviours through qualitative methods (e.g. Levison et al., 2011), I decided to use the integrated fear appeal framework in conjunction with a mixed methods approach. As elaborated in my methodology (Chapter 3), my research design draws on quantitative survey data but also qualitatively explores contextual factors in the analysis of my semi-structured interviews.

## 2.3 Structural Enablers and Constraints

The first section of this literature review chapter defined 'safe' water and evaluated the uncertainties associated with water quality data (Section 2.1). Recognising that systems evolve with lower and higher levels of organisation, the middle section focused on data user perceptions and behaviour (Section 2.2). In this section, I shift focus again to review governance structures that enable and constrain water management in rural Sub-Saharan Africa. The purpose here is to account for higher levels of organisation that influence the behaviour of individuals who interact at local levels (Section 1.2); in other words, to understand the institutional context within which my empirical research is situated. This is done to support a response to my third guiding research question: what are the key institutional enablers of and constraints on monitoring activity and data use? It is not intended to be a comprehensive review of water governance models nor a basis from which to advance those models, such an undertaking is not the focus of this thesis.

My use of the terms 'governance' and 'institution' in this section and throughout this thesis is based on definitions that recognise resource management decision-making as considerably more than a narrow, technical process. Governance is understood as "a practice of coordination and decision-making between different actors, which is invariably inflected with political culture and power" (Bakker, 2010, p8). It is a term with widespread use in development discourse, having been defined for example as the exercise of power in managing socioeconomic resources for purposes of development (World Bank, 1994). Reforms promoted and funded through development aid are generally concerned with notions of 'good governance', which is linked to principles like participation, accountability, transparency, responsiveness, efficiency, equitability, inclusiveness, and legality (UNESCAP, 2009).

Governance is practiced through institutions, which are commonly conceptualised as "humanly devised constraints that structure political, economic and social interaction" in order to "create order and reduce uncertainty" (North, 1991, p97). Extending this definition with a structurationist view, institutions are an enduring form of rules and resources, the structural components of society, that are continuously reproduced through interplay with human agency, and which not only constrain but also enable that agency (Giddens, 1983, 1984). Institutions operate through rules, which North describes as both formal (e.g. laws) and informal (e.g. customs) and Giddens conceptualises as processes of signification, legitimation, and domination (in that rules relate both to the "constitution of meaning" and the "sanctioning of modes of social conduct", and cannot be conceptualised separately from resources – such that structural properties of systems "express forms of domination and power" (Giddens, 1984, p18)).

This understanding of institutions supports a richer analysis of water quality data use than has previously been conducted in research from Sub-Saharan Africa. For example, analysis of why water quality monitoring programmes succeed or fail has noted supply oriented factors like "provision of infrastructure, equipment, and training sessions" and highlighted the importance of institutional conditions including "motivation and leadership, knowledge, staff retention, and [access to] transport" (Peletz et al., 2018, p907), but has not explored the determinants of these conditions. Additionally, analysis of the barriers to sharing and use of water quality information within and between institutions in Sub-Saharan Africa has summarised data sharing and use practices, recommending improvement in data aggregation and analysis capabilities and enforcement of data sharing requirements, but not engaging the underlying structures that enable or constrain these practices (Kumpel et al., 2020).

In the following sub-sections, I briefly review the evolution of governance policy for rural water management in Sub-Saharan Africa (Section 2.3.1): first, with particular attention to the influential community-based management (CBM) model and then through discussion of tripartite models for pluralistic rural water governance, which are linked to contemporary policy approaches guiding water governance structures in bureaucratic, market-based, and community institutional domains. This is followed by a discussion of water quality governance in particular, differentiated as it is from other aspects of water governance by increased overlap with health governance (Section 2.3.2). Having outlined the institutional context for water management in rural Sub-Saharan Africa, I then identify an analytical approach to guide my enquiry into the enablers and constraints of water quality data use in this context (Section 2.3.3).

### 2.3.1 Historical Overview of Key Governance Policy

The contemporary prevalence of community-based water management in Sub-Saharan Africa is rooted in policy from decades ago. Before the 1980s, delivery of welfare services, including water supply, to citizens through much of Europe and the colonial regimes in Africa and Asia was considered to be solely a government function, with policy drawing on Weberian ideals of effective organisation and the welfare state (Barr, 1993; Mugumya, 2013). As discussed in the following two subsections, a major shift towards reducing the role of the state in direct delivery of welfare services saw new models of water governance and water sector development emerge and continue to evolve since the 1980s. The purpose of this brief discussion of the evolution of water governance theory and practice is to establish the contemporary institutional context of rural water supply in Sub-Saharan Africa.

***Evolution of the Community-based Management Model***

The community-based management (CBM) model gained widespread influence during the United Nations' International Drinking Water Supply and Sanitation Decade in the 1980s. It normalised the expectation that after rural water projects were constructed with government, NGO, or donor funding they would be managed in perpetuity by rural communities (Harvey & Reed, 2007; Lockwood & Smits, 2011). The emergence of the CBM model coincided with a major shift towards reducing, or at least changing, the role of the state in public service delivery. Reacting to the widespread inadequacy of government service delivery, policy developments promoted by the World Bank and the International Monetary Fund (IMF) in the 1980s were built on concepts like 'withdrawing the state' or 'liberalisation', and ideas of 'community management', 'community self-help', and 'cost sharing' became influential in rural water policy (Briscoe & de Ferranti, 1988; Mugumya, 2013). Additionally, researchers have noted that the CBM approach suited NGO and donor project timelines and was underpinned by "Western 'cultural idealization' of communities in low-income countries" (Harvey & Reed, 2007, p366).

Poor performance of the CBM model, with widespread operational failure rates of between 30 to 60%, was attributed to poor leadership prohibiting effective institution building (Mugumya, 2013) and to community-level issues "such as limited demand, lack of affordability or acceptability among communities, perceived lack of ownership, limited community education, and limited sustainability of community management structures" (Carter et al. 1999, cited in Harvey & Reed, 2007, p366). Recognising that CBM was partly promoted through an idealised view of communities, researchers have pointed to inter-community dynamics and hierarchies preventing community-based management from meeting "the demands of distributive justice" (Bakker, 2010, p14) and to the ineffectiveness of sensitisation or capacity building efforts to change attitudes or practices for example around acceptance of volunteerism or paying for water (e.g. Bonsor et al., 2015).

The recognition of widespread operational failure under the CBM model resulted in policy evolving to emphasise pre-construction efforts to increase community input in water projects (Whittington et al., 2009). The CBM model was reframed as demand-responsive where "the choices that people make should be linked transparently to prices so that people can make informed choices about their participation" and be aware that they face "an economic trade-off for a higher level of service" (Katz & Sara, 1997, p6). With promotion from the World Bank, the CBM continued to have widespread influence through development-oriented water sector policy (Katz & Sara, 1997; Lockwood & Smits, 2011). Interestingly, given the emphasis on choice in the demand-responsive approach, a choice experiment in rural Kitui County, Kenya found that: “Water user choices unambiguously identify community management of maintenance services as the least preferred option” when compared to other models that would disrupt that status quo (Hope, 2015, p674).

Early proponents of the CBM model upheld an assumption that post-construction community management was “feasible from a technical perspective”, however, arguments for post-construction support (PCS) to ensure sustainability of supplies became prominent in the early 2000s (Lockwood & Smits, 2011, p699) and have been increasingly supported through research and policy reviews (Andres et al., 2017). For example, Harvey and Reed, 2007, concluded that community-based water managers need PCS support for ongoing motivation, monitoring, planning, capacity building, and technical assistance (based on research in Ghana, Kenya, Uganda, and Zambia). And S. Banerjee and Morella, 2011, noted that the expectation that communities in rural Sub-Saharan Africa will successfully manage water supply operations and maintenance fails to adequately account for the challenges of this role, and is not mirrored in institutional arrangements for other services (like energy or transportation).

The importance of PCS is now widely acknowledged, but its fulfilment in practice lags behind (e.g. Andres et al., 2017; McNicholl et al., 2019; Whittington et al., 2009). Societal risk logics are evolving, however, and rather than focusing on delivery of “goods”, institutional mandates are increasingly focusing “on mitigating and managing the distribution of uncertainty, hazards, vulnerabilities, and exposure in relation to water quality, supply, reliability, and equitable access” (Fischer et al., 2020, p2). The shift of focus in development policy from provision of infrastructure towards provision of services (Lockwood & Smits, 2011), as reflected by the Sustainable Development Agenda, is being met with pluralistic institutional arrangements for water management as briefly explored in the next subsection.

### ***Tripartite Models of Pluralistic Governance***

Recognising the inadequacy of a model that envisions infrastructure built by government or other funds being turned-over to unsupported community-based management in perpetuity, water governance literature increasingly discusses more pluralistic institutional arrangements. Often these discussions are founded on a tripartite categorisation that aims "to describe the residual lying beyond the dualities of governments and markets" and that reflects "characterizations of modern society offered by a variety of thinkers, from Arendt (private, public, and the social realm) to Hegel (family, civil society, and the government)" (Bakker, 2010, p25). Although their formulations and labels vary (and hybrid institutions exist) pluralistic models of water governance (see for example Bakker, 2010; Koehler et al., 2018; Mugumya, 2013) often bound three broad domains as either:

- bureaucracy, government, authority, state, or public sector
- market, private-sector, corporate, business, or professional
- community, voluntary, or civil society

For convenience, these are hereafter referred to as the bureaucratic, market, and community domains.

As recorded in the influential 1992 Dublin Statement, recognition of the inefficiency of centralised water management led to high-level policy recommendations to change the role of governments – "to ensure a more active participation of people and local institutions, public and private" (Clause 7.2, WMO, 1992, p39). Government was to fulfil the role of an authority "capable of defining priorities, policy directions, targets and, where appropriate, prescribing standards" to facilitate "a system of checks and balances to safeguard public and national interests and to promote improved management", but not necessarily to directly execute a service delivery function (Clause 7.3, WMO, 1992, p39). In Sub-Saharan Africa, interventionist structural adjustment policy "led to waves of deregulation, privatisation and institutional reforms" (Hilgers, 2012, p82), largely because government acceptance of neoliberal reformation was a condition of receiving aid from the IMF[1]. The "conventional view" by the end of the 1990s was that "government should enable and regulate the private and community sectors or arms-length public agencies rather than directly provide services" (Batley, 1999, p. 761). And research on rural water supply in Sub-Saharan Africa, specifically, was highlighting the need for new partnerships between institutions in the bureaucratic, market, and community domains (J. Thompson et al., 2001).

In models of pluralistic institutional arrangements, the government is viewed as having a steering role, as articulated in the 1992 Dublin Statement, or a more flexible position as a collaborator within a complex network - which nevertheless requires a strong public sector to guide progress (Peters, 2011). Processes of decentralisation (both inter-governmental decentralisation and horizontal decentralisation to market and community institutions) were expected to serve this end (Conyers, 1983), as was the New Public Management (NPM) approach, which promotes cost-efficiency through principles of customer service, competition, and output-oriented management (Hood, 1991). This approach "advocates for greater citizen participation, cross-functional partnerships and networks between government, civil society and profit oriented market institutions" (Nguyen 2010, Rodall and Martin 2009, and Page 2005 cited in Mugumya, 2013, p52).

Ideas of risk sharing are also important foundations for pluralism, or 'networked governance', in the water sector, whether derived through theory on risk management cultures (Figure 2.6, Koehler et al., 2018) or through management concepts of 'public leverage' and 'strategic partnering' (Skelcher, 2005).

[1]Thirty-eight African governments accepted 244 conditional loans from the World Bank and IMF in the 1980s (Bratton van de Walle, 1997, cited in Hilgers, 2012).

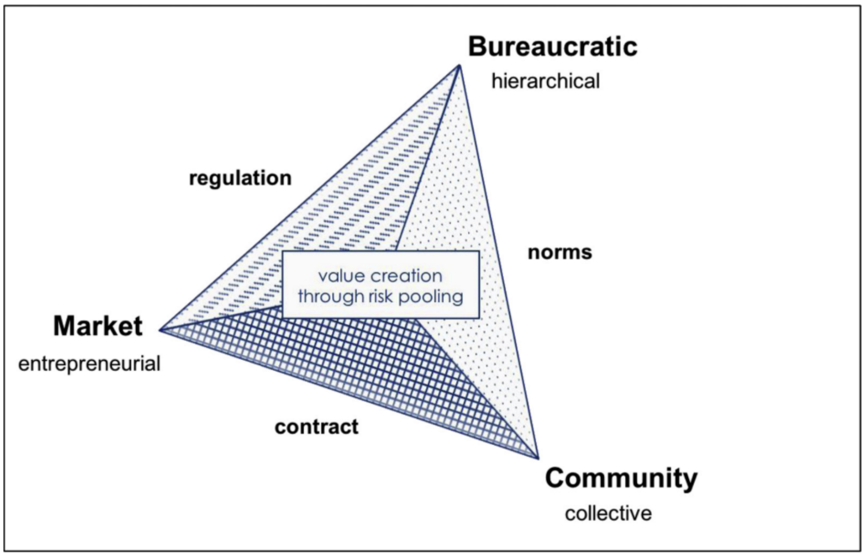



**Figure 2.6:** Visualisation of the pluralist institutional network model developed by Koehler et al., 2018, to promote cooperative management cultures in the rural water sector.

Additionally, in his thesis on rural drinking-water governance in Uganda, Mugumya, 2013, draws attention to concepts of enablement as long-standing foundations of pluralistic arrangements for public service delivery. Drawing on literature from social work and public management, (particularly Helmsing, 2002; Lund, 1994; B. Smith, 2000), he discusses political, market, and community enablement as distinct but interrelated processes that must be well-balanced for pluralistic institutional arrangements to be effective. In brief, the three forms of enablement are:

- **Political enablement,** which is linked to democratisation and political and administrative decentralisation, maintains that goods and services can be more effectively delivered through relationship-building within and between institutions in the bureaucratic, market, and community domains.
- **Market enablement,** which is linked to contracting and consumerism, maintains that goods and services can be more cost-effectively supplied by encouraging entrepreneurship and innovation, and removing market impediments that obstruct efficient production and delivery of services.
- **Community enablement,** which is linked to community leadership and pluralist collectivism based on principles of self-determination and values of

> social justice and inclusiveness, maintains that goods and services can be better aligned with user preferences and priorities through "the formation of partnerships intended to maximise economies of scale by responding to community problems using a diversity of experiences, skills and financial resources brought into a common pool" (Mugumya, 2013, p61).

Despite the strong and diverse theoretical foundations of pluralistic institutional reforms, there are key pitfalls to consider. For example, reviewing four modes of accountability in networked governance arrangements, Hertting and Vedung, 2012, states that accountability "is the Achilles heel of network governance"(p37). Blurring of responsibilities through overlapping mandates in pluralistic institutional arrangements "can lead to blame avoidance and scapegoating" (Mugumya, 2013, Ewalt 2001 cited in). Additionally, researchers have highlighted poor outcomes of pluralistic institutional reforms in Sub-Saharan Africa. In his review of the critical literature, Mugumya, 2013, emphasised two dimensions in particular 1) fragmentation leading to increased competition for scarce resources within the bureaucratic domain and between public agencies and private firms, and 2) exacerbated problems of rent-seeking and corruption including bribery, elite capture, patronage, and clientelism. Reflecting on his review, Mugumya emphasises that NPM and much of the theory underpinning pluralistic institutional arrangements originated in countries that "enjoy comparatively high levels of public trust, but also high levels of social, financial, and downward accountability" (p54).

Despite these challenges, water sector reforms in Sub-Saharan Africa (and the orientation of contemporary policy and literature) point to a future for the rural water sector that lies in pluralist institutional arrangements (Koehler, 2018; Lockwood & Le Gouais, 2015; Mugumya, 2013; Ndaw, 2016; M. Thompson, 2013). These arrangements are intended to account for the multiplicity of stakeholder perspectives and attempt to build compromise solutions that cater, at least in part, to the strengths and needs of bureaucratic, market, and community stakeholder groups. To improve water service delivery outcomes, both the underpinning theory and practical short-comings of institutional pluralism demonstrate the importance of trust building and cooperation between stakeholder groups within and between the bureaucratic, market, and community domains. Understanding this as the context in which water quality monitoring is intended to influence change towards increased provision of safe water supply, it is apparent that the implications of monitoring, data use, and data sharing on stakeholder cooperation will constitute key enablers and constraints of decision-making. Water quality monitoring addresses one of numerous aspects of water service provision and in order to productively contribute to improved management of water supply risks generally, its influence on institutional cooperation must be accounted for.

### 2.3.2 Drinking-Water Quality Governance

The importance of monitoring and active control of water safety in service delivery is now widely recognised in national and international norms and standards, but in many places practice has yet to substantially reflect this policy shift: "with most countries subscribing to either national or UN defined norms, whilst in practice seldom if ever systematically monitoring for quality" in rural areas (Moriarty et al., 2013, p340). In rural Sub-Saharan Africa, a lack of adequate provisioning for water safety management is the norm rather than the exception. Although policy has evolved from a focus on infrastructure provision towards a service delivery approach that explicitly considers water quality, change is slow in practice. The potential improvements in rural water supply to be gained by implementing PCS through pluralistic institutional arrangements are recognised, but the legacy of the original CBM model continues to shape water services in Sub-Saharan Africa and beyond (e.g. Andres et al., 2017; McNicholl et al., 2019). And the inadequacy of current governance structures is only further apparent when we look beyond CBM and account for self-supply arrangements (where individuals or small groups manage supplies that they construct by their own means) (Fischer et al., 2020; Sutton & Butterworth, 2021).

Guidance from the WHO, 2017a, recommends that in the absence of a formal, utility-style water supply, decentralised surveillance agencies should be partnered with community organisations to provide feedback from water quality sampling. This recommendation is proposed to "initiate a process of discussion and decision-making within the community concerning water quality" (WHO, 2017a, p90). And it is grounded in the view that: "The right of consumers to information on the safety of the water supplied to them for domestic purposes is fundamental" (WHO, 2017a, p89). But the recommendation is not matched by reality in Sub-Saharan Africa. As explained in the introduction (Section 1.1), more than 95% of water quality testing in Sub-Saharan Africa is done for operational monitoring of urban piped networks and there is very little surveillance monitoring of rural water, which the majority of people rely on (Peletz et al., 2016). Thus, most water users and LWMs find themselves without partnerships that provide feedback on water quality. Some regulators and donors are considering options (through pluralistic institutional arrangements) to enable monitoring of the small, numerous rural schemes that are currently not visible to them (for example, Gerlach, 2019; WASREB, 2019a). But there is not a lot of existing research for them to build on.

***Key Weaknesses in the Evidence-base***

In reviewing the literature, I found a dearth of research specifically on governance of drinking-water quality in 'developing country' contexts. Kayser et al., 2015, identified this as a gap, noting that research "has focused on the study of technical water management challenges and the study of specific interventions – household water treatment and safe storage, source water protection, and water safety plans – and their impact on public health or drinking water quality" but they identified an unmet need for "contextualised analysis of drinking water quality governance" (p187). Responding to this need with systems-based analysis and case study investigations in Brazil, Ecuador, and Malawi, they developed a water quality governance framework to summarise key governance challenges (Figure 2.7).

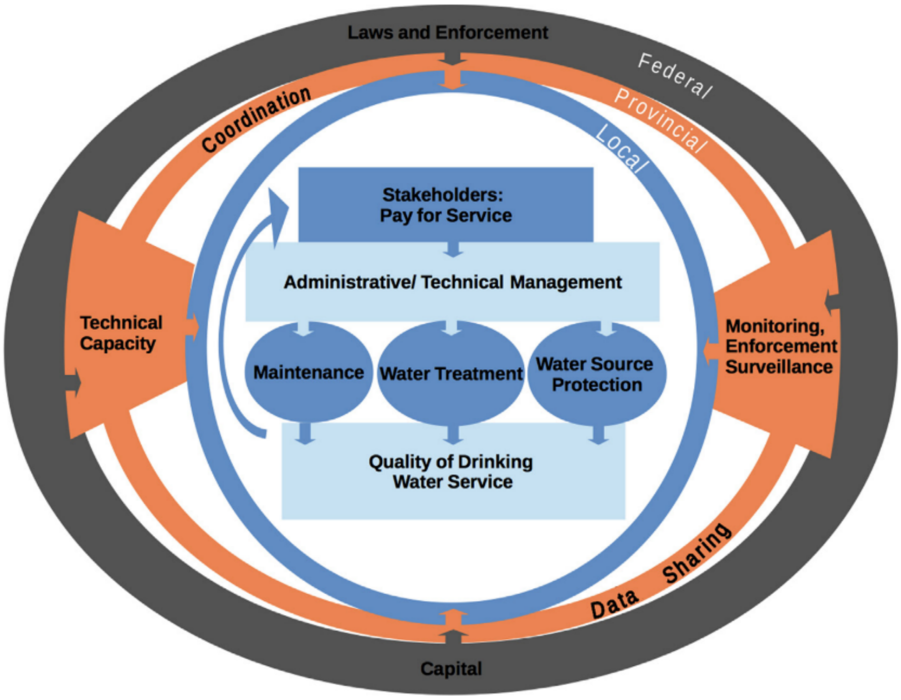



**Figure 2.7:** Visual representation of systems-based case study analysis presented by Kayser et al., 2015, as a framework for drinking-water quality governance.

The framework acknowledges the importance of institutional coordination and data sharing and identifies national-level laws and budgets as key constraints on monitoring and, thus, on maintenance, treatment, and source protection activities, which are required for provision of safe drinking-water. The consequent impact on the quality of water service provision is shown to impact payment for services, which creates a feedback loop that further reduces capacity for safe water management.

This feedback loop is well-supported. By the early 1990s, the relationship between water user choices and their awareness of water-related hazards (as discussed in Section 2.2.2) had been identified as an important factor for water supply performance[1]. And more recently research has pointed to water quality as a key determinant of operational and financial sustainability for rural water supplies (Bonsor et al., 2015; Hope & Ballon, 2019).

Despite recognition of this feedback loop, however, much of the post-construction support (PCS) narrative to date has focused on functionality of water systems without explicit consideration of water safety (Harvey & Reed, 2007; Kleemeier, 2000; Lockwood & Le Gouais, 2015). The case study investigations that informed the framework in Figure 2.7 took a broad view that has limited value for understanding how water safety can be included in PCS for rural water supplies. This is an important research gap because as policy and practice embrace pluralistic institutional models for PCS, opportunities arise for water quality monitoring to be implemented through partnerships that include market-based service providers (hereafter referred to as rural water service providers: RWSPs[2]), which provide a spectrum of PCS services through performance-based funding mechanisms that leverage economies of scale (McNicholl et al., 2019).

In additional to financial sustainability challenges, however, networked efforts to implement PCS face substantial challenges in mapping and solidifying responsibility/accountability and trust/relationship building is an important prerequisite for effective collaboration between institutions (as discussed in Section

[1] Clause 6.15 of the influential 1992 Dublin Statement made this point clearly, stating that: "Insufficient funds, insufficient trained manpower, poor operation and maintenance of systems and lack of community participation were identified as constraints to sustainable water supply and sanitation services in rural areas. **Lack of knowledge on health consequences of unhygienic services contributes to poor performance of water supply and sanitation systems after commissioning.** The major strategy consists of strengthening the rural water supply and sanitation sector with emphasis on institutional development, efficient management and an appropriate framework for financing of the services" (WMO, 1992, p36).

[2] To clarify terminology, RWSPs are conceptualised as market-based in this thesis because they are characterised by professionalism and funding structures that are reliant on user demand to varying degrees. In practice, they represent hybrid arrangements that leverage resources from the private sector, donors, and governments, as well as from water users. RWSPs are founded on the idea that networking small supplies together can provide the economies of scale that are necessary for affordable, sustainable water services; but most are not financially independent entities because they rely on external support to address the financing gap that results from consumers' low ability to pay for services. RWSPs may be organised as social enterprises, private utilities, parastatals, NGOs, or as community or civil society associations.

2.3.1 and reflected in Lockwood, 2002; McNicholl et al., 2019). Water quality issues, specifically, can be particularly challenging because of additional overlap with health governance structures (Kayser et al., 2015) and because unlike other aspects of water services like quantity and reliability, water safety is difficult to assess without technical means.

Thus, there is a need for research that explores how water quality data generated by a RWSP embedded in a pluralistic institutional structure can lead to improved drinking-water safety outcomes. The third undertaking of this thesis (to determine the key structural enablers and constraints for water quality monitoring activity and data use) responds to this need, with particular attention to the influence of monitoring and data use on cooperation between bureaucratic, market-based, and community stakeholders. In the next section, I identify an analytical approach that enables this undertaking.

### 2.3.3 Using Dilemmas as Units of Analysis

In assessing whether and how to include water quality monitoring among the services that they provide, rural water service providers (RWSPs) must consider their own interests and those of the bureaucratic and community stakeholders that they engage with. These interests are interrelated and subject to contradiction and instability, particularly because the relative absence of existing rural water quality monitoring programmes leaves procedures and responsibilities poorly defined. Thus, the conception and design of water quality monitoring programmes presents as an aggregate of dilemmas – a situation characterised by systematic complexity in which courses of action may be difficult to resolve. For water quality monitoring to effectively lead to sustained improvements in drinking water safety, it's necessary to understand and mitigate conflicts of interests within and between RWSPs, bureaucratic institutions, and communities. Thus, in responding to my third guiding research question (Section 1.3), I use a qualitative approach to analyse stakeholder views on including water quality monitoring in rural water services.

To do this, I decided to use dilemma analysis – a method that was first described by Winter, 1982 and has been used primarily within educational action research (Altrichter et al., 1993)[1]. Broadly, its purpose is "to find and juxtapose inconsistencies and contradictions that inhabit professional practice and decision-making" (Saldaña, 2016, p.139). Before proceeding with this approach, I considered alternatives including social network analysis or mapping causal loop diagrams, which are commonly used in systems-based research (e.g. Neely, 2019b). I also considered fuzzy set qualitative comparative analysis, as another approach for assessing causality, and a few different methods of coding qualitative data (e.g. process, values, and evaluation coding). These approaches and my main reasons for not pursing them are summarised below:

- **Social network analysis (SNA)** focuses on cliques, which form through homophily – the social aggregation of individuals based on their commonalities, and on brokers who create connections between cliques (S. Wasserman & Faust, 1994). One of the strengths of SNA is in identifying brokers and thereby pathways to increase knowledge-sharing and cooperation between cliques within a network. It is very useful for highly case specific research to identify courses of action towards specific end goals (for examples of WASH applications see McNicholl, 2019). For my research, SNA would generate unnecessarily specific information about the relationships between individuals within the networks in my case study area, but not enough information about the decisions and priorities that are characteristic of the positions that they occupy in their respective institutions.

- **Causal loop diagrams (CLDs)** focus less on interpersonal relationships and instead aim to comprehensively map systems through feedback loops and the causal relationships between the attributes and behaviours of people and the interconnected socioeconomic and environmental processes that they engage with

[1]This version of dilemma analysis is not equivalent to social dilemma analysis, which focuses on conflicts between individual and collective interests, nor with confrontation analysis, a game theory method that is also sometimes referred to as dilemma analysis.

(Sterman, 2000). These diagrams help visualise system structure to identify how changing one factor may influence change throughout the system. Bonsor et al., 2015, for example, created a CLD to map the factors that influenced whether a water point was functional or not in a pilot study in Uganda (p34). CLDs become complex very quickly, in keeping with the systems that they reflect, and are often more useful when applied to systems that are narrowly bound around a particular outcome of interest. The broad complexity of water safety management, particularly when considering governance aspects that span bureaucratic, market, and community domains, would be difficult to represent in a single, comprehensive CLD. I have already specified my interest in how data influence decision-making, but here CLDs paradoxically provide insufficient detail because they take an ostensibly objective 'birds-eye' view of a system without specifying an observer or informing on the differing perspectives of decision-makers within the system.

- **Fuzzy set qualitative comparative analysis (fsQCA)** is used for causal analysis that aims to discover what factors or case characteristics are necessary or sufficient to produce an outcome of interest. It combines a case-oriented qualitative approach with a variable-oriented quantitative approach and is intended for application in "intermediate-N" research circumstances (Ragin, 2012). It was used effectively by Peletz et al., 2018, to consider how different characteristics contributed to the performance of water quality monitoring programmes in Sub-Saharan Africa. I decided against this approach, however, because it relies on predefined outcomes that are consistent across all cases, so it is not well-suited to work that engages different types of stakeholder groups in which multiple and varied outcomes are of interest. Additionally, fsQCA requires case characteristics to be formulated as binary or quasi-binary, which flattens uncertainties and contradictions in the views expressed by case study participants.

Having ruled out the SNA, CLDs, and fsQCA approaches, I explored more general methods for coding qualitative data, as usefully summarised by Saldaña, 2016, in *The Coding Manual for Qualitative Researchers*. After reviewing multiple options[1], I focused on versus coding because it enables exploration of views

[1] I considered process coding, which can be useful to study processes of change, but I wanted to focus equivalently on action and inaction. I then considered affective methods including values and evaluative coding (before settling on versus coding). For values coding, I felt my own perspective and relationship with interviewees would be too central in the analysis. For evaluative coding, I felt it would direct my focus too much to specific programme details and would be difficult to apply to broader discussion of water safety and monitoring information use.

between and among stakeholder groups, it does not lock onto themes early in the coding process, and it aligns with a higher-level analytical method that is well-suited to my research aim and problem-framing. That method is dilemma analysis.

Recognising that effective pluralistic governance is supported by balancing the three forms of enablement discussed in Section 2.3.1, I found that dilemma analysis was useful to assess the views of RWSPs, bureaucratic representatives, and LWMs, "as parallel rationalities, without the hierarchical valuation which conventionally discriminates between them" (Winter, 1982, p.167). Additionally, dilemma analysis is similar to other post-structuralist approaches (narrative-style polyvocal analysis for example) in that it recognises the coexistence of multiple truths that are "always partial, local, and historical" (Hatch, 2002, p.202). It does not require stakeholder views to be static and unequivocal and is, therefore, well-suited to explorations of decision making under conditions of uncertainty.

Dilemma analysis directs focus not to the specific opinions of stakeholders, but rather to the issues about which their various opinions are held. Applied to the case of rural water quality monitoring, it allows contrary perspectives to be expressed within and between individuals and organisations. Importantly, this approach ascribes equal weight to bureaucratic and community priorities, which are both important for a RWSP's ability to operate. In my methodology chapter (Section 3.6), I explain how I used versus coding and dilemma analysis to explore the enablers and constraints of water quality monitoring activity and data use among bureaucratic, market-based, and rural community stakeholders.

## 2.4 Summary

In summary, the three-part literature review presented in this chapter corresponds with the research questions presented in Section 1.3 and forms a foundation for the empirical work that follows.

In the first part, Section 2.1 recognised water quality as a compound property that is nevertheless engaged through limited means of organoleptic perception and reductionist microbial and chemical assessment methods. It explained why this thesis focuses on microbial water quality (based on health impacts and uncertainties in assessment methods) but also includes chemical and organoleptic aspects (based on long-term and under-recognised health consequences, and the decision-making implications of interactions and trade-offs between different aspects of quality).

This section also explored how monitoring programmes are influenced both by prioritization of potential contaminants and by measurement capabilities. In particular, the indicator-based approach for microbial contamination assessment was reviewed and uncertainty in the relationship between pathogens and faecal indicator bacteria (predominantly *E. coli*) was discussed. The key takeaway from this discussion was that links between faecal contamination and occurrence of *E. coli*, in the environment generally, and in water supplies specifically, may be obscured to an unknown extent by naturalised *E. coli* populations. Temporal variability was also explored as a key dimension of uncertainty, and the discussion highlighted the challenge of implementing monitoring at a frequency that reasonably balances the competing demands of affordability and insight. The section concluded by identifying DNA sequencing, fluorimetry, and sanitary inspection as key methods for research that may help advance water safety monitoring design and data interpretations.

In the second part, Section 2.2 established that understanding the data-user's perspective is critical to evaluate the effectiveness of monitoring as a feedback mechanism, and to avoid designing monitoring programmes that suffer from the 'data-rich but information-poor syndrome'. It went on to identify key weaknesses in the evidence base regarding behaviour change in response to water quality data sharing. In doing so, it highlighted the need for research with greater temporal scope (including assessing the impact of repeated messaging) and increased attention to contextual factors (like intra-community variability in socioeconomic conditions, prior knowledge of water safety, or perceptions of information trustworthiness), as well as research that considers LWMs as potentially key agents of change within the rural water sector.

The latter part of this section explored potential theoretical groundings for research to address these gaps. A broad range of options were considered, including approaches informed by behavioural economics, studies of public engagement in environmental risk decision-making, health literacy and environmental health literacy, WASH behaviour change models, and more general psychosocial and stage change models of health-related learning and behaviour. The section concluded by explaining why an integrated fear appeal conceptual framing that draws on the extended parallel process model (EPPM) and precaution adoption process model (PAPM) is well-suited to guide the research.

In the third part, Section 2.3 outlined the institutional context that enables and constrains data use in the rural water sector in Sub-Saharan Africa. It provided an overview of governance policy that has informed contemporary institutional arrangements, with particular attention to the evolution of the community-based management (CBM) model and discussion of tripartite configurations of pluralistic water governance. Key processes and underpinnings of pluralistic governance were highlighted (including decentralisation and the New Public Management approach, and ideas of risk sharing and enablement) and accountability, fragmentation, and corruption challenges were discussed. Key takeaways from the discussion were that, despite many implementation challenges, the future of rural water supply in Sub-Saharan Africa likely lies in pluralistic institutional arrangements. And that it is important, therefore, to understand how water quality data sharing and use may influence trust-building and cooperation between stakeholder groups in bureaucratic, market, and community domains.

The latter part of this section focused on drinking-water quality governance specifically. It discussed the legacy of the CBM model and the slow pace of change in water safety management practices in response to policy shifting from emphasising infrastructure provision to emphasising service delivery. WHO guidance and research publications are discussed, highlighting that there is an unmet need for contextualised research on drinking-water quality governance. In particular, research is needed to guide the inclusion of water safety in post-construction support efforts for rural water supplies. The section concluded by identifying dilemma analysis as a useful approach to explore how water quality data generated by a rural water service provider (RWSP) embedded in a pluralistic institutional structure can lead to improved drinking-water safety outcomes.

The next chapter builds on the findings of this literature review and explains the empirical setting of the research, covering key environmental, institutional, and water sector specific context. It also provides method execution details, and discusses the ethics and positionality of the research.

*The settings and circumstances within which action occurs do not come out of thin air; they themselves have to be explained within the very same logical framework as that in which whatever action described and 'understood' has also to be explained. It is exactly this phenomenon with which I take structuration theory to be concerned.*

— Anthony Giddens, The Constitution of Society, 1984

*It can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience.*

— Albert Einstein, 1933

# 3 Methodology

The discussion in the preceding literature review chapter underpins my research design, which embeds an interdisciplinary mixed-methods analysis within the context of rural water supply in Sub-Saharan Africa, specifically northern Kitui County in Kenya. As discussed, my methodological design is underpinned by a variety of theories. Structuration theory informs the overall framing and conceptualisation of change in complex adaptive systems. Decision-theory informs the alignment of my guiding questions with normative, descriptive, and prescriptive modes of inquiry, directing focus to data uncertainty, drivers of decision-making, and structural enablers and constraints. My research questions are:

How can systemic links between data and decision-making be elucidated to identify leverage points for implementing monitoring as an effective feedback to mitigate health risk?

1. How do uncertainties in understandings of hazard flows based on monitoring data influence the potential effectiveness of monitoring as a feedback mechanism?
2. How do understandings of data interact with other drivers of decision-making to influence the actions of individuals?
3. What are the key institutional enablers of and constraints on monitoring activity and data use?

In approaching a response to these questions, my literature review engaged further with a variety of theory and paired knowledge gaps and analytical approaches by exploring:

- **water safety conceptual frameworks** (including the WHO conceptual framework for implementing safe drinking-water guidelines and a recent framing that distinguishes monitoring processes at four levels from measurements to security), which constitute theories of change that direct how data should be generated and used towards desirable outcomes in water management. This exploration informed my decision to focus on the utility of *E. coli* as an indicator of microbial contamination, but also to capture chemical and organoleptic aspects of water quality as key context. Furthermore, it directed my choice to proceed with DNA sequencing, fluorimetry, and sanitary inspections methods.
- **psychosocial theories of health behaviour change**, which informed my development of an integrated conceptual framework that models decision-making in response to fear appeal communications. This framing directs attention to key aspects of cognitive and affective message processing while encouraging a longitudinal study design and inclusion of qualitative inquiry – to retain time and situational differences as crucial and under-researched dimensions of behaviour change in response to fear appeals.
- **rural water governance policy models**, which informed my choice to focus on cooperation between stakeholders in bureaucratic, market, and

community domains and my use of a case study design to explore monitoring activity embedded in institutional context.

In this chapter, I provide the details of the methods I used in executing the research for this thesis. Figure 3.1 outlines the timelines, sample sizes, and connections between my methods, depicting how they are organised in five work packages to respond to my research questions.

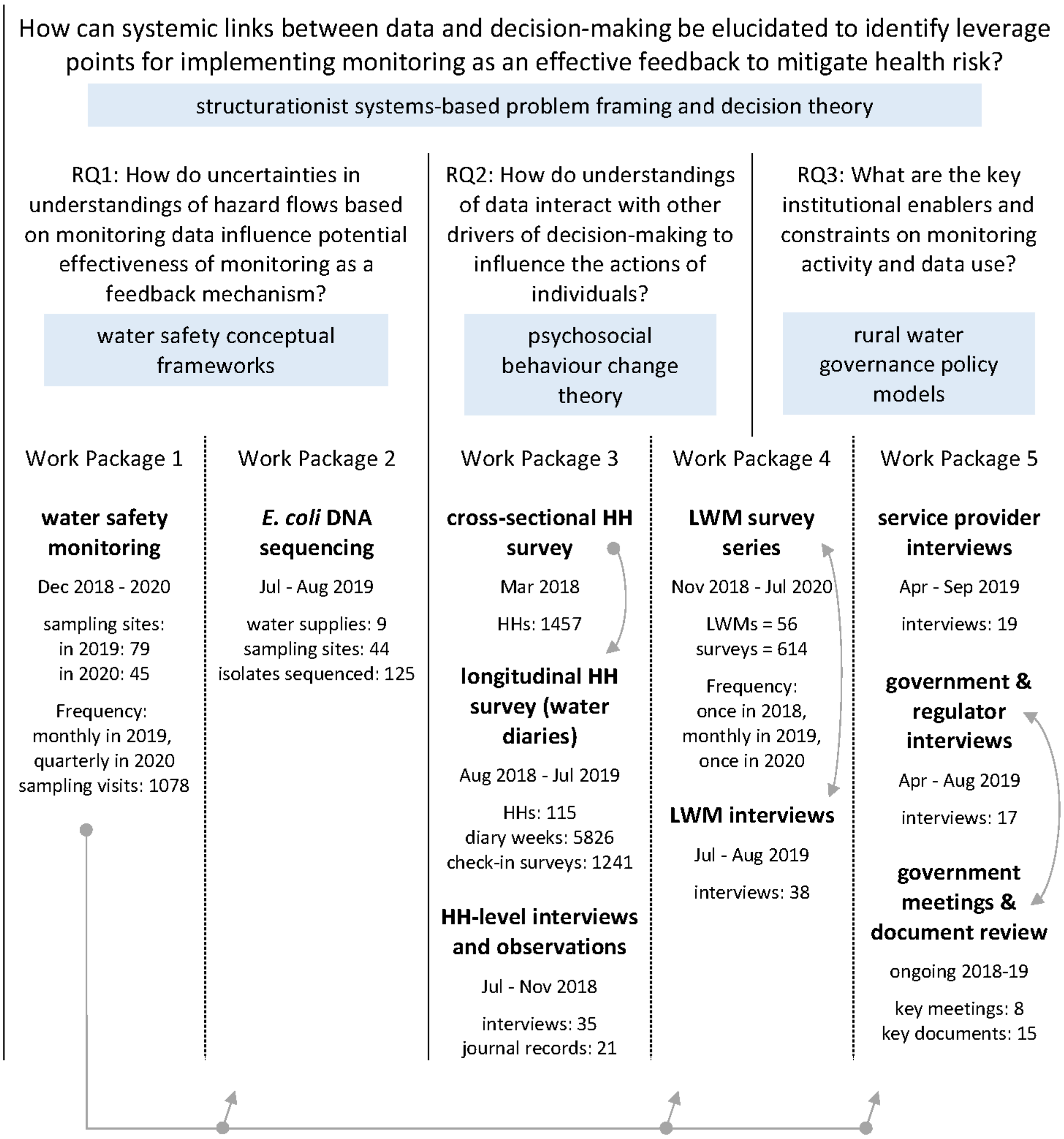



**Figure 3.1:** Overview of work packages summarising links to research questions and framing literature (blue boxes). *Grey arrows show which research instruments are informed by preceding results as explained in the following sections of this chapter.*

In Section 3.1, I explain my choice to locate my empirical research in rural Kenya and provide contextual background on the geographic and institutional setting. I then explain how I designed and implemented a monitoring programme in collaboration with a RWSP (Work Package 1, Section 3.2) and used it as a foundation to explore: data uncertainty through genomic characterisation of *E. coli* (Work Package 2, Section 3.3); water user decision-making through a mixed-method assessment of baseline data (Work Package 3, Section 3.4); lay water manager (LWM) decision-making through a mixed-method evaluation of an information intervention (Work Package 4, Section 3.5); and stakeholder cooperation through interviews and dilemma analysis (Work Package 5, Section 3.6). Table 3.1 provides an overview of the methods and collaborations that apply to each work package.

**Table 3.1:** Overview of data collection and analysis methods. *All stages of this research were made possible through collaboration with the REACH programme, the County Government of Kitui, FundiFix, and Rural Focus Ltd.*

| Work Package | Data Generation | Data Analysis | Further Support |
|---|---|---|---|
| (1) Water safety monitoring (results in Ch 4) | *E. coli* & TCs by quanti-tray MPN; electrode probes & turbidimeter; TLF and CDOM by fluorimetry; sanitary inspections; chemistry by IC & ICP-MS | summary statistics; time series analysis; correlations | SOGE Geolabs team; UoN geology team |
| (2) Genomic characterisation of *E. coli* (results in Ch 5) | *E. coli* incubation after membrane filtration & after agar streaking; Illumina Miseq whole genome sequencing | bioinformatics (phylogeny, MLSTs, virulence and AMR); allelic diversity | KEMRI Kilifi pathogen sequencing team |
| (3) Water user perceptions (results in Ch 6) | household welfare survey*; water diaries** & bimonthly survey; participant observation & semi-structured interviews** | summary statistics; $\chi^2$ tests & association plots; thematic analysis | USAID SWS Learning Partnership; UoN anthropology team; study participants |
| (4) LWM responses (results in Ch 6 & 7) | LWM survey series & semi-structured interviews | timeline construction; correspondence, thematic, & dilemma analysis | participant LWMs |
| (5) Stakeholder group perspectives (results in Ch 7) | service provider, government, & regulator semi-structured interviews; government meetings & document review | dilemma analysis | Aquaya Institute; USAID SWS Learning Partnership; interview participants |

*indicates data generation where I contributed a section to a larger design led by others
**indicates data generation for which I did not have design input

**List of acronyms:** AMR = antimicrobial resistance, CDOM = coloured dissolved organic matter, IC = ion chromatography, ICP-MS = inductively-coupled plasma mass spectrometry, KEMRI = Kenya Medical Research Institute, LWM = lay water manager, MLST = multi-locus sequence type, MPN = most probable number, SOGE = School of Geography and the Environment, SWS = Sustainable Water Systems, TC = total coliform, TLF = tryptophan-like fluorescence, UoN = University of Nairobi

In conducting this work I spent five fieldwork periods in Kenya (as summarised in Table 3.2) and otherwise managed collaborations and data collection from the UK. My research ethics approvals are covered in Section 3.7 and I conclude this chapter with a discussion of positionality in Section 3.8.

**Table 3.2:** Overview of fieldwork activities.

| **Period** | **Location** | **Main Activities** |
|---|---|---|
| Mar 2018 | Kitui | Study area scoping and preliminary meetings with stakeholders. |
| Nov/Dec 2018 | Kitui, Kilifi | Meetings with government; hiring and training research assistants; setting up a fit-for-purpose laboratory; selecting monitoring sites; securing informed consent and commencing monitoring and the LWM survey series; conducting check-in meetings with longitudinal household survey enumerators; conducting introductory meetings with KEMRI collaborators in Kilifi. |
| Jan/Feb 2019 | Kitui, Nairobi | Meetings with government; conducting debrief meetings with research assistants and household survey enumerators; conducting meetings with the UoN geology team during fieldwork overlap in Kitui; supervising ongoing monitoring and conducting quality assurance checks; trouble-shooting equipment problems. |
| Apr/May 2019 | Kitui, Nairobi | Conducting meetings and interviews with government, regulators, and formal water service providers (FWSPs); supporting ongoing monitoring in Kitui. |
| Jul-Sep 2019 | Nairobi, Kitui, Kilifi, Stockholm | Conducting meetings with government; interviewing LWMs; sampling sites for full chemistry analysis; conducting field and laboratory work for the *E. coli* whole genome sequencing; supporting ongoing monitoring; interviewing RWSPs in Kenya and at the Stockholm World Water Week. |
| Mar/Apr 2020 | Nairobi, Kitui | Travel was prevented due to COVID-19 (cancelled meetings for member checking and results-sharing; and round two of full chemistry sampling). From the UK, I coordinated with my research assistants to adapt to changed priorities and proceed with monitoring activity on a reduced (quarterly) schedule; recognising the increased strain on all stakeholders, I focused on a few demand-driven opportunities to share some of my results (Section 8.2.1). |

Following this chapter, my results are presented in four parts. First, I provide an overview of the monitoring programme results (Chapter 4), insofar as they provide useful context for the analyses and discussion that follow in the subsequent chapters. In Chapter 5, I present the results of the genomic characterisation of *E. coli* isolates. In Chapter 6, I present the results of the water user decision-making baseline assessment and LWM information intervention evaluation. In Chapter 7, I present the stakeholder dilemma analysis results. The cross-cutting themes from these pieces of work are further discussed in Chapter 8, which responds to each of my research questions and concludes this thesis.

## 3.1 Empirical Research Setting

The empirical work for this study was conducted in Mwingi North, the northernmost sub-county of Kitui County in Kenya. The work is centered around a water quality monitoring programme that I designed and executed in collaboration with a rural water service social enterprise, FundiFix Miambani Ltd., which operates out of Kyuso in Mwingi North. Kyuso is a small market centre located 170 km (direct ground-length distance) from Nairobi and 90 km from Kitui town, which is the seat of the County Government of Kitui (Figure 3.2). I chose this location as the base for my fieldwork to leverage an existing foundation of research and relationship building developed over many years through programmes led by Oxford researchers including the Water Programme of the Smith School of Enterprise and the Environment and the REACH Water Security Programme. It is also a suitable choice because of strong comparability with the wider rural water supply context described in Chapter 1 for Sub-Saharan Africa.

### 3.1.1 Institutional Setting

In 1999, the Kenyan Ministry of Water Development, as it was called at the time, published a National Policy on Water Resources Management and Development, which called for decentralisation of decision-making in the water sector – it emphasised that the private sector and communities should have increased involvement in water service provision, although it did not clearly allocate roles (Juuti et al., 2007). By 2010, access to safe water had become a constitutional right in Kenya, and the 2016 Water Act established that County governments are responsible for rural water provision that meets national regulatory standards, as upheld by the national government through the Water Services Regulatory Board (WASREB) (Government of Kenya, 2016).


**Figure 3.2:** Map of Kenya showing the location of Kyuso in northern Kitui County. *The black lines show county borders. The background of the map is satellite imagery from ESRI World Imagery. A more detailed map of Kitui County showing sub-counties, wards, roads, towns, market centres, and some villages is provided in Appendix C.*

In Kitui County, two formal water service providers (FWSPs[1]) have been established, the Kitui Water and Sanitation Company (KITWASCO) and the Kiambere-Mwingi Water and Sanitation Company (KIMWASCO). These companies are licensed and regulated by WASREB to manage water and sanitation services in different areas of Kitui County. They serve approximately 30% of the County population with especially limited coverage of the rural areas (communication from WASREB cited in Nyaga, 2019). This pattern is repeated throughout Kenya, with FWSPs serving mainly urban and peri-urban populations while most rural areas are classified as not 'commercially viable' (Government of Kenya, 2016). WASREB has limited oversight of water supplies in rural areas; they explain that:

> "most community water schemes operate in isolation and are not registered as legal entities. Hence, they are unable to access credit facilities, legally contract support services, acquire assets such as land, seek redress in court or sign agreements as a water service provider. There are no control systems to protect the rights of the customers, as it excludes those groups from government financial and/or technical support mechanisms. This poses a serious threat to the sustainability of the community water schemes. To support the sector's efforts towards the full realisation of the Right to Water, and considering the predominance of community-managed systems in rural areas and the related non-functionality issues, it is important that national standards in water service provision also apply to community water systems."
> – WASREB, 2019a, p9.

For water quality surveillance, there is some overlap with the activities of the Water Resources Authority (WRA), which monitors surface and groundwater quality from 160 gauging stations and 63 boreholes nationally (as of 2016); issues water use permits that involve water quality analysis; and operates a laboratory where County governments and other permit applicants send one-time samples for analysis following installation of new water supply infrastructure (WRA, 2017,

[1]To clarify terminology, in Kenya these providers are referred to as 'water service providers' and the acronym 'WSP' is used in documents that discuss them. In this thesis, I use 'formal water service providers' with the acronym FWSP so that there is no confusion with the use of 'WSP' for 'water safety plan', which is common in the water and health literature.

and communication from the WRA and the County Government of Kitui in meetings in 2019). Generally, however, the WRA is more concerned with large-scale abstraction and pollution control and has little operationalised responsibility for rural water supplies (and ongoing reforms in the water sector indicate that this is unlikely to change).

Based on mandates from the 2016 Water Act (Government of Kenya, 2016), WASREB are developing models to work with County governments to improve surveillance of rural supplies (WASREB, 2019a, and communication from WASREB in a meeting in 2019). Article 94 of the Act applies to rural regions and supports contract-based professional service provision and pluralistic institutional arrangements (including blended finance mechanisms). The models that are in-development, therefore, align with the trend towards pluralistic governance discussed in Section 2.3 and reflect that communities and external funders have key roles in financing water services in Kenya. An estimated[1] 30% of the financing for water, sanitation and hygiene services in Kenya comes directly from household expenditures, with another 50% from external aid and 20% from government spending (WHO, 2017b). For infrastructure alone, in Kitui County, an audit of 3,126 water sources completed in 2017 found that 48% were developed with funding from NGOs or donors, 23% were government funded, 10% were solely community funded (the remainder were recorded as unknown) (Nyaga, 2019).

Beyond the concerns of regulation, the relatively young county governments are developing their water sector plans and legislation more broadly. The Kitui County government's overall strategic planning includes considerable focus on water, which is upheld as one of five development pillars (alongside food, health-care, women empowerment, youth education and skills training, and wealth creation). 'Water' appears 1839 times in the *County Integrated Development Plan 2018-2022* in relation to water resource management (for agriculture and drought

[1]It is noted that this estimate is now several years out of date and the balance of financing may be shifting, especially as County governments develop their policy on water services.

and flood management) and water supply and sanitation (County Government of Kitui, 2018a). The water supply development programmes under the Ministry of Agriculture, Water and Livestock Development (hereafter referred to as the Kitui Ministry of Water) focus largely on infrastructure development (conducting feasibility studies for water project design, drilling new boreholes, extending piped schemes, constructing earth and sand dams, and installing water storage tanks); however, operations and maintenance are also considered, with the list of programmes including supporting maintenance and repair and subsidising water service providers. It is written that repair and maintenance efforts are intended to increase "access to safe water for domestic use" (County Government of Kitui, 2018a, p109).

Excepting a high-level mention of constructing water treatment plants, aspects of water safety planning like water quality testing, source protection, and decentralised treatment are not discussed in the development plan. But provision of safe water is also part of the remit of the Ministry of Health and Sanitation (hereafter referred to as the Kitui Ministry of Health), which has programmes to improve water safety and sanitation at household level and to reduce communicable disease by supporting health facilities and extending community health services – with a focus on health messaging to promote behaviour change through community health volunteers (County Government of Kitui, 2018a).

A County Water Bill that makes provisions to coordinate sector stakeholders in monitoring, delivery, and financing of water services (including rural water services) has been in development in Kitui (the Bill was in draft form as of October 2020). If passed into law, it will provide critical support for ongoing efforts to advance rural water maintenance service provision in the County. In particular, the Bill would introduce important enabling structure for FundiFix to continue and expand their services.

***FundiFix Miambani Ltd.***

FundiFix Miambani Ltd. was established as a maintenance service provider in northern Kitui County in 2013, with the primary intention of resolving water supply breakdowns within three days - substantially improving on the status quo month-long average repair times (Koehler et al., 2015). The organisation developed out of a research project led by the University of Oxford, the Smart Handpumps Project; it initially focused exclusively on handpumps but then expanded to include small piped schemes. By the end of 2020, FundiFix had performance-based contracts (with community-based management committees, private owners, or facilities) to provide maintenance services for 27 handpumps and 24 small piped schemes, which serve an estimated 64,000 people.

*The FundiFix Miambani Ltd. office in Kyuso and Annah Kavata, FundiFix technical officer, out front with one of the motorbikes that is used for maintenance work.*

FundiFix is a social enterprise that is financed through a blended arrangement, which aims to combine funding streams from water users, the government, and investors through a legally registered Water Services Maintenance Trust Fund (Figure 3.3). Although I refer to FundiFix as a rural water service provider (RWSP) in this thesis, it must be noted that there are legal implications to calling a company a water provider in Kenya, and FundiFix is purposefully positioned as a water supply *maintenance* service provider to distinguish it from formal water service providers, which are regulated under the Kenyan Water Services Regulatory Board (WASREB).

When I began my research for this thesis, the directors of FundiFix, although committed to prioritising water supply repair work, had expressed interest in including water quality monitoring as part of their service package. Thus, a collaboration with FundiFix presented an opportunity for a case study to explore the addition of water quality monitoring to post-construction support (PCS) efforts – in a pluralistic institutional setting that has good comparability with RWSP situations elsewhere in Sub-Saharan Africa (McNicholl et al., 2019).

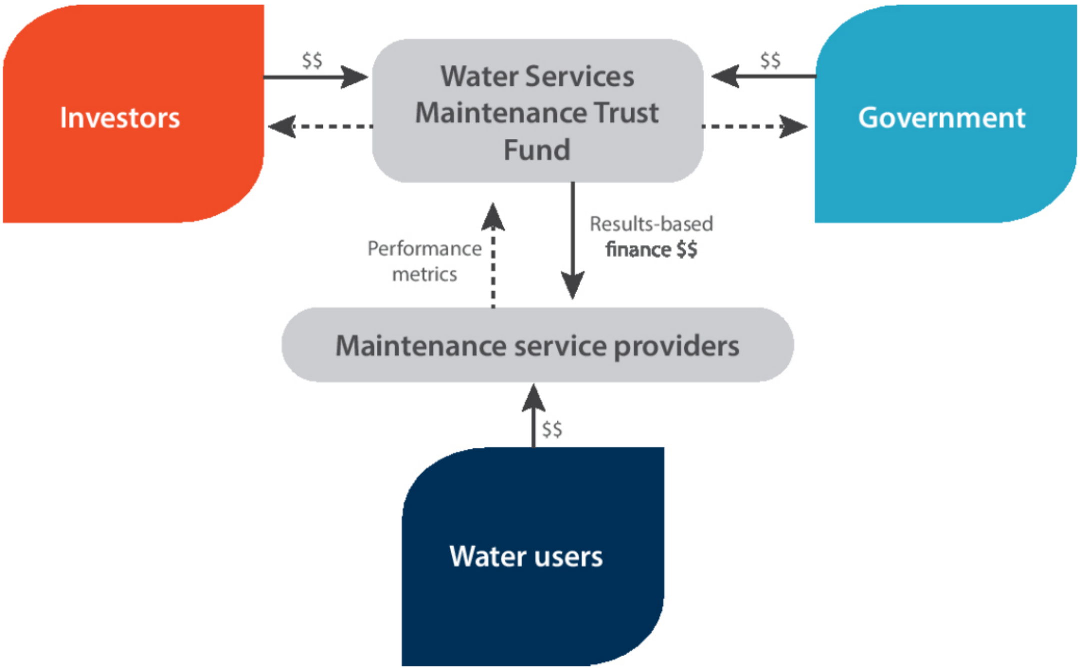



**Figure 3.3:** Conceptual model of the Water Services Maintenance Trust Fund in Kenya from (McNicholl et al., 2019).

### 3.1.2 Geographic and Demographic Context

Kitui County covers 30,430 km$^2$ and has a population of 1.1 million, with 4.3 people per household and only 37 people per km$^2$ on average (KNBS, 2019). Kitui town is the main urban center in the County, but the majority of people (95%) live in rural areas where agro-pastoral livelihoods are predominant. Most identify as Kamba and speak the Bantu language Kikamba. The literacy level in the County (83%) is almost on par with the national average (85%) based on population over 15 years of age that are able to read and write (KNBS, 2018).

The Kenya National Bureau of Statistics (KNBS) produced a report on the 2015/16 Kenya Integrated Household Budget Survey (KIHBS) that provides data on key socioeconomic indicators for each county (KNBS, 2018). Cash transfers to households from individuals (usually family members) inside and outside Kenya, NGOs, the government, or the private sector were reported in the KIHBS to track the extent that household income was augmented by external assistance. Nationally, 40% of rural households received transfers (25% in urban areas) and female headed households were more likely to receive transfers. The KIHBS recorded that Kitui County had more female household heads (46%) than the national average (32%). And 49% of households in the County had received a cash transfer in the 12 months preceding the survey, which was higher than the national average of 34%. The households that received transfers in Kitui, reported spending the money on food (48%), health (31%), school fees (16%), business / investment (5%), or other (5%). Conversely, 50% of households in Kitui reported having given out a cash or in-kind transfer in the preceding year (the national average was 53%).

Crop yields and livestock are the major source of earnings in rural Kitui County, so households are particularly vulnerable to drought and flooding, which frequently[1] impact the region (Government of Kenya, 2009; KNBS, 2018). Kitui County has an arid to semi-arid climate that is generally expected to follow a bi-modal pattern, with 'the long rains' expected from March to May and the 'the short rains' expected from October to December (County Government of

[1]Kitui County had the highest proportion of households that reported having experienced a shock in the five years preceding the KIHBS, 96% compared to the national average of 62% (KNBS, 2018). Rise in food price (35%) and drought or flood (26%) were the most common shocks. Other reported shocks included crop disease or pests (9%); livestock death (9%); severe water shortage (4%); livestock theft (3%); death of a family member (2%); job loss or salary non-payment (1%); fall in sale prices for crops (1%); robbery, burglary, or assault (1%); or other (9%).

Kitui, 2018b, 2019) – although in reality the rainfall in the County is described as "erratic and unreliable" (County Government of Kitui, 2018a, p18). I was able to request data from two Trans-African Hydro-Meteorological Observatory (TAHMO[1]) weather stations at government offices in my study area (Figure 3.4) to capture daily precipitation (Figure 3.5) and average daily temperature (Figure 3.6) from November 2018 to June 2020. This data provides important context for my study because rainfall impacts water quality and also strongly influences water infrastructure suitability and usage patterns, as particularly discussed in Chapter 6.

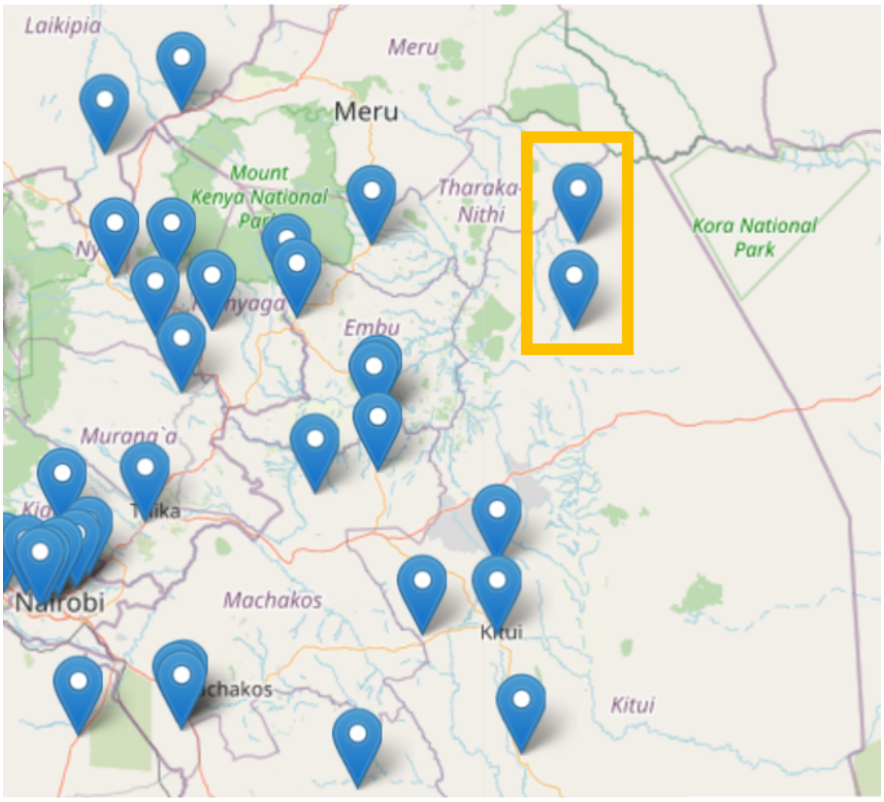



**Figure 3.4:** Map of TAHMO weather stations near my study area in Kitui County. *I was able to source data from the two stations indicated by the orange box. The stations are at government offices in Tseikuru (Station TA00187; -0.31385 latitude, 38.21999 longitude) and Kyuso (Station TA00186; -0.54978 latitude, 38.2128 longitude).*

[1]https://tahmo.org/

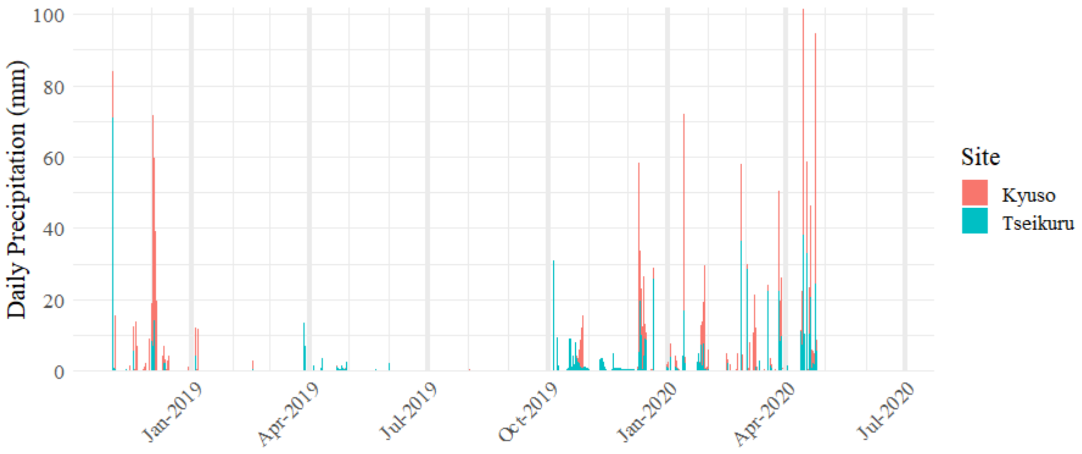



**Figure 3.5:** Daily precipitation at the two TAHMO weather stations in Mwingi North from November 2018 through June 2020.

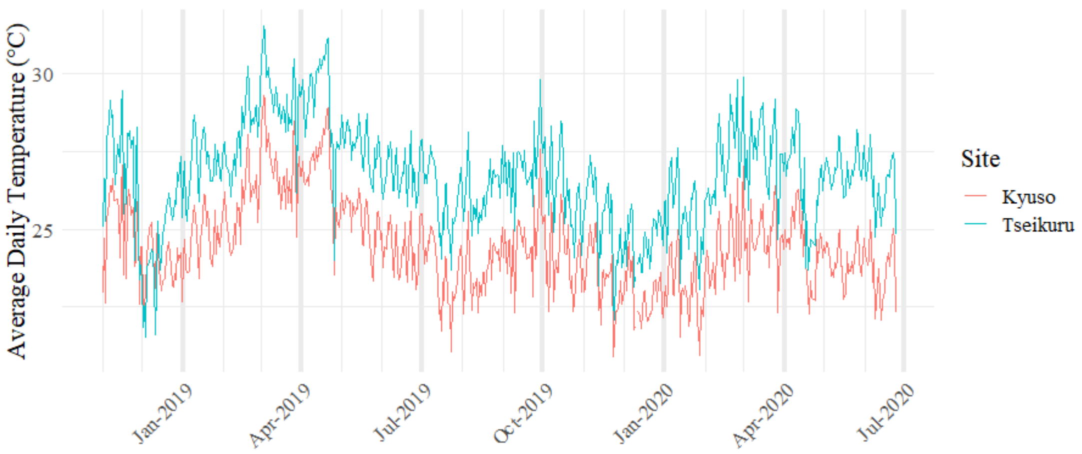



**Figure 3.6:** Average daily temperature at the two TAHMO weather stations in Mwingi North from November 2018 through June 2020.

### *WASH Infrastructure and Water Quality*

As of 2017, only 49% of the population in rural Kenya had access to a basic water source (defined as an 'improved' source located less than a 30 minute round-trip from a household premises including queuing time), and data are not available to judge the quality of the water that is supplied (JMP, 2020). In Kitui County, only 8% of households have water piped to their yard and only 2% piped into their home (KNBS, 2018). Others report their main water source as surface water (39%), public taps / standpipes (16%), boreholes equipped with handpumps

(12%), protected wells or springs (8%), harvested rainwater (5%), informally vended water (5%), unprotected wells or springs (3%), or bottled water (3%). The majority of households (58%) use sources that are more than a 30 minute round-trip away. The long distances to water points are a product of the low population density and clustering of water supply infrastructure near sparse road networks, which is a common pattern throughout Sub-Saharan Africa (Harvey & Reed, 2004).

An audit of water supply infrastructure in Kitui County completed in 2017 recorded a total of 3,126 equipped and non-equipped water sources – including 687 handpumps and 460 piped distribution schemes (Figure 3.7). At the time of the audit, 60% of the water sources were fully functional, 25% were non-functional and the remainder were partly functioning (Nyaga, 2019). In Mwingi North, specifically, the audit recorded 49 piped water schemes and 78 handpumps, but most non-equipped sources were not recorded because the audit was done in earlier campaigns (in 2011 and 2016) unlike for the other sub-counties (which were audited in 2017).

Water supply for the majority of households in Kitui County is not treated, although some households report that they drink water which is made safer by chlorination (16%), boiling (8%), solar disinfection (0.9%), or waiting for sedimentation (0.6%) (KNBS, 2018). The general lack of water treatment has health consequences, particularly diarrhoeal disease, which are also influenced by sanitation and hygiene conditions. Only 0.1% of households in the County have piped sewerage and 2% use systems that flush to septic tanks or pit latrines; the majority use pit latrines with slabs (42%) or without slabs (29%), ventilated improved pit latrines (12%), composting toilets (0.2%), or no facility (14%). Of those who use a facility, 40% are sharing with other households and 89% do not have a hand-washing station nearby (KNBS, 2018).

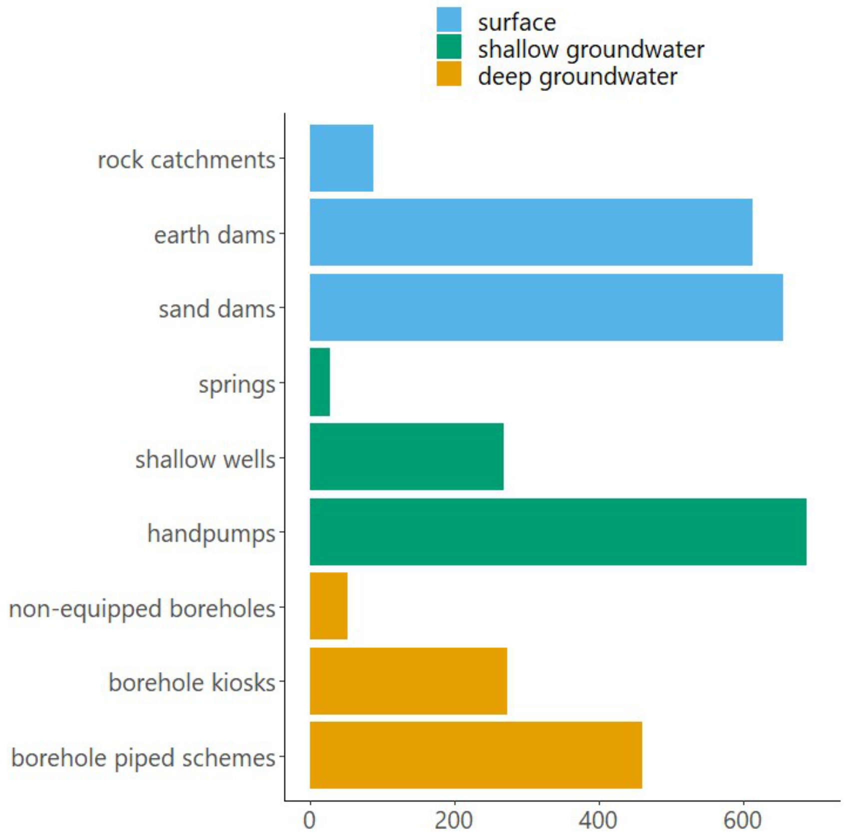



**Figure 3.7:** Counts of water sources recorded in the Kitui County Water Audit, which focused in greater detail on piped schemes but also recorded other source types (as described by Nyaga, 2019).

Besides diarrhoeal disease from microbial pathogens, chemical contaminants in water can also have health consequences as discussed in Section 2.1. Based on information that I sourced from the Kitui Ministry of Water and colleagues at the University of Nairobi and University of Oxford, the main chemical contaminants of concern for water supply in Kitui County are geogenic fluoride and salinity, which includes high concentrations of sodium as well as other ions (Garside, 2013, and unpublished data from the Kitui Ministry of Water). The general geology of the area (which is still understood with reference to the mapping work for the *Geological Survey of Kenya* undertaken prior to 1962) is dominated by two main zones – the eastern side of the County is characterised by holocene quaternary sediments (colluvial deposits, red soils), which are associated with higher salinity groundwater, and the western side is characterised by much older precambrian basement rock (Mozambique belt), which is expected to produce less mineralised water (Akech et al., 2013; Crowther, 1957; Hope et al., 2021).

***Health Data Overview***

Diarrhoeal disease is estimated to account for 8.2% (6.6 - 9.8%) of disability adjusted life years (DALYs) in Sub-Saharan Africa, and 6.5% (4.7 - 8.8%) of DALYs in Kenya, specifically, with 83% (67 - 93%) attributed to unsafe water sources (IHME, 2020). Although substantial improvements[1] have been achieved, it continues to be among the top three causes of health loss in the country, after HIV/AIDS and lower respiratory infections (GBD Collaborators, 2020). In Kitui County specifically, diarrhoeal disease is estimated to account for 7.8% (4.6 - 12.8%) of DALYs, with 85% (69 - 94%) attributed to unsafe water sources (IHME, 2020). In 2015/16 when the household budget survey was conducted, 18% of the population in Kitui County were sick or injured, slightly less than the national average of 19%. Of those who reported being sick, illness was attributed[2] to malaria (37%), upper respiratory infection (14%), headache (11%), diarrhoea (9%), skin problems (5%), backache (5%), flu (4%), typhoid (3%), stomach problems (3%), lower respiratory infection (3%), vomiting (2%), dental problems (2%), blood pressure (2%), HIV/AIDS (0.4%), or something else (KNBS, 2018).

In the early stages of my research, I sought access to more specific health data from the Kenya District Health Information System (DHIS) database through the Ministry of Health in Kitui County, but I was unsuccessful after repeated information request attempts. The Kenyan DHIS was open access initially, but I was informed in meetings with Ministry of Health representatives in Nairobi that this was changed so that data must be requested from the Ministry to allow

[1] In Kenya between 2005 and 2016, premature deaths from HIV/AIDS, lower respiratory infections, and diarrheal disease reduced by 60%, 23%, and 30%, respectively (Frings et al., 2018). Between 2009 and 2019, they reduced by 42%, 5%, and 30% (IHME, 2021).

[2] Diagnosis was by a health worker in only 15% of cases, most respondents reported diagnosis by a traditional healer (44%) or herbalist (22%) (KNBS, 2018).

them to track data use better. I was also told by public health officers in Kitui County that multiple data quality issues, related to collection and input of data to the DHIS, prevented reliable sub-county trend or comparative analyses, at which point I decided not to further pursue access.

## 3.2 Water Safety Monitoring Programme Design

The monitoring programme commenced in December 2018, with visits to sampling sites conducted monthly throughout 2019. In 2020, monitoring continued on a quarterly basis for a subset of sites (only the equipped water supplies that were registered for maintenance services with FundiFix). This section explains how I selected sites for water safety monitoring and set up a fit-for-purpose lab to support water quality analysis. It also provides an overview of the protocols that were implemented for microbial and chemical water quality testing and sanitary inspections. Further protocol details are provided in Appendix D for the water quality sampling and Appendix E for the sanitary inspections.

### 3.2.1 Monitoring Site Selection

In November 2018, I worked with FundiFix (especially Peter Musili, Annastacia Kalee, and Cliff Nyaga) to select sites for water safety monitoring. Since the monitoring activities were intended to inform further work, the selection process balanced multiple priorities to support both a focused view on data uncertainty and a wider view to capture perspectives on water safety from different stakeholder groups. A key aim was to capture the variety of supply arrangements in Mwingi North including:

- Water source type: deep groundwater, shallow groundwater, surface water, or rainwater.

- Water distribution arrangements: piped networks, handpumps, or direct scooping / drawing. I selected a larger sample size of equipped supplies because they are associated with higher service levels (in the UNICEF-WHO Joint Monitoring Programme drinking-water service ladder[1]). A smaller sample size of earth dam and open well sites where water is drawn directly was included to allow comparison with contamination at surface water and unimproved points of collection (PoCs).

- Water treatment arrangements: chlorination, reverse osmosis filtration, or no treatment.

- Water management arrangements: community-based management (CBM), school or health facility management, a combination of community-based and facility management, private 'self-supply' management, FWSP management, or unmanaged public access.

- Water supply maintenance arrangements: registered for maintenance services with FundiFix or not.

Given the long distances between water supplies, sites were selected in eighteen cluster arrangements (based on feasibility of sampling all sites in a cluster within a day) so that all sites could be sampled within a month. Rather than using geolocations to determine the clusters, they were mapped through an exercise with the FundiFix maintenance team, who understand the road networks and water management arrangements in the area and were able to judge the feasibility of the clusters. Timing estimates had to account for the widely varying conditions of different roads and the operating schedules of the water points (many of which are locked except during specific hours so each sampling visit required coordination with the management to gain access).

A total of 87 sampling points were selected including 79 PoCs and eight restricted access source sites for reservoirs and boreholes (Figure 3.8). The full list of sites is provided in Appendix F. Groundwater was sampled from 12 handpumps and 25 piped schemes. Multiple sites were sampled for most of the piped

[1] https://washdata.org/monitoring/drinking-water

schemes including four boreholes with direct access junctions and 52 PoCs (ten of which were mixed tanks containing both groundwater and rainwater from roof catchment schemes). Surface water and shallow unprotected open wells were expected to have consistently high microbial contamination and consistently low concentration of geogenic contaminants, so fewer sites were selected: three earth dams, five open wells, and four piped surface water schemes (including the formal water service provider network that ends in Kyuso). Again, multiple sites were sampled for the piped schemes including four restricted access reservoir sites and seven PoCs. Only six PoCs served treated water – four by chlorination and two by reverse osmosis filtration.

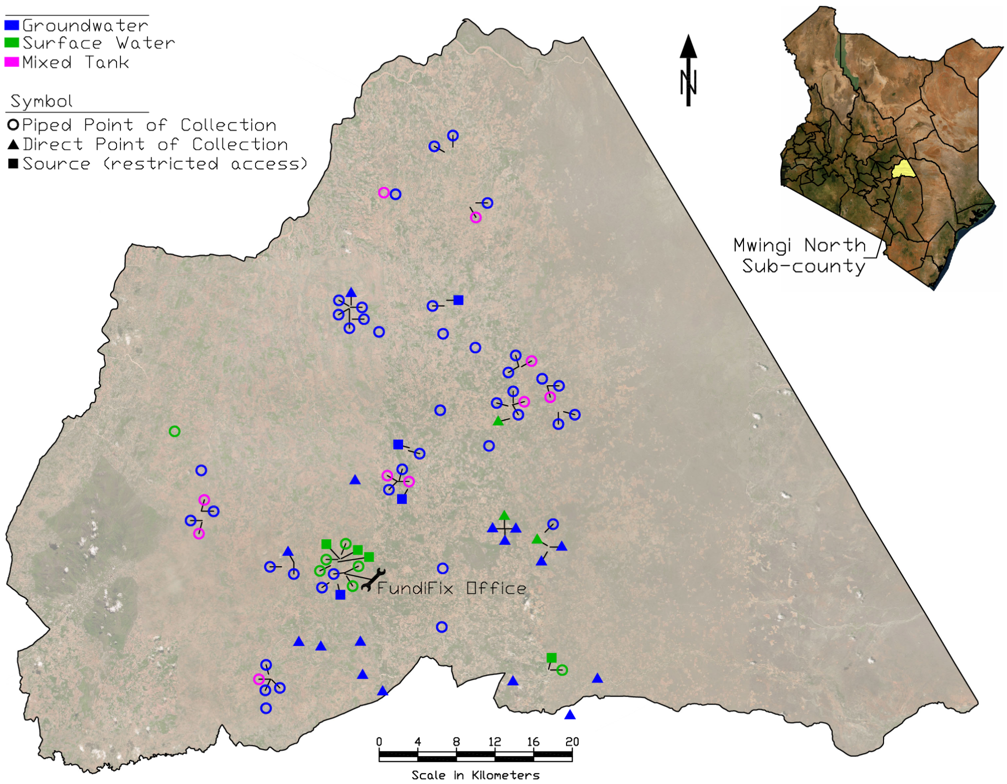



**Figure 3.8:** Map of the water quality monitoring sites including 79 points of collection and 8 restricted access source water sites.

The selected sites correspond with management by thirty CBM committees, twenty facility-based administration structures (seventeen schools, three health facilities), and six private owners of self-supply infrastructure. Just over two-thirds (70%) of the equipped water supplies were registered with FundiFix for maintenance services at the start of the programme. The others were chosen to include perspectives from LWMs that had not decided to engage with the maintenance service.

### 3.2.2 Establishing a Fit-for-Purpose Laboratory

Before commencing the monitoring, in November 2018, I worked with FundiFix to establish a fit-for-purpose laboratory in Kyuso. The lab is adjacent to the FundiFix office and is outfitted with customized work benches and shelving that were made in Kyuso, a fridge and freezer, two small incubators, and a solar-charged battery back-up system to ensure consistent power supply (multi-day power outages are common in Kyuso especially in periods of heavy rainfall). During this period, I also interviewed, hired, and trained Mary Musenya Sammy and Martin Mbogo Mwaniki to manage the lab and carry out the water quality testing and sanitary inspection activities for the monitoring programme[1].

Most of the water quality testing equipment for the lab was sourced from outside of Kenya (from manufacturers including Hach, Boekel Scientific, Hanna Instruments, Chelsea Technologies Group, and IDEXX). Most of the consumable lab supplies were purchased in Nairobi through Kenyan distributors of Hach, Hanna, and IDEXX products or general chemistry suppliers. These include reagents for the various water quality tests, standards for calibrating probes, disinfectants including bleach and ethanol, and deionised and distilled water for quality assurance testing).

[1]In carrying out the monitoring, they were positioned as FundiFix staff but, as elaborated in Section 3.8, the water quality monitoring programme was presented to LWMs as a trial-based research activity not a contracted FundiFix service.

*Before and after photos of the laboratory. Mary Musenya Sammy and Martin Mbogo Mwaniki are pictured in the bottom right image.*

### 3.2.3 Water Quality Measurement

The aim of the monitoring programme was to sample each of the 79 water collection sites monthly in 2019, with continuing quarterly sampling in 2020 for the equipped sites that were registered for maintenance services with FundiFix (45 sites). This would have generated a total of 1128 site visits. In reality, a total of 1078 sampling visits were completed successfully. Missing data are due to sampling being prevented by breakdowns (52%); PoCs being closed usually due to water users moving to surface sources during wet periods(14%); PoCs closing due to school holidays (11%); PoCs drying out (11%); broken piped connections (9%); no power for pumping (3%) or impassable roads (1%).

Water quality parameters were selected for routine monitoring based on my research aims and literature review (Section 2.1) and following document review and meetings with the Kitui Ministry of Water to identify key contaminants of concern for the area (Section 3.1). The following subsections provide details of the chemical and microbial water quality measurement methods and my data management process.

***Chemistry Assessment***

Specific electrical conductivity, temperature, and turbidity were routinely measured during site visits using a Hach multimeter (HQ 40D) with a conductivity (CDC40101) probe and a Hanna turbidimeter (HI93703). Fluoride and pH were also routinely measured but not on site. During the site visits, samples were collected in amber glass bottles and transported to the lab for same-day analysis using plastic beakers and the Hach multimeter (HQ 40D) with an ion-selective electrode probe for fluoride (ISEF12101) and a pH probe (PHC10101). Fluoride and pH were measured in the lab rather than in the field due to the optimal storage requirements of the probes and the need for pre-analysis steps (stabilising temperature and adding ionic strength adjustment powder to buffer the pH of the sample between 5 and 5.5 to avoid interference from hydroxyl ions in the fluoride measurement).

The turbidimeter and the probes were calibrated weekly, and duplicate samples and deionised water field blanks were analysed each week for fluoride. The blank measurements ranged from $<0.01$ to 0.4 ppm (mean = 0.07 ppm) and the median relative percent difference of the duplicates was 0.6%. Details of the sampling, analysis, and quality control protocols can be found in Appendix D.

In addition to the routine analyses, samples were collected in July and August 2019 for major ion (chloride, nitrate, nitrite, sulfate, bromide, fluoride, phosphate, potassium, sodium, calcium, and magnesium) and trace element (e.g. aluminium, manganese, selenium, uranium, etc.) analysis. This was done to screen for potential contaminants besides fluoride and to provide insight into the contribution of different ions to the conductivity measurements. Samples were collected in 15 mL metal-free tubes following filtration (by syringe with 0.22 $\mu$m filter tips to remove non-dissolved constituents), stored in the fridge, and transported back to the laboratory at the School of Geography and the Environment (SOGE) in Oxford. With support from the SOGE lab manager (Mona Edwards) and trace elements analysis technician (Jack Longman), I diluted and acidified[1] (the trace elements samples only) the samples according to standard protocol to prepare them for analysis of major ions by ion chromatography (Dionex ICS-5000 chromatograph) and trace elements by inductively-coupled plasma mass spectrometry (ICP-MS) using a PerkinElmer NexION 2000 ICP mass spectrometer. The samples were analysed within three months of being collected.

*The turbidimeter in use in the field and the spectrometer autosampler in Oxford.*

The dry-season period was chosen for the in-depth chemistry sampling because this is when groundwater is used most extensively in Kitui (as surface water becomes scarce) and the water chemistry is expected to become more concentrated (less dilution from rain), representing a potential worst-case period for exposure to geogenic contaminants. A second round of sampling for major ion

[1]The 0.22 $\mu$m filtration removes particulates and microbial organisms so the samples would be sufficiently inert, especially with cold storage. I would have preferred to acidify the samples in the field for additional preservation assurance but I was not able to source ultra-pure, 'trace metal grade' nitric acid in Kenya despite exploring options through the University of Nairobi and a commercial geochemistry lab, and I could not travel with it in my luggage.

and trace element analysis was conducted by Musenya and Martin in February and March 2020 with the intention of producing a second data set for comparison, but COVID-19 complications made it infeasible to transport the samples to the lab for analysis. The cost of having the analysis done at a commercial lab in Kenya was not justifiable given that this data is not a central focus of my research.

#### ***Microbial Assessment***

The fit-for-purpose lab in Kyuso also supported analysis of *Escherichia coli* and total coliforms, which were measured using an IDEXX Quanti-Tray system (including a quanti-tray sealer, incubator, and ultraviolet lamp viewing cabinet). The system enables quantification of *E. coli* and total coliform bacteria by the most probable number (MPN) approach using Colilert-18 growth medium[1]. I selected it because it is fast and easy to implement, less subjective than colony forming unit (CFU) count approaches, and more statistically robust than other MPN approaches that use fewer compartments (the quanti-tray method uses 97 compartments whereas most compartment bag test methods use between two and five) (Rompré et al., 2002; Stauber et al., 2014). Colilert-18 also comes with a quality control certificate that is ISO 11133:20004 compliant, which is useful for communicating the credibility of the test results. It is worth noting, however, that the quanti-tray method generates more plastic waste than other alternatives[2].

During site visits, the samples for bacterial analysis were collected following

[1] Colilert-18 contains two nutrient indicators: o-nitrophenyl-$\beta$-D-galactopyranoside (ONPG) and 4-methylumbeilliferyl-$\beta$-D-glucuronide (MUG). Under incubation at 35°C, total coliforms readily metabolise ONPG using $\beta$-galactosidase enzymes, producing a yellow colour in the process that signals their presence. *E. coli*, specifically, can also metabolise MUG using $\beta$-glucuronidase enzymes (which other types of coliforms do not produce), producing a fluorescent compound that can be seen under an ultraviolet lamp.

[2] For operations that do not have a research component, especially where data resolution above 100 MPN/mL is unnecessary, membrane filtration or simpler MPN methods may be preferable when waste management is considered.

standard guidance (APHA et al., 2018; BSI, 2006). Samples were collected in sterile 100 mL bottles with sodium thiosulphate to neutralise potential residual chlorine. Flame disinfection was used on taps and handpump spouts (taps with plastic components were disinfected with ethanol wipe only) and approximately twenty litres of water was pumped or flushed prior to taking a sample. Samples were transported back to the field lab in a cooler box with ice packs and processed for incubation immediately. Sampling times and incubation start and end times were recorded. Samples were normally processed within 6 hours of collection in keeping with standard protocol. Duplicate samples and distilled water field blanks were analysed weekly. All blanks were *E. coli* negative, and the *E. coli* duplicates had a median relative percent difference of 10% with 92% of pairs indicating the same WHO risk category (WHO, 2017a).

In addition to the lab-based bacterial quantification work, effort was made to assess microbial water quality through on site measurements of tryptophan-like fluorescence (TLF). TLF was measured during the site visits using a UviLux probe manufactured by the Chelsea Technologies Group (CTG). Sampling was done according to a protocol that I helped develop (during earlier fieldwork prior to my DPhil) for the UviLux probes in collaboration with researchers from the British Geological Survey (J. Ward et al., 2018). A colored dissolved organic matter (CDOM) probe was used alongside the TLF probe to track concentrations of humic substances, which complicate interpretations of TLF measurements (Nowicki et al., 2019). Blank samples and duplicates were also conducted for TLF on a weekly basis. Further details of the sampling, analysis, and quality control protocols for the bacterial quantification and TLF measurement work can be found in Appendix D.

*E. coli sample collection and rinsing the UviLux probes.*

*Adding Colilert-18 to a sample and feeding a quanti-tray through the sealer.*

### *Data Management*

Musenya and Martin recorded the field and laboratory water quality measurements in notebooks. At the end of each week, they digitised the data using a password-protected Excel template that I provided. On a weekly basis, I reviewed the data (checking for calibration results, duplicate and blank sample results, outlier measurements, and missing data) and followed-up with them for clarifications and any quality assurance concerns (through email, with WhatsApp calls for additional clarification when necessary). When the data were confirmed, I uploaded them into a relational Access database (Figure 3.9). All subsequent data analysis was conducted using R Studio, in which I wrote a script to import data directly from the Access database.

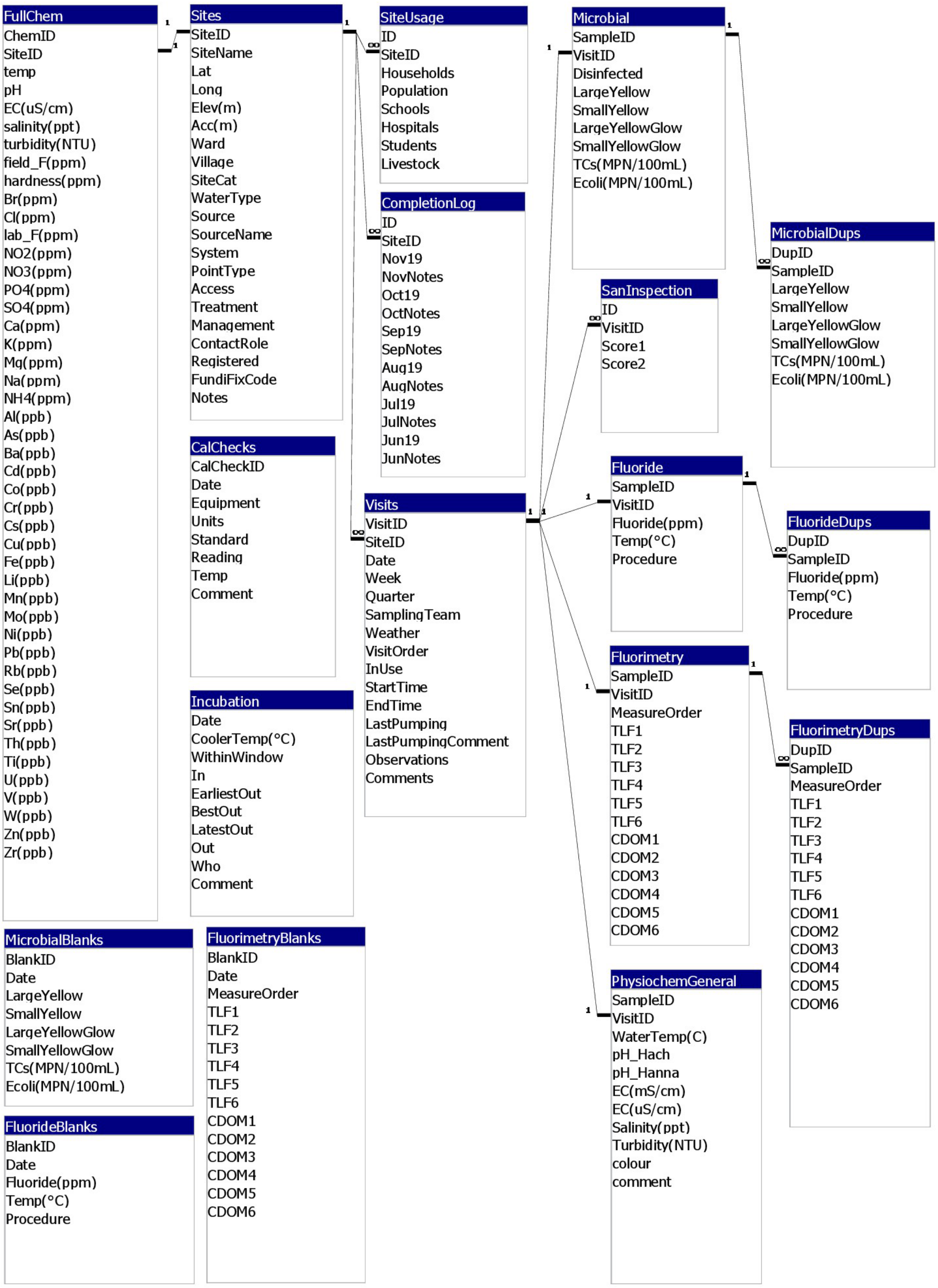


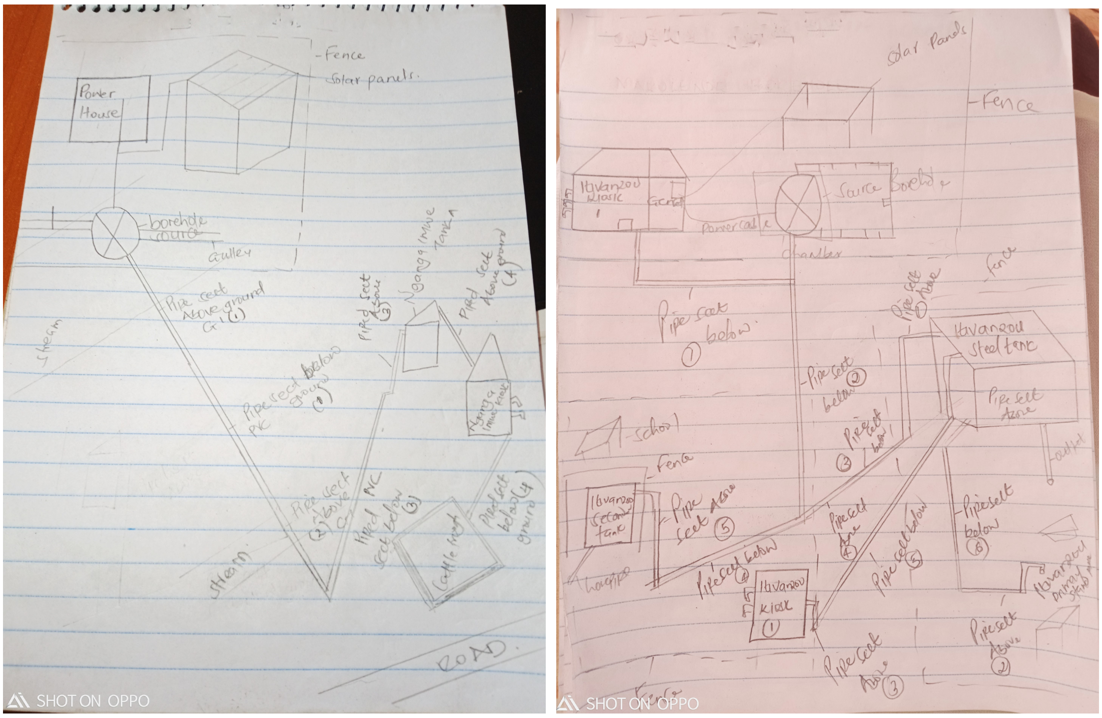

**Figure 3.9:** Relationship report from the monitoring programme Access database.

### 3.2.4 Sanitary Inspections

Sanitary inspections (SIs) were conducted during site visits, with protocols developed based on the WHO guidance and adapted to the local context as is recommended (WHO, 1997). SI was approached as "a fact-finding activity that should identify system deficiencies – not only sources of actual contamination but also inadequacies and lack of integrity in the system that could lead to contamination" (WHO, 1997, p44). The SI protocol included three phases: scheme mapping, vulnerability identification, and scoring (Appendix E). I developed it with input from my supervisor and feedback from FundiFix, and it was refined through a week of piloting.

As part of the mapping phase, an inventory of components was compiled for each water supply scheme with parts and materials listed, GPS locations recorded, and sketches of each scheme drawn out for visualisation. For the second phase, inspection guides were set up in an Ona Systems mobile survey form so that Musenya and Martin could record the results through their phones and share the data with me without an intermediary digitisation step. The form included steps to attach photos of each identified vulnerability, which I used for quality assurance checks to confirm accuracy and consistency between inspections.

I used the data to calculate SI scores for each point of collection. Two scores were calculated: the first considering only vulnerabilities, the second including discounting based on safety measures (Appendix E). No attempt was made to prioritise the relative importance of different vulnerabilities because there is insufficient evidence to justify a weighting scheme (Daniel, Gaicugi, et al., 2020; Pond et al., 2020). The scores were calculated to facilitate a comparison between SI results and *E. coli* variability, an objective that was informed by my literature review (Section 2.1). The SI scores were not communicated to LWMs – instead system vulnerabilities were discussed with them directly (Section 3.5).




*Examples of water supply scheme drawings used in the initial mapping phase for the sanitary inspection work.*

*Examples of photographs taken through the SI survey form showing vulnerability from livestock use and ponding due to a broken trough.*

The vulnerabilities in water supply schemes generally vary at a slower rate than water quality parameters, and given the time demands of these comprehensive inspections, they were not conducted on every site visit. For each scheme, inspections were conducted two to four times, capturing conditions at least once in a dry period and a wet period. The inspections provided a baseline understanding of scheme conditions and communication with LWMs signalled when conditions had changed (e.g. fence repaired, tank developed a leak, pipe blockage or breakage, damage to any system components from flooding, etc.).

## 3.3 Isolating and Sequencing *E. coli*

As discussed in my literature review (Section 2.1.2), links between faecal contamination and occurrence of *E. coli* in water supplies may be obscured to an unknown extent by naturalised *E. coli* populations. This introduces important uncertainty into the use of *E. coli* in rural drinking-water monitoring, but advancements in DNA sequencing capabilities present an opportunity for research to better understand the origins and behaviours of *E. coli* in water supplies. In this section, I explain how I selected methods and developed a protocol to a) isolate *E. coli* from some of the water supplies that were included in the water safety monitoring programme and b) extract and sequence their genomes.

### 3.3.1 Selecting a Sequencing Approach

Meta-analysis is a powerful tool to distinguish genetic differences in the bacterial populations of different environments by leveraging large sample sizes. For example, a meta-analysis of research from Australia was able to associate different genetic backgrounds of *E. coli* with specific habitats by analysing sequencing data from more than 5000 (mostly) non-clinical *E. coli* isolates (Touchon et al., 2020). Such a meta-analysis is not yet possible for Kenya, however, nor the African continent more broadly, because genetic studies of non-clinical *E. coli*, especially *E. coli* isolated from water supplies, are sparse[1] (Zhou et al., 2020).

[1]There is limited information on the genetic background of *E. coli* sampled from the environment in Kenya. As of May 2020, 80% of the 1654 Kenyan *E. coli* genome sequences in the Enterobase database were from human clinical samples, livestock, or food; 13% were sampled from wild animals; 6% from soil or household surfaces; and just over 1% from water (Zhou et al., 2020).

Consequently, a meta-analytical approach was not suitable for my research to better understand the occurrence of *E. coli* in rural drinking-water. Instead, I considered DNA methods that could be used to conduct primary research at sub-organism level (investigating biomarkers, gene fragments that are associated with particular organisms or functionalities), organism level (investigating whole genomes to characterise likely origins and behaviour), or supra-organism level (using a metagenomic[1] approach to investigate the relationships between *E. coli* and other microbial life in water supply microbiomes[2]). Considering each option as described below, I determined that an organism-level focus best served the aims of this thesis.

Although the search for biomarkers has been ongoing for years (Khatib et al., 2002), there are no known biomarkers that can definitively distinguish whether an *E. coli* isolate[3] comes from a naturalised population or human or animal faecal matter (Devane et al., 2020). Some studies have attempted to specify and work with enteric versus environmental indicator genes (e.g. Julian et al., 2015) or more commonly to differentiate animal versus human sources (Gomi et al., 2014; Warish et al., 2015; Zhi et al., 2015) and predictive genomics software platforms have been developed to support these efforts (Whiteside et al., 2016). Nevertheless, the source specificity of potential markers remains equivocal and context-specific and it is unknown whether "environmentally-associated [*E. coli*] strains have the ability to switch between their environmental reservoirs and the enteric environment by expressing genes required for either lifestyle" (Devane et al., 2020, p18).

Ruling out the use of biomarkers, I considered a metagenomic approach to concurrently assess the occurrence of *E. coli* and microbial pathogens in wa-

[1]Metagenomics is the study of genetic material sampled directly from the environment with no intermediate culturing or isolation steps.

[2]Microbiomes consists of all the microorganisms, or alternatively the combined genetic material of all the microorganisms, in an environment

[3]In microbiology, isolates are individuals or strains that are separated from a mixed population of microbes so that they can be studied.

ter samples. The emergence of a new paradigm in DNA sequencing (nanopore sequencing) has lowered barriers to examining and understanding microbiomes. Application of nanopore technology has increased capacity for rapid sequencing with increased read lengths and real-time analysis (Greninger et al., 2015), which is well-suited to the high throughput requirements of microbiome analysis (Edwards et al., 2016). Oxford Nanopore Technologies (ONT) produce a portable device called 'MinION' that enables sequencing of DNA in some field conditions (Jain et al., 2016). At only four inches long and weighing less than 100 g, the MinION is powered through a USB laptop connection. It works by measuring changes in electrical current, which reveal the nucleotide sequence as DNA passes through a biological protein nanopore. ONT's devices have been used for epidemiological applications dealing with both viruses (Hoenen et al., 2016; Quick et al., 2016) and bacteria (Quick et al., 2015), and have been applauded for opening a new frontier in citizen science (Krol, 2015).

The key challenges that I foresaw with using the MinION device for DNA sequencing relate to collection and preparation of samples. At the time that I was selecting methods for my research, there were no published studies that used the MinION sequencer to investigate microbial communities in water supplies. However, I was able to speak with Jack van de Vossenberg, a microbiologist from the IHE Delft Institute for Water Education, who had access to MinION devices through ONT's early access programme. His team investigated viruses in urban groundwater in Ghana, Uganda, and Tanzania. They found sample preparation and analysis was challenging under field conditions due to equipment and reagent requirements. Capabilities of the MinION device had advanced in the two years since they undertook their fieldwork, and a rapid sequencing preparation kit had been developed, removing the need for a lot of specialised equipment. Cold-chain requirements for the MinION devices and other reagents, however, continued to present challenges for sequencing at remote field sites. When I was planning my fieldwork, even getting nanopore sequencing supplies reliably through customs to the best equipped microbiology labs in Kenya was proving prohibitively difficult (personal communication from the DNA sequencing lab manager at the Kenya Medical Research Institute facilities in Kilifi, Kenya).

Additionally, the rapid sequencing preparation protocol does not include an amplification step. This has advantages for speed and interpreting the distribution of different organisms in a sample, but the key drawback is that without amplification it is difficult to detect organisms that are present in low concentrations. This is particularly a concern for viral pathogens that have low infectious doses. Dr. van de Vossenberg's team had to filter samples of 100 L to obtain a sufficient quantity of viral genetic material (which made up only 5% of the total genetic material that they recovered). Achieving such large volume samples is logistically difficult and would considerable lower the acceptability of my study for the communities whose water supplies I wished to sample, given the time implications and scarcity of water in the study area. Without visibility of viral pathogens, the suitability of a microbiome study to address my research aims is substantially undercut. Consequently, and due to wider concerns about fieldwork and supply chain practicalities. I decided to pursue a different approach.

I decided to use whole genome sequencing (WGS) to focus on *E. coli* strains at water collection points and in household stored water. For WGS, nanopore sequencing is at a disadvantage because it produces lower sequence quality scores than the established next-generation sequencing (NGS) approach (communication from the instructor on the ONT training course I attended). Nanopore sequencing is generally recommended for establishing the scaffolding of a genome that is then further developed through higher-accuracy sequencing using NGS. For my research, the additional advantage of including nanopore sequencing for scaffolding prior to NGS was not worth the cost, especially considering the logistical difficulties of transporting the MinION flow cells to Kenya without compromising them. I decided, therefore, to exclusively use NGS. Specifically, I used the Illumina MiSeq platform, which is highly regarded for analysis of genetic material from environmental samples, including water samples in particular (Tan et al., 2015). In the subsequent sections, I provide the details of how I used NGS after explaining my site selection and sampling protocol.

### 3.3.2 Site Selection

After monitoring had been conducted for seven months, I chose nine water supplies to sample for the *E. coli* sequencing study. I sampled a total of 44 sites, including fourteen points of collection (PoCs) and thirty points of use (PoUs). Since my choice of PoC sites was partly informed by the monitoring results, details of the selection are presented in Chapter 5 following the overview of monitoring results in Chapter 4. The sampling for *E. coli* isolates was conducted between July $18^{th}$ and August $2^{nd}$, 2019, which is dry season in Kitui (see the 2019 daily precipitation measurements in Figure 3.5, Section 3.1.2). This timing was chosen to control for rain events, which would differentially impact the quality of PoC water versus PoU water that was stored for multiple days.

### 3.3.3 Sampling Protocol

I collected two samples at each PoC or PoU site in sterile 100 mL Whirl-pak bags with sodium thiosulphate to neutralise residual chlorine. At the PoCs, taps and handpump spouts were disinfected by flame and at least 20 L of water was pumped or flushed prior to sample collection. Samples were transported in a cooler box with ice-packs to the Kyuso lab where they underwent membrane filtration.

Based on previous *E. coli* monitoring results, I used multiple dilutions for each site to maximise the chance of growing well-isolated colonies. Following filtration, the samples were incubated with m-ColiBlue24 broth (EPA Approved Hach Co. 10029 method), which indicates *E. coli* colonies by blue colouration resulting from hydrolysis of 5-bromo-4-chloro-3-indolyl-$\beta$-D-glucuronide (BCIG). In all cases, the time between sample collection and filtration was less than six hours. Between filtration and incubation, the samples had resuscitation time of one to four hours.

Samples were incubated at 44.5°C for 18-24 hours. I chose the incubation temperature to discourage growth of non-thermotolerant coliforms and improve isolation of *E. coli* colonies. I considered that incubation at 44.5°C could disadvantage naturalised *E. coli*, but studies have shown that although environmental strains grow better than enteric strains at low temperatures, their maximal growth rate and optimal temperature for growth are not distinct from enteric strains (Ingle et al., 2011; Matthews & Tung, 2014).

I selected up to six colonies per site for streaking on agar plates (ReadyPlate CHROM Chromocult Coliform Agar ISO 9308-1:2014), which inhibit growth of non-coliforms and distinguish *E. coli* based on $\beta$-glucuronidase activity. The plates were incubated at 37.5°C for 18-24 hours. To increase the likelihood of selecting single strain *E. coli* colonies, I selected colonies that were well isolated and consistent in colour and morphology.

The goal was to select six colonies per site, although this was not possible in a few sites that had low *E. coli* concentrations. With six colonies selected, a strain that composes 25% of the population of *E. coli* in the sample is 80% likely to be selected at least once. Increasing the number of selected colonies gives diminishing returns in terms of the likelihood of sampling at least one isolate of a strain with a given prevalence (Figure 3.10).

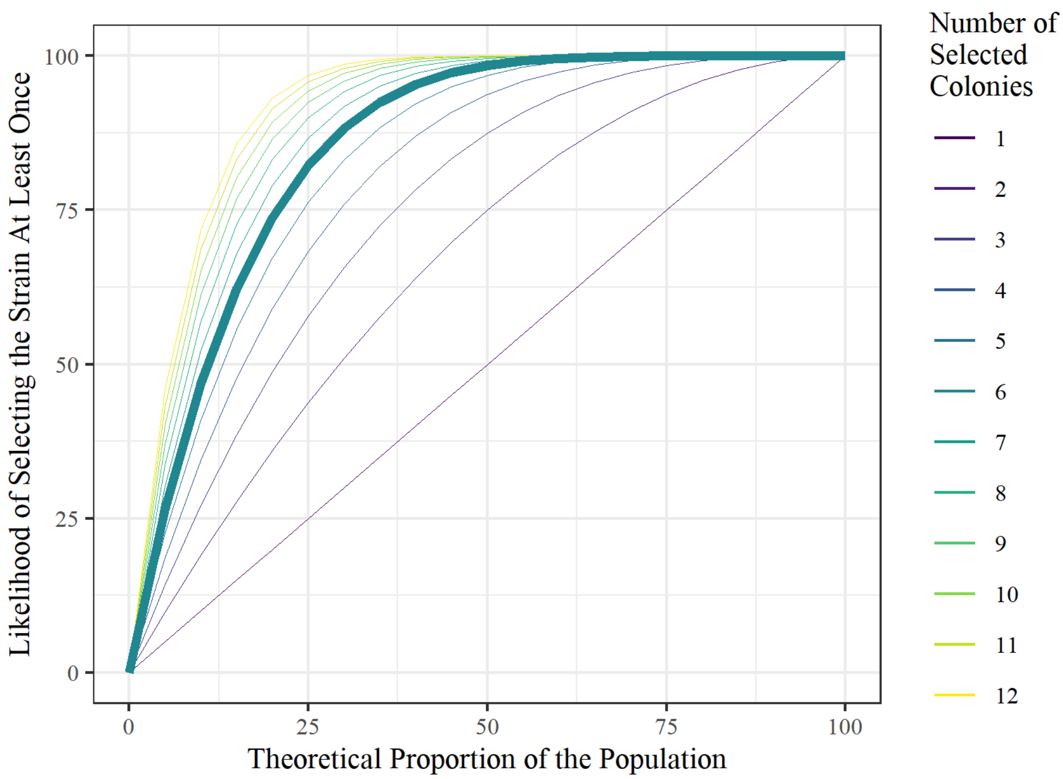



**Figure 3.10:** Likelihood of strain selection given number of selected colonies and strain prevalence.

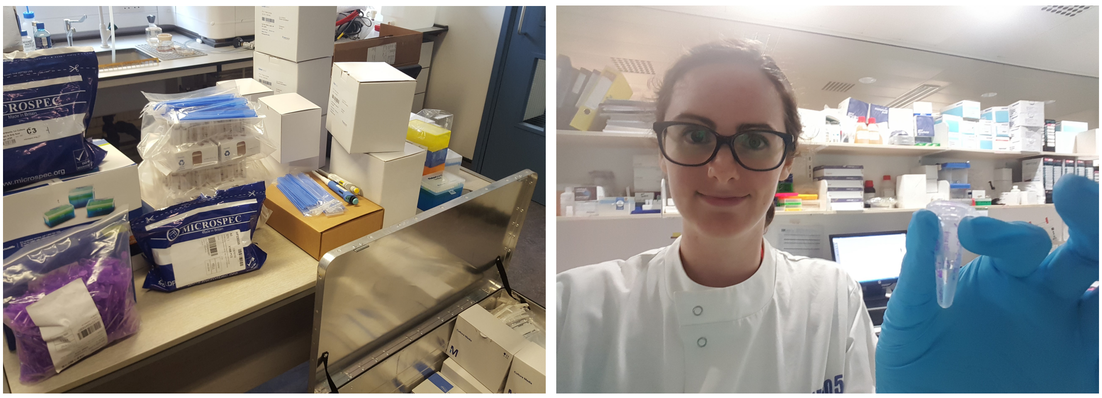
Two key factors constrained my total sample size: 1) I was limited to sampling one set of sites (water supply and associated PoUs) per day because of the long distances between sites and the need to walk to many of the homesteads for collecting PoU samples, and 2) the Kyuso lab was not equipped for freezing samples nor doing clean DNA extractions, thus limiting the window of time available to me before samples had to be transported to a better-equipped lab to proceed with DNA extraction.

Following incubation, I scraped the *E. coli* growth from the agar with a sterile inoculation loop, taking care to minimise inclusion of agar and off-colour growth (pink growth observed in 12% of samples and colourless growth in 3% of samples). I mixed the *E. coli* growth into 1 mL of DNA Shield (Zymo Research R1100) for preservation in a sterile microcentrifuge tube. The tubes were stored in a fridge before I flew with them to the Kenya Medical Research Institute (KEMRI) lab in Kilifi, Kenya.

### 3.3.4 DNA Extraction and Sequencing

With the help of a sequencing specialist at the KEMRI lab, Zaydah deLaurent, I completed the DNA extractions within one to three weeks of the date of sampling using a Zymo Research Quick-DNA Mini-prep kit. I adjusted the recommended protocol for monolayer cells to suit *E. coli* that is already lysed by preservation in DNA Shield. Thus, we combined 175 $\mu$L of sample lysate with 525 $\mu$L of genomic lysis buffer and then proceeded with the monolayer cell protocol as recommended by Zymo Research.

Samples were normalised to 5 ng following DNA quantification using a Qubit dsDNA HS Assay Kit and Qubit 3.0 Fluorometer (Life Technologies). We proceeded to library preparation with Illumina Nextera XT DNA Sample Preparation kit as per manufacturer instructions with half reaction alteration. Following tagmentation and indexing, we did a size selection bead clean-up using 0.6x AMPure XP beads (Beckman Coulter) to select for >500 bp fragments. The libraries were then quantified using Qubit and fragment size distribution was determined on a 2100 Bioanalyser using the High Sensitivity DNA Kit (Agilent Technologies). We proceeded to manual normalization bringing all samples to 2 nm and thereafter pooling the libraries.



*Packing sampling and culturing supplies in Oxford before travelling to Kenya and holding a micro-centrifuge tube containing the pooled libraries from half of my samples.*

The pooled libraries were then denatured, spiked with 8% Phix, and run on an Illumina MiSeq platform using the 600 cycles v3 reagent kit with an output of 2 x 200 bp. We did two runs, with 59 libraries pooled in the first run and 68 in the second. One library that was poor quality in the first run, was sequenced again in the second. The full protocol and equipment list for the DNA sampling, extraction, and sequencing work is provided in Appendix G.

### 3.3.5 Bioinformatics

As covered in my explanation of selecting a sequencing approach, there are no known biomarkers that can definitively distinguish whether an *E. coli* isolate comes from a naturalised population or other source (Devane et al., 2020). So I used multiple characteristics including phylogroup, sequence type, allelic diversity, and presence of virulence and antibiotic resistance genes as suggestive evidence of likely isolate origins. I chose the Nullarbor pipeline to process the sequencing reads (Seemann et al., n.d.) and two bioinformaticians (Etienne de Villiers and George Githinji) helped me to run the analysis on the high-performance computing cluster at the KEMRI lab.

Reads were filtered and trimmed using Trimmomatic (Bolger et al., 2014) and only reads that were >100 bp with PHRED quality score >20 were retained. Kraken2 was used for species identification (Wood & Salzberg, 2014) and SPAdes v3.13.1 was used for de novo genome assembly (Bankevich et al., 2012).

The assembled genomes were assigned as *E. coli* sensu stricto (phylogroups A, B1, B2, C, D, F, E, or G), *Escherichia* cryptic clades I-V, *E. fergusonii*, or *E. albertii* using the ClermonTyping in silico approach based on standard polymerase chain reaction (PCR) assays and Mash genome distance estimation (Beghain et al., 2018; Clermont et al., 2019). The threshold for minimal nucleotides for a contig to be included in the analysis was set at 100.

Twelve of the assembled genomes were overlarge (ranging from 5.8 to 11.9 Mbp) so, suspecting chimeric genomes, we conducted Benchmarking Universal Single-Copy Ortholog (BUSCO) assessment (Simão et al., 2015; Waterhouse et al., 2013) to check the assembled genomes for completeness and duplication.

For the non-chimeric genomes, we used Roary (Page et al., 2015) for pan-genome analysis. With Roary, genes that are present once in every isolate are combined in a multiple FASTA[1] alignment, enabling phylogenetic tree construction from the core genes. We used FastTree version 2.1.10 SSE3 (M. Price et al., 2010), with generalised time reversible model for nucleotide alignment, to construct an approximately-maximum-likelihood phylogenetic tree. To compare the strains from my samples with the wider diversity of *Escherichia spp.*, I also selected 14 strains from the ClemonTyping Mash database (Beghain et al., 2018) to include in the analysis. I used GrapeTree (Zhou et al., 2018) to visualise the tree including metadata.

The multi-locus sequence typing was also done through Nullarbor using the PubMLST database, and virulence and antimicrobial resistance (AMR) gene identification was done using the Abricate package (Seemann, n.d.) by screening contigs against the Virulence Factor Database (VFDB) (Chen et al., 2016) and NCBI AMRFinderPlus database (Feldgarden et al., 2019), respectively.

For multi-locus sequence typing, I chose to use the Achtman MLST scheme (Wirth et al., 2006), which uses genes *adk*, *fumC*, *gyrB*, *icd*, *mdh*, *purA*, and *recA*, because it is most congruent with an established phylogeny for *E. coli* that is based on whole genome sequencing (Sahl et al., 2012). In addition to the Nullarbor typing, I also ran the raw sequencing reads through the MLST screening tool hosted by the Centre for Genomic Epidemiology (CGE) (Larsen et al., 2012) for confirmation of the allele identifications.

[1]The FASTA format is widely used in bioinformatics, it originated with the FASTA DNA sequence alignment software that was initially published in 1987.

### 3.3.6 Statistical Analysis

To investigate possible relationships between genetic diversity and sample source, I segregated the sampling sites into groups based on location (PoC or PoU) and *E. coli* concentrations (lower or higher) on the day that the isolates were sampled, as shown in Table 3.3. The cut-off between 'lower' or 'higher' was set at 50 CFU/100 mL to balance the number of isolates in each group as evenly as possible.

Focusing on the seven Achtman MLST scheme genes, I used an approach developed for estimating average population heterozygosity from a small number of individuals (Nei, 1978) by calculating the genetic diversity ($H$) of each group based on the diversity of alleles ($h_j$) as:

$$h_j = \left(1 - \Sigma p_i^2\right)\left(\frac{n}{n-1}\right)$$

where $p_i$ is the frequency of allele $i$ at locus $j$ and $n$ is the number of isolates. Genetic diversity ($H$) was then calculated as the average diversity of alleles using:

$$H = \frac{\Sigma h_j}{m}$$

where $m$ is the total number of loci. I assessed the significance of differences in the diversity of the groups using permutation tests derived from the Strasser-Weber framework for conditional inference procedures (Strasser & Weber, 1999) and performed using the 'coin' package in R version 3.6.1 (Hothorn et al., 2008). In doing so, I used the general independence test function with asymptotic null distribution as computed by the randomised quasi-Monte Carlo method (Genz & Bretz, 2009).

**Table 3.3:** Site groupings for allelic diversity analysis based on source type and concentration of *E. coli* on the day that isolates were sampled.

| **Groups** | **Sites Included in Each Group** | **Counts** | | | | ***E. coli* MPN/100mL** | | |
|---|---|---|---|---|---|---|---|---|
| | | **Sets** | **Samples** | **MLSTs** | **Isolates** | **Min** | **Med** | **Max** |
| All | all sites | 9 | 25 | 46 | 108* | 1 | 45 | 2420 |
| PoU | PoU sites | 7 | 15 | 30 | 59 | 1 | 16 | 2000 |
| PoC | PoC sites | 7 | 10 | 24 | 49 | 2 | 64 | 2420 |
| Higher | sites with *E. coli* >50 MPN / 100 mL | 9 | 11 | 26 | 57 | 50 | 460 | 2420 |
| Lower | sites with *E. coli* <50 MPN / 100 mL | 5 | 14 | 22 | 51 | 1 | 13 | 45 |
| PoU-H | S1C2U1, S2C1U1, S5C1U3, S7C1U1, S8C1U1, S8C1U2 | 5 | 6 | 15 | 31 | 50 | 125 | 2000 |
| PoU-L | S1C1U2, S2C1U2, S2C2U1, S2C2U2, S2C2U3, S3C1U3, S5C1U2, S6C1U1, S6C1U3 | 5 | 9 | 16 | 28 | 1 | 10 | 17 |
| PoC-H | S3C2, S4C2-A/B, S8C1, S9C1 | 4 | 5 | 14 | 26 | 84 | 1120 | 2420 |
| PoC-L | S1C1, S2C1, S2C2, S2C3, S6C1 | 3 | 5 | 10 | 23 | 2 | 42 | 45 |

*This includes 5 chimeric isolates that contained only one match for each MLST gene with perfect identity matches for each allele as explained in the sequencing results overview in Section 5.2.

## 3.4 Household Level Water Safety Perceptions

As discussed in my introductory chapter, this thesis engages with community level decision-making through water users (household level) and LWMs. The reviewed literature on water user behaviour change in response to water quality data cast doubt on the effectiveness of data sharing for motivating behavior change, specifically it highlighted a need for research with greater temporal scope and increased attention to contextual factors (Section 2.2). Thus, I determined that a baseline assessment of water user judgements of drinking water safety was warranted prior to contemplating an information intervention at household level. In conducting this assessment, I used data from cross-sectional and longitudinal surveys (Figure 3.11) and semi-structured interviews.

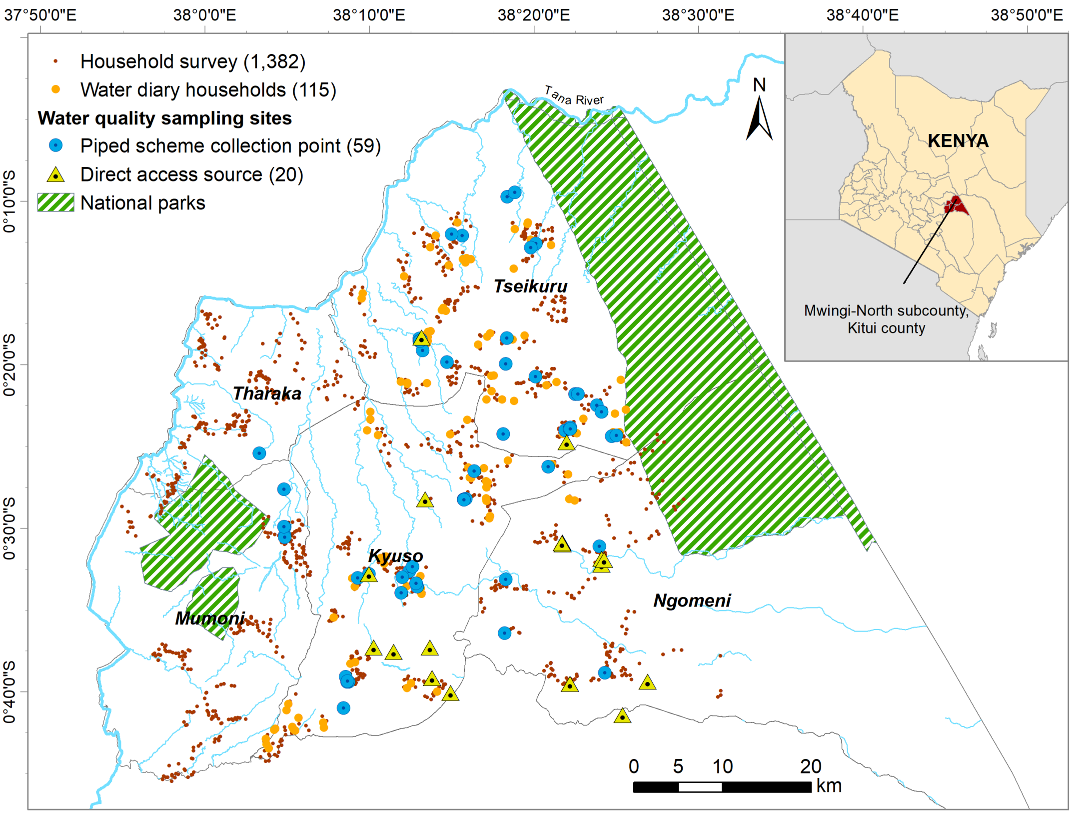



**Figure 3.11:** Map of surveyed households and sampled water points (created by Sonia Hoque). *The total sample size for the cross-sectional household survey was 1457 but GPS data were missing for 75 households, which are not depicted on the map. The water diary households are the subset from the cross-sectional survey that were included in the longitudinal work. The 79 point of collection sites from the water safety monitoring programme are also depicted (the eight restricted direct access sites are not shown).*

All of the data were generated through collaborative efforts of the REACH and USAID Sustainable Water Systems (SWS) Learning Partnership programmes with instruments designed to meet multiple objectives. The cross-sectional household survey collected data on indicators of multidimensional poverty, including domestic water services, and the questionnaire included a subsection that I wrote focusing on perceptions and decision-making around drinking water safety (Section 3.4.1).

Following the cross-sectional survey, households were selected to participate in a longitudinal study, which followed households over the course of a year by asking them to fill out diary forms to capture their daily water collection practices (Section 3.4.2). To complement the diaries, participants also responded to check-in surveys approximately twice monthly, providing information on water costs, water supply problems and interventions, as well as answering a short questionnaire that I designed to capture perceived changes in water quality, water treatment practices, and illness of household members.

I sought qualitative depth to complement the cross-sectional and longitudinal survey data from a series of semi-structured interviews and participant observation records, which were designed and carried out through the REACH programme by a team from the University of Nairobi to explore the diversity of water perceptions and interactions within communities, including which factors influence source selection (Section 3.4.3).

### 3.4.1 Cross-sectional Household Survey

Dates: 8 – 20 March, 2018

Participants: 1457 household representatives (71% household heads, 22% spouses of the household head, 6% other relatives). 60% were between 30 and 59 years old and 44% presented as female.

Sample selection: Households were selected by mapping all villages on a ten kilometer grid and randomly sampling forty households around each village. Households were selected for each of the five wards in Mwingi North sub-county (Figure 3.11), which have varying population densities (27% of households were from Kyuso, 27% from Tseikuru, 17% from Mumoni, 14% from Ngomeni, and 14% from Tharaka).

Data collection: The questionnaire is available via the UK Data Service ReShare online public repository (Katuva et al., 2021). In addition to questions about sourcing and affording water for domestic uses, it includes a subsection that I wrote focusing on perceptions and decision-making around drinking-water safety

– respondents were asked what they thought of the quality of their drinking-water, about the basis for their judgements, and whether they acted to improve the quality of the water they drink (through source selection, treatment, and storage practices). The questionnaire also asked about household concerns, enabling a comparison of water services concerns with other priorities like education, employment, and health care. Seventeen enumerators were locally recruited from each ward and trained on data collection, ethics, and code of conduct. Tablets and the Open Data Kit and Enketto mobile survey platforms were used.

Data quality: A pilot survey was conducted with households in Kyuso to refine the questionnaire and trouble-shoot technical problems. Data were digitized in the field so daily quality checks were done by the research leaders throughout the survey, with continuous feedback to enumerators. The final data were checked for consistency and coherence, with incomplete forms excluded from the cleaned data set.

### 3.4.2 Longitudinal Household Survey

Dates: August 2018 – July 2019

Participants: Representatives from 115 households completed 5826 diary weeks and 1241 check-in surveys (min 4, max 19, mean 11 surveys each). 78% of participants presented as female and the mean age was 45 years (SD = 15).

Sample selection: The sampling frame was restricted to Kyuso and Tseikuru wards for logistical efficiency and only considered households from the cross-sectional survey for which geolocations and phone numbers were available (n = 546). Households were allocated to one of six categories in a three-by-two matrix based on their wealth quartiles and main water supply concerns (poor and costly; poor and unsafe; non-poor and costly; non-poor and unsafe; poor and other; non-poor and other). Wealth quartiles were determined using an index calculated by principal component analysis of twenty-five variables under six dimensions including: 1. education, 2. durable assets, 3. consumable goods, 4. housing material, 5. cooking fuel, and 6. lighting fuel (as per Katuva et al., 2020). Households were grouped as poor or non-poor, where those belonging to the bottom two wealth quartiles were classified as poor. 'Water is costly' and 'Water is unsafe to drink' were used as proxy indicators of affordability and quality concerns, respectively. Using ArcGIS 10.5, 150 households were randomly selected to include thirty from each of the first four categories and fifteen each from the last two categories.

Data collection: The water diary forms were designed by Hoque and Hope, 2018. Details of the form design are presented in Appendix H with their permission. The forms capture information about daily water collection practices including water sources used, payments made for water, and sufficiency of water for different tasks. Participants from the selected households were invited by phone to attend a two-hour training session, which was conducted in groups of twenty. A total of 81 participants attended the training sessions, and 39 were trained during individual home visits. Five dropped out but 115 participated in filling out daily water diary forms. Three research assistants (Grace Muisyo, Annah Kavata, and Lucy Wambua) collected the diary forms and used tablets and the Ona Systems mobile survey platform to digitise the data. They also conducted bimonthly check-in surveys, for which I wrote questions to ask about changes in water quality, water treatment practices, and illness of household members (see my questions in Appendix H).

Data quality: The diaries are designed to minimize the need for reading and writing, but the literacy of participants was assessed at the start of the process to ensure their understanding and ability to complete the task accurately. All participants did a one-week pilot to practice filling in the diary forms, clarify questions, and resolve misunderstandings and logistical issues. Throughout the year, data were digitised continuously by the research assistants and were reviewed by Sonia Hoque (the water diaries) and I (the bi-monthly survey). Follow-up visits with participants to seek explanations for unexplained changes in behaviour were conducted as needed. The main concern with this method is response fatigue. Mid-week check-in phone calls and bi-weekly visits to collect the diaries were implemented to counteract disinterest. Participants frequently requested financial and other support for household needs, but the research assistants made continuous efforts to manage expectations and express gratitude; participant retention was high for most of the year (for the bimonthly survey, 100% of participants engaged in the first three months, 98% after six months, 83% after nine months, and 63% by the end).

### 3.4.3 Household-level Interviews and Observations

Dates: July – November 2018

Participants: Thirty-five people were interviewed. They were primary fetchers of water (13), and/or primary managers of water within the home (17), and/or household heads (19). Eighteen presented as female, six were single parenting, five were physically disabled, and four were more than sixty years old.

Sample selection and data collection: Two anthropology graduate students from the University of Nairobi (Mercy Musyoka and Faith Wambua) lived in the communities during the study period to build rapport and interact with community members at their homesteads, around water sources, in market areas, and during special functions. They recorded interactions and observations through journaling on twenty-one days, and conducted interviews in Kiswahili and Kikamba, which they translated and transcribed in English. Participants were purposively selected to capture a diversity of views (based on gender, age, ability, roles) within two Kamba communities in Tseikuru ward. I did not have input in the design or execution of this work, which was supervised by Salome Bukachi and Dalmas Omia from the University of Nairobi Institute of Anthropology, Gender and African Studies.

Data quality: The fieldwork began with a pilot phase to establish support from community leaders, familiarise with the location, and conduct informal scoping conversations and observations to adjust the interview guides. Information from the interviews and participant observation records were compared for consistency during the fieldwork and later analysis.

### 3.4.4 Analysis for Baseline Assessment

Since no message effect was being evaluated for the assessment of user perspectives on drinking-water safety, I did not focus on allocating respondents to the stages of my integrated fear appeal framework (Figure 2.3). Rather, I conducted a descriptive analysis guided by its core concepts. I explored key variables from the cross-sectional and longitudinal (water diaries) surveys using summary statistics, $\chi^2$ tests, and association plots.

To complement the quantitative results, I conducted a concept-driven qualitative analysis - coding the interview transcripts and observation journal entries in two cycles using NVivo 12. For the initial deductive coding, I started with nodes that correspond to the core concepts of my fear appeal framework. This includes perceived threat and efficacy, precautionary actions, and defensive rationale. Through the coding process, I built more specific nodes to capture key themes that reflect the complexity of water user engagement with microbial water quality threats. I then conducted a second cycle of coding to check my intrarater reliability and increase consistency. The final coding structure had fifty-five nodes[1], to which I coded 1267 references from the interview transcripts and participant observation journal entries. The node structure and coding results were discussed with my supervisor, Katrina Charles, but I did not have other coders with whom to do an interrater comparison.

## 3.5 Lay Water Manager Responses to Monitoring

Although this thesis engages with community level decision-making through both water users and LWMs, I decided against a study design that would involve sampling and sharing water quality results at household level. This was due to concerns about low self-efficacy and was partly based on the results of the cross-sectional household survey (Section 3.4) and on discussions with government stakeholders (Chapter 6). I reasoned, however, that the potential effects of increasing perceived threat (from microbial hazards in drinking-water) among LWMs warranted further investigation. This is partly due to economies of scale and because, by designing a water quality monitoring programme in collaboration with a RWSP (FundiFix), we could ensure ongoing informational support and explore the possibility of establishing a supply chain for treatment resources or training if LWMs expressed interest.

I designed a messaging intervention study to track LWM responses to water quality monitoring information. In keeping with my integrated fear appeal framework (Figure 2.3) and to understand the influence of test result variability on attitudes and behaviour, I prioritised repeated measures over cross-sectional sample size. The messaging intervention was built around the 56 LWMs who were purposively included in the monitoring programme to represent different management arrangements including community-based management (CBM) committee

[1] Due to length and word count, the codebook is not presented with this thesis, but it can be made available separately on request.

members, school or health facility administrators[1], and private owners (Section 3.2). A primary contact was selected to represent each committee or facility. Thus, the resulting analysis does not consider dynamics within CBM committees or facility administrative teams.

The *E. coli* monitoring results and identified sanitary vulnerabilities[2] were reported to the LWMs (the chemistry results were not shared in keeping with directives from the Kitui Ministry of Water following concerns about the limited efficacy of LWMs to manage fluoride and potential political implications). Reporting was conducted in Kiswahili, Kikamba, or English according to the LWM's preference.

The first reporting was conducted in-person; a hard-copy information sheet was used as a guide for explaining the results and was shared with each contact for future reference. It included information explaining the WHO *E. coli* risk categories and water safety response options and was iteratively created through discussion with the research assistants who worked on the monitoring programme and the longitudinal household survey (Appendix I). After the first reporting, subsequent reports were delivered verbally over the phone to minimize the time between completing the analysis and sharing the result. At the end of 2019 a hard-copy report of all test results from the year was delivered to each LWM (Appendix I).

I used a series of surveys to understand how the LWMs judged and re-

[1]Facility management was included in recognition of the importance of WASH services in relatively under-researched non-household settings (Cronk et al., 2015). However, water management in facilities can be difficult to categorise into only one of the three broad institutional domains (bureaucratic, market-based, community) discussed in my literature review (Section 2.3). In Mwingi North, daily management of water in schools and health facilities is the responsibility of administrators who have no specialised training in water management (fitting the description of 'lay managers'). They are community members but also intermediaries between their ministries of Education or Health, FundiFix, the Ministry of Water, and their students or patients, and staff. They are grouped among the community-based and self-supply water managers but my analysis, particularly the dilemma analysis, does maintain their distinction.

[2]Sanitary inspection scores were not reported but identified vulnerabilities were discussed with the LWMs directly.

sponded to the monitoring information (Section 3.5.1). The survey series tracked changes in LWM perceptions, intentions, and behaviours. Additionally, I conducted semi-structured interviews to gain richer, better contextualised insight into LWM perceptions of water safety and the monitoring programme (Section 3.5.2).

### 3.5.1 Lay Water Manager Survey Series

Dates: November 2018 – July 2020

Participants: Fifty-six LWMs participated, although four are excluded from the timeline analysis because they could not participate in at least 50% of the study period due to persistent water supply breakdowns. The remaining fifty-two include CBM committee members (28), school administrators (15), health facility clinical officers (3), and private owners (6). The majority (81%) presented as male. For each CBM committee I engaged one primary contact who was a self-selecting and active member of the committee – often the chairperson (64%) or secretary or treasurer (18%).

Sample selection: The LWMs were selected in collaboration with FundiFix during the set-up of the monitoring programme (Section 3.2). Rather than focusing on management of earth dams and uncovered dug wells, for which there is higher awareness of water contamination threats (Chapter 6), I focused on equipped supplies including groundwater piped distribution schemes (69%), dug wells with handpumps (17%), boreholes with handpumps (8%), and surface water piped distribution schemes (6%). Just over two-thirds of the supplies were registered for maintenance services at the start of the programme.

Data collection: A series of surveys, as outlined in Table 3.4, were used to explore how LWMs judged and responded to the *E. coli* monitoring results. Most of the survey questions were open-ended. The surveys were conducted by my research assistants (Musenya Sammy and Martin Mwaniki) with paper forms that I later digitised. The final survey in mid-2020 used more multiple-choice questions and was conducted with tablets and the Ona Systems mobile survey platform. The surveys focused on baseline awareness of water quality threats and tracked changes in perceptions of threat and efficacy, affective state, intentions, actions, and defensive responses.

**Table 3.4:** Integrated fear appeal framework concepts assessed through LWM surveys.

| **Survey** | **Description** | **BA** | **PT** | **PE** | **AS** | **I** | **A** | **DR** |
|---|---|---|---|---|---|---|---|---|
| (1) before monitoring | Assessed perceptions of water safety prior to commencing monitoring, it included questions on water use, efforts to manage water cleanliness, and prior exposure to water quality testing or water safety information. | X | X | X | | | | X |
| (2) after first report | Conducted immediately following the first sharing of *E. coli* results, it focused on capturing the LWMs' affective and cognitive responses to the information. | | X | X | X | X | | X |
| (3) monthly check-ins | Recorded observations and conversations from site visits and results-reporting with attention to affect display, stated intentions, questions, and actions of the LWMs in response to the monitoring results. Each sharing of results brings the LWM back to the message processing (undecided) stage and the short-term outcomes are a) stay undecided, b) no decision and move to uninvolved, c) intend to act (or continue acting), or d) intend no action. | | X | X | X | X | X | X |
| (4) end-2019 | Conducted after the final reporting for 2019. LWMs were invited to reflect on the set of results, the utility of monitoring, and their experience with implementing water safety measures, where relevant. | | X | X | | X | X | X |
| (5) mid-2020 | The supplies that were registered for maintenance services in 2020 continued to be monitored quarterly and a final survey of perceptions and intentions was conducted mid-year. | | X | X | X | X | X | X |

BA = baseline awareness. PT = perceived threat. PE = perceived efficacy. AS = affective state. I = intentions. A = actions. DR = defensive response.

I created the questionnaires (see Appendix J) in consultation with Musenya and Martin (who are local to the region and had experience discussing water topics with people in the study area through their previous work) and with feedback from Cliff Nyaga and Jacob Katuva (who have years of experience conducting research surveys about water in Kitui County). Affective state was judged on unprompted self-reported emotions and observations of facial and vocal display immediately after LWMs received results[1]. The affective state data is, therefore, strongly informed by the perspective and biases of my research assistants. Accordingly, it is not heavily weighted in my analysis or discussion of the information intervention (Chapter 6).

A total of 605 surveys were completed. The median level of participation per LWM was 86%; seventeen LWMs participated less than 86% of the time, with the minimum participation at 50% (four LWMs). Sixteen LWMs participated 86% of the time, and nineteen participated more than 86% of the time, with the maximum participation at 100% (seven LWMs). LWMs were not always available to answer the survey questions in-person each month, so phone calls were used when possible and necessary. Participation was limited mainly by water system functionality problems (which made monitoring impossible or irrelevant) and absence of LWMs (some of whom were away for weeks or months at a time). For the final survey in 2020, only 60% of the LWMs were engaged because the monitoring programme in 2020 included only water supplies that were registered for maintenance services.

Data quality: I observed the surveys process in the beginning (late 2018) and again over three periods in 2019 (for about a week each time) and provided immediate feedback to Musenya and Martin on how they queried LWMs and recorded responses. The key aims in training were to ensure that we had a common understanding of the purpose of the questions, to avoid leading the participants, and to agree on a reasonable level of detail for recording the responses.

[1]Displays were grouped as positive if describable with terms like happy, grateful, pleased, glad, good-humoured, keen; as negative with terms like worried, concerned, afraid, anxious, disappointed, angry; as disinterested with terms like preoccupied, unsurprised, distracted, dismissive, unconcerned; uncertain with terms like sceptical, questioning, inquiring; as surprised with terms like shocked or amazed; or as undetermined when LWMs were neutral, reserved, or evasive.

As further discussed in the later section on positionality (Section 3.8), the initial training period and subsequent check-ins were needed for data quality assurance (while accompanying them on site visits I was also verifying how the water quality sampling protocols were being followed), but I conducted myself as an observer and otherwise minimised my presence during the surveys and monitoring work so that the activity would be associated more with local efforts from FundiFix rather than a research effort from a UK university. Throughout the monitoring programme, I checked the survey responses for comprehensiveness and consistency and followed-up with Musenya and Martin for clarifications or adjustment as needed. When I was in Kenya, this process happened daily. When I was not in Kenya, I reviewed incoming data weekly and did weekly follow-ups using email and WhatsApp messaging and calls.

### 3.5.2 Lay Water Manager Interviews

Dates: July – August 2019

Participants: Thirty-eight LWMs were interviewed.

Sample selection: Repeated attempts were made in July and August to interview all 56 LWM contacts who were engaged in the monitoring programme. Four school and thirteen CBM committee LWMs were not available during the period that I was in Kitui to conduct interviews, and one private LWM declined to be interviewed.

Data collection: I conducted the interviews with support from Musenya and Martin. Most were primarily in English (n = 27) but for eleven of the LWMs we used a blend of Kiswahili and Kikamba. We worked together to agree on translations of both questions and responses before, during, and after the interviews. Audio recording and transcription was used for all but one school water manager who was not comfortable with recording (so only hand-written notes were used). The interviews were designed to elicit views on the utility and drawbacks of the water quality monitoring programme. Terminology from the conceptual framework was not used in the interview guide, which was designed to facilitate relatable discussion focused on practical and specific issues rather than abstract concepts that are likely to create miscommunication (Newell, 2012).

The questions encouraged LWMs to share their perceptions of microbial and chemical water quality hazards, whether the monitoring results had changed their perceptions, the options they consider viable for managing these hazards, and their own role and responsibilities for responding to the monitoring information. Although I used an interview guide (Appendix K) – which was reviewed by my supervisor and refined based on feedback from Cliff, Musenya, and Martin – I intentionally made space for the LWM participants to direct the conversation on water safety as they felt was relevant and appropriate.

The discussion was not limited to their individual perspectives and response options, they were also encouraged to reflect on the roles of the wider community, water service providers, and the government in addressing water safety concerns. Inclusion of this content reflecting the wider multi-stakeholder context within which the LWMs operate is explained in the following Section (3.6). Additionally, prior to each interview I reviewed the preceding survey responses from each LWM and made note of particular topics to ask them about for purposes of clarification or elaboration. This process typically generated one to five additional questions per LWM. The interviews took between thirty and ninety minutes depending on the availability and interest of the LWMs. I did verbatim transcription for all of the audio recordings and included notes from our post-interview debrief discussions in each transcript.

Data quality: Musenya and Martin each have more than four years of education and experience in water management and they are familiar with the study area context, having lived and worked in rural Kitui prior to working with me. They were also familiar with each of the LWMs, having spoken with each of them monthly in the preceding half year. Their input was essential in assuring the quality of the interview work. They assisted me with clarifications during the interviews and provided feedback and impressions in debrief meetings after each interview. They also collaborated with one another on translations of both questions and responses when the meanings were not straightforward.

To further decrease chances of miscommunication, complex responses were paraphrased back to the LWMs during the interview to confirm understanding and allow clarification or elaboration. During the transcribing process, where I discovered inconsistency or obscure responses I discussed these with Musenya and Martin and added annotations to guide my interpretation. In four cases we reached out to the LWMs for further clarification. During the analysis phase, results from the interviews were cross-referenced with the survey series results.

### 3.5.3 Evaluation of Responses

My analysis of LWMs responses to the *E. coli* monitoring results was guided by my integrated fear appeal framework (Figure 2.3). Drawing on the water quality monitoring results, surveys and interviews, I tracked perceptions of threat and efficacy, affect display, information seeking and intentions, reported actions, and defensive responses. To manage the complexity of the data, I used NVivo 12 for deductive coding and then built a summary timeline for each LWM in Excel. For the coding, I started with nodes that correspond to the core concepts of the integrated fear appeal framework. Through the coding process I added sub-nodes for different forms of intention, action, and defensive response. I then conducted a second cycle of coding to check my intrarater reliability and increase consistency[1]. With this information I judged stage of change for each LWM across fourteen timeline steps including the end of 2018, twelve months in 2019, and mid-2020. I used the timelines to assess how LWM perceptions of threat and efficacy changed over time and to compare response patterns.

Information about water protection, treatment, and storage, which can influence perceived efficacy, was shared alongside the water quality monitoring results. This information was kept consistent so perceived efficacy was not intentionally manipulated with each reporting of the monitoring results. Similarly, the severity component of perceived threat was not manipulated since the information on waterborne disease accompanying the test results was kept consistent. The second component of perceived threat, susceptibility, was the key message processing variable that was influenced by the reporting of monitoring data. The reports emphasised that the higher the concentration of *E. coli*, the higher the likelihood of waterborne disease transmission. Additionally, susceptibility with respect to specific water supplies was contingent on use. If the source was in regular use, perceived susceptibility was coded based on the *E. coli* concentration per 100 ml sample: low (<0), medium (1 – 10), high (>10).

This method of assessing susceptibility was supported by the LWMs in two important ways. First, the interviews confirmed that trust in the water quality test results was high because those doing the monitoring were perceived as experts who presented the information in a reliable manner without false exaggeration or minimisation to serve ulterior motives. For comparison, this same level of trust was not afforded to information provided by fellow community members or government officials except on a case-by-case basis where trusted relationships

[1]The final coding structure had forty-eight nodes to which I coded 740 references. Due to length and word count, the codebook is not presented with this thesis, but it can be made available separately on request.The node structure and coding results were discussed with my supervisor, Katrina Charles, but I did not have other coders with whom to do an interrater comparison.

were established. Second, when fewer people were using a water point, for example, due to seasonal change in availability of alternate sources, kiosk closure (caused by difficulty paying attendants or conflict amongst the committee), or school being on break, the LWMs consistently expressed that the quality was not a near-term priority regardless of the test result or intended future use. Thus, perceived susceptibility was coded as low if the source had limited use such that the LWM spoke of the quality as inconsequential.

To assess the associations between perceived susceptibility, affect display, and stage of change, I used correspondence analysis (CA) with contribution biplots (Kassambara, 2017). CA is an extension of principal component analysis that is useful for categorical variables. It enables exploration of the associations between categories of one variable and categories of another variable in a two-way contingency table. Contribution biplots are a method of visualising the output of CA in low-dimensional space, where the relative positions of the categories reflect their associations in the contingency table (Greenacre, 2013). This analysis was done using the 'FactoMineR', 'vcd', and 'factoextra' packages with R version 3.6.1.

Moving beyond this focus on perceived susceptibility, I used the LWM timelines to explore more of the complexity in their responses to the monitoring results. By iteratively grouping the LWMs based on similarities in water quality profiles, perceived efficacy, intended actions, defensive responses, and reported actions, I identified patterns in the LWM responses over time.

## 3.6 Pluralistic Stakeholder Perspectives

The water safety monitoring programme and collaboration with FundiFix formed a foundation for engaging with bureaucratic, market-based, and community stakeholders around actual, rather than hypothetical, activity (Figure 3.12). This work centred on FundiFix and their key government and community relationships in Kitui County, but perspectives were also sought from national level bureaucratic stakeholders, these being the Kenyan regulators (WASREB and WRA) and Ministries of Water and Health; Kenyan formal water service providers (FWSPs), which supply high-density areas and are subject to regulation; and other rural water service providers (RWSPs), which operate across five countries in Sub-Saharan Africa. A mix of methods were used to elicit stakeholder views on water quality sampling activity itself and on the use and sharing of monitoring data (Table 3.5).

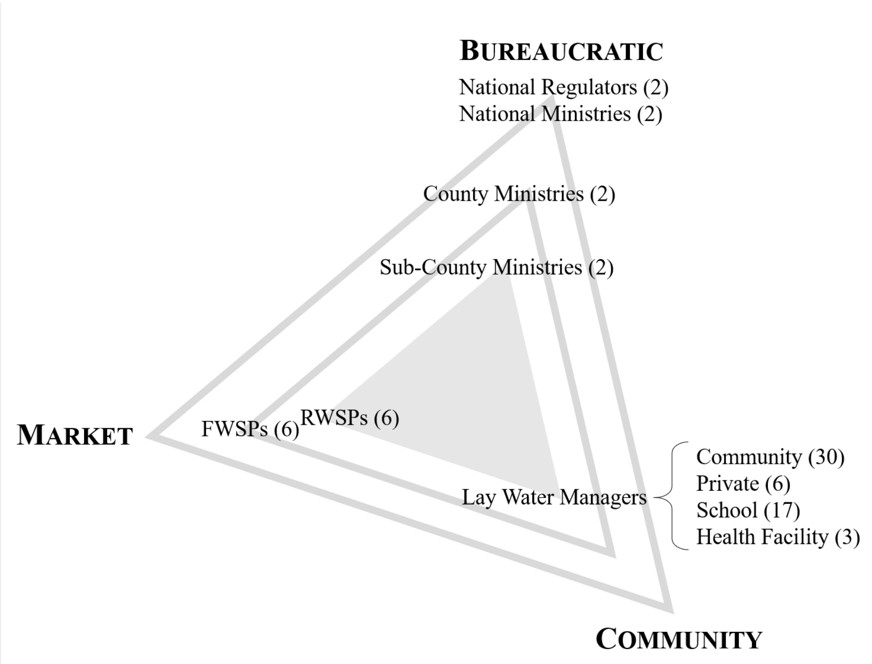



**Figure 3.12:** Stakeholder grouping nested from local to national level. *The numbers in brackets indicate the number of organisations or bureaucratic divisions included in each category.*

The LWM semi-structured interviews and survey series were introduced in Section 3.5. In addition, I conducted interviews with bureaucratic and market-based stakeholders and incorporated meeting notes and document review in my qualitative coding work – which was guided by the dilemma analysis method.

**Table 3.5:** Dilemma analysis data collection between Nov 2018 and Sep 2019.

| **Method** | **Activities** |
|---|---|
| Semi-structured Interviews | National bureaucracy (n = 4): Apr \| FWSPs (n = 6) Apr to May \| LWMs (n = 38): Jul to Aug \| County and sub-county bureaucracy (n = 4): Jul to Aug \| RWSPs (n = 6): Sep |
| Survey Series | LWMs (n = 56): before monitoring survey (Nov 2018), after first report survey (Jan 2019), monthly check-in survey (Dec 2018 - Aug 2019) as described in 3.4 |
| Meeting Notes | County and sub-county government (n = 4): Nov 2018 and Feb 2019 |
| Key documents reviewed | County-level: County Integrated Development Plans; National Drought Management Authority County Long and Short Rains Reports; County WASH Forum Meeting Minutes |
| | National-level: (Kenyan) Water Act 2002, 2016; The (Kenyan) Water Resources Regulations 2019; The (Kenyan) Water Services Regulations 2019; WASREB Guidelines on Drinking Water Quality and Effluent Monitoring; Ministry of Water Strategic Plan 2018-2022; Ministry of Water National Water Services Strategy 2007-2015 |

### 3.6.1 Market and Bureaucratic Stakeholder Interviews

Dates: April, July - September 2019

Participants: Thirty-six people were interviewed including representatives from the Ministries of Water and Health at sub-county, county, and national level; from two Kenyan regulators at national level (WASREB and WRA); from six RWSPs operating across five countries in Sub-Saharan Africa (including FundiFix); and from six FWSPs operating across five counties in Kenya (including KIMWASCO and KITWASCO in Kitui County). Multiple interviews were conducted in each organisation where possible (with the number of individuals interviewed ranging from one to four per organisation). Seventeen people were interviewed from the eight bureaucratic organisations and nineteen were interviewed from the twelve service providers (Table 3.6).

**Table 3.6:** General positions of interviewed bureaucratic and market-based stakeholders. *Positions and organisations are grouped to protect confidentiality.*

| | **Bureaucratic** | **FWSPs** | **RWSPs** | **Total** |
|---|---|---|---|---|
| Senior Director | 5 | 4 | 3 | 12 |
| Mid-level Director | 2 | 4 | 2 | 8 |
| Senior Strategy / Policy Position | 6 | 0 | 2 | 8 |
| Technician | 4 | 3 | 1 | 8 |

Sample selection: My rationale for engaging bureaucratic, market-based, and community stakeholders from local to national level is detailed in my literature review (Section 2.3) and is further informed by the Kenyan institutional context (Section 3.1). Connections with most of the interview participants were initiated with assistance from Cliff Nyaga (who has over a decade of experience working in the Kenyan water sector) and Pauline Kiamba (who was based at the Kitui Ministry of Water through the USAID SWS Learning Partnership programme). Additional connections were made through the Aquaya Institute (for FWSPs operating outside of Kitui County and in the Ministry of Health at national level) and through the REACH programme (for RWSPs operating outside of Kenya). Interview requests were initially directed to contacts in senior management positions, most of whom agreed to be interviewed themselves or directed me to more junior colleagues. Following initial interviews in each organisation a snowball sampling approach was used to arrange additional interviews where feasible and appropriate.

Data collection: I conducted the county and sub-county bureaucratic interviews, the RWSP interviews, and the FWSP interviews in Kitui County. I co-led the national level bureaucratic interviews with Kara Stuart and Clara Macleod, researchers from the Aquaya Institute[1], and they conducted the interviews with the four other FWSPs without me (and shared their interview notes). All interviews were conducted in English and followed interview guides that were developed with input from my supervisor, the Aquaya team, Cliff Nyaga, and Pauline Kiamba. The bureaucratic interview guide reflected stakeholder roles in policy development and data use, the FWSP guide reflected stakeholder roles in water service provision and water quality data production and use, the RWSP guide reflected stakeholder roles in maintenance service provision and actual or potential water

[1] I collaborated with the Aquaya Institute for these interviews because they were conducting research that was supported by REACH partnership funding to explore water quality data flows with organisations that had participated in their 2012-16 Monitoring for Safe Water (MfSW) programme and there was considerable overlap in our interview objectives (Section 2.2.1, Kumpel et al., 2020; Kumpel et al., 2016).

quality data production and use (Appendix K).

As with the LWM interviews, the market-based and bureaucratic participants were not asked to engage with academic terminology (e.g. questions did not explicitly reference governance concepts or water safety management frameworks) and they were not asked to identity contradictions or dilemmas outright; these were uncovered during the subsequent analysis[1]. The conversations were focused on practical and specific issues rather than abstract concepts to mitigate miscommunication (Newell, 2012). The general structure of the interviews was to establish an overview of the participants' role and the activities of their organisation with respect to water quality monitoring; then to focus on water quality data generation, sharing, and interpretation; then to focus on modes of response to identified hazards; and finally to conclude by inviting participants to emphasise or raise any subject that they felt had not been covered sufficiently.

The interviews took between one and two hours; most were audio recorded but hand-written notes were relied on in one instance with a bureaucratic interviewee who was not comfortable being recorded. I transcribed the interview recordings verbatim and included debrief notes in the transcripts.

Data quality: In ensuring and assessing the quality of the interview work, I prioritised response reliability and accuracy of my understanding of responses. Complex responses were paraphrased back to the participants during the interview to confirm understanding and allow clarification or elaboration. Since I was joined by Aquaya researchers for the national level interviews, we were able to compare notes and discuss our impressions and understandings following each interview.

Similarly, for the county level interviews, Pauline Kiamba joined me to provide introductions and help clarify the conversation based on her extensive experience working with the County government. Following these interviews, she

[1] The dilemma analysis method itself is informed by theory, though it does not impose a theory-based interpretation on the subject under study (Winter, 1982).

shared valuable feedback that helped me to interpret the transcripts. Based on these debriefing discussions and queries I developed during the transcribing process, I sought clarifications from interview participants or additional interviews with other representatives in the organisation. During the analysis phase, I also cross-referenced transcripts (from the same organisation and organisation types), informal meeting notes, and reviewed documents.

### 3.6.2 Dilemma Analysis

The dilemma analysis produced three successive outputs: a compilation of contradictions, a perspective document, and a summary of links between dilemma topics. First, data were gathered into NVivo 12 and subjected to two cycles of versus coding (Saldaña, 2016), the objective of which is to draw out contradictions, including both those that indicate polar opposition and inconsistency (Gibson & Brown, 2009). During the initial round of coding, I grouped contradictions by their relevance to generation of, sharing of, engagement with, and mode of response to water quality information. These groupings broadly mirror the structure of the interviews, which elicited participants' views on the various stages of monitoring in chronological order. During the coding process, I added nodes under each of the aforementioned stages to reflect emergent subgroupings of contradictions. I then conducted a second cycle of coding to check my intrarater reliability and increase consistency. The final coding structure had fifty-three nodes[1], to which I coded a total of 1707 references from the interview transcripts, survey responses, meeting notes, and document review. Thus, the first output of the dilemma analysis was an organised compilation of contradictions that captures tensions in the views expressed by and between stakeholders.

[1]Due to length and word count, the codebook is not presented with this thesis, but it can be made available separately on request. The node structure and coding results were discussed with my supervisor, Katrina Charles, but I did not have other coders with whom to do an interrater comparison.

The compilation of contradictions does not exhaustively include all contradictions expressed by FWSP and bureaucratic representatives; priority was given to contradictions that have relevance in comparison with the RWSP situation. For example, contradictions concerning the lack of engagement between county Ministries of Water and FWSPs around water quality monitoring were not included. Contradictions relating to overlapping mandates and information sharing between bureaucratic divisions were also left out. As were contradictions around (dis)empowerment of actors on the lower rungs of the bureaucratic hierarchy.

The second output of the dilemma analysis is a perspective document, which condenses the listed contradictions into dilemmas, organised by stakeholder group. Here dilemma is defined in the narrow sense as a choice between two alternatives, neither being unambiguously preferable. The perspective document was not shared back with stakeholders due to sensitivity of some of the dilemmas (taking care to avoid breach of confidentiality or negatively impacting on existing institutional cooperation) and linguistic complexity (as a barrier to meaningful engagement). The supplementary information published with my dilemma analysis paper (Nowicki et al., 2020) provides an excerpt of the perspective document[1].

In the perspective document, dilemmas are articulated in an inclusive form that is more elaborate than any one individual would have expressed, but which any one individual of the relevant group would assent to. They are expressed by a 'on the one hand' / 'on the other hand' construction and are categorised at multiple levels: first by stakeholder group (market, bureaucracy, community), then by monitoring stage (generate, share, engage, respond), and finally by topic. As shown in the summary table in Chapter 7 (Table 7.1), topics are categorised as ambiguities, judgements, and problems to indicate the severity and importance of the component dilemmas (as perceived by the interviewed stakeholders).

[1]The perspective document excerpt can be found at https://www.nature.com/articles/s41545-020-0062-x#Sec13. The full document is not appended for confidentiality reasons and because it is more than 10,000 words long, but it can be made available for a specified purpose on request.

- **Ambiguity dilemmas** relate to aspects of a situation that are viewed as unavoidable, they describe "background awareness of inevitable and deep-seated complexities" (Winter, 1982, p.169), but are well-tolerated because they do not link directly to a course of action.
- **Judgement dilemmas** relate to choosing a course of action when the decision is deemed complex but not inherently negative. Judgement dilemmas can be satisfactorily resolved with skilful handling.
- **Problem dilemmas** also relate to choosing a course of action, but in this case the necessity of deciding is itself negative. Problem dilemmas represent strong, intractable conflicts of interest within and between stakeholders.

In order to explore the interrelatedness of the dilemmas, the final stage of the analysis was to compile a list of associations between dilemmas. These associations were both between and within stakeholder groups (market, bureaucracy, community) – in many cases dilemmas are formed around the assumptions made by individuals in one group about the impact of choices on and by another group. Furthermore, as the analysis is organised by different stages of the monitoring process (generating, sharing, engaging, responding), within a stakeholder group dilemmas of one stage related to dilemmas in other stages.

I developed the list of associations through an iterative process of recording links between dilemmas that were either directly expressed by stakeholders or which I inferred during the coding process and afterwards upon review of the perspective document. I then assessed the associations at topic level disaggregated by stakeholder group. Where the associations between the dilemmas of two topic groups were such that generating, using, or sharing monitoring information is discouraged, on balance, by the prevalence of conflicting standpoints I classified the link between the two topic groups as a barrier. Where dilemmas were overall aligned to facilitate water safety improvement, I classified the link as an enabler. I gave a neutral classification to links when the associations between dilemmas have value for informing design of cooperative monitoring programmes but are not sufficiently impactful to be considered sources of substantial conflict or enablement.

I used an axial hive network visualisation to depict the links between topics disaggregated by stakeholder group. The purpose of the visualisation is to demonstrate the complexity of links between the dilemma topics and to emphasise that there are numerous barriers to effective water quality monitoring because of divergent stakeholder views. It was created using R version 3.6.1 (2019-07-05) with the package 'ggraph' (Pederson, 2019).

#### *Member Checking for Accuracy*

Member checking of findings or "negotiating conclusions with participants" is a valuable process to assess and improve how research represents the experience and views of participants (Armstrong, 2020, p5). I was able to share outputs from my dilemma analysis work with representatives from three of the RWSPs that participated in the research. They provided assurance towards the credibility of the analysis, confirming that my summary did not misrepresent their views. Their feedback precipitated my decision to discuss the dilemma analysis findings in relation to Water Safety Planning and led me to draw out dilemmas relating to laboratory ownership and accreditation that were not fully realised in my initial analysis (Chapter 7).

My plans to gather additional feedback from stakeholders on the findings and initial policy-facing conclusions of my thesis were curtailed, however, by cancelled travel due to COVID-19. I was able to improve my work based on feedback from academic peers who have experience working in the rural water sector in Kenya and elsewhere, but lack of late-stage feedback from bureaucratic and community stakeholders who participated in the research is a key limitation. An advantage of the dilemma analysis method, however, is that it is designed to evoke "the main areas of tension in a situation without generating immediate controversy by seeming partisan", to create "an account of a situation which would be seen by a variety of others as convincing, i.e. as 'valid'" (Winter, 1982, p167). It supports two legitimation processes: ironic legitimation (from tolerance of multiple realities and revelation of co-existing opposites) and rhizomatic legitimation (from mapping interlocking perspectives), both of which improve credibility in qualitative research (Onwuegbuzie & Leech, 2007).

## 3.7 Ethics Approval and Research Permits

The ethical approvals and permits for this study were issued by the University of Oxford Central University Research Ethics Committee (CUREC references: SOGE 18A-177; SOGE 18A-193; SOGE 18A-121) and the Kenyan National Council of Science, Technology and Innovation (NACOSTI/P/18/3232/20890; NACOSTI/P/18/22793/24858; NACOSTI/P/19/1259). Collaboration and approval were further secured from the County Government of Kitui. Additionally, a Special Pass was granted by the Kenyan Department of Immigration to permit me to work at the KEMRI laboratory in Kilifi in August 2019 (eFNS reference: 680048).

In designing and conducting my research I was guided by the Research Ethics Guidance from the UK Social Research Association (SRA) and the Statement of Professional Ethics from the Association of American Geographers (AAG). Key aspects discussed in applying for CUREC approval were selection of participants, training (of myself and research assistants and enumerators) in ethical working practices, data management to protect confidentiality, and obtaining informed consent.

Participation in this study was monetarily uncompensated and prior to agreeing to take part, all participants were informed of the study process and objective and were assured of confidentiality and that they could withdraw their participation at any time. The informed consent process was conducted verbally for the household level engagement, and with additional provision of written information for the LWMs and bureaucratic and market-based stakeholders. Engagement with the LWMs also received express prior approval from the Kitui Ministry of Water, this was particularly important for the LWMs from schools and health facilities.

During the research process, effort was made to manage expectations and avoid overstating the potential benefits or outcomes of the research for the individual participants – their participation was positioned as a generosity on their part towards research that is intended to contribute to wider social benefit. Nevertheless, given the visibility and relevance of FundiFix services in practice, and that data were shared and hazard control options were discussed, the monitoring programme and stakeholder engagement did have direct and immediate relevance for participants. There were three areas of particular sensitivity.

First, the questions directed to water users and LWMs were generally low-risk and non-invasive, however, in asking people about their physical and psychosocial health as it relates to drinking water quality there is potential to make participants uncomfortable or distressed. Second, for the LWMs and bureaucratic and market-based participants, my questions revolved around understanding the protocols and reasoning for generating, sharing, and/or using water quality information – so participants considered that their responses could have professional consequences. Third, the study generated data that inform on health risks that are relevant to the participants, and informing on health risks can have both positive and negative consequence for water users and the stakeholder groups who are perceived to hold responsibility for water provision.

The process of obtaining informed consent provides the initial opportunity to elect to participate with knowledge of the study topics. This process assured participants of confidentiality, made it clear that they had no obligation to share information, and highlighted that they could stop the interview or survey process at any time. Furthermore, the interviews were semi-structured and conducted so that participants maintained control of how much and what they were comfortable discussing. The AAG cites the Belmont Report as a guide for research at the nexus of health and behaviour (NCPHS, 1979). The fundamental principles set out in this report (respect for persons, beneficence as an obligation, and justice with respect to the benefits and burdens of research) guided the design and conduct of my work. There is minimal specific guidance, however, for the data sharing scenario that this thesis engages. The question of whether and how to share water quality data, and with whom, became a core area of my research – as discussed at length in the chapters that follow.

## 3.8 Positionality

The interdisciplinary research described in this thesis is born out of a paradigm of pragmatism (Section 1.2) and has been influenced by my personal history and belief system as a researcher – recognising that research paradigms are comprised of shared beliefs about the design and conduct of research, including which questions and methodologies are regarded as important and appropriate (Kaushik & Walsh, 2019; Morgan, 2014). In this final methodology section, I discuss key influences on the early development of my thesis objectives and reflect on the significance of prior research activities in northern Kitui County, my collaboration with FundiFix, and my status as a researcher and actor within the complex adaptive system under study.

Study Design

My intention to study links between data and decision-making was informed by a longstanding interest in the science-policy interface, which I trace back to an impactful lecture in my undergraduate degree (BSc Environmental Science). I began to appreciate the complexity of linking water quality monitoring to hazard control responses, and to understand the institutional context of the water sector in Kenya, while working on my master's dissertation in 2016 (MSc Water Science, Policy and Management). From there, the development of my thesis framing, specific objectives, and method choices was an iterative process. At each stage I considered multiple possible approaches, most of which I rejected, some of which I pursued and then diverged from, and a few of which directed the research presented in this thesis (Chapter 2).

For example, the IBM-WASH behaviour change model influenced my early fieldwork plans; I considered using environmental health literacy concepts to frame my thesis; and I attempted to develop indices to compare professional and lay judgments of water safety before opting for a more contextualised approach with stronger emphasis on qualitative analysis. My initial literature review and study designs were informed by normative and descriptive decision theory but lacked a comprehensive overarching frame. Conversations with my supervisors, in which they reflected on the complexity of my approach and the early findings of my fieldwork, led me to read about complex adaptive systems. Concurrently, I was learning about approaches to health geography and I found the synergy between structuration theory and systems theory to be compelling and useful for thinking through the problems that I had begun to engage.

Study Location and FundiFix Collaboration

I chose to focus my empirical work in Kitui County in part to leverage an existing foundation of relationship building that was developed through programmes led by Oxford researchers (Section 3.1), who have engaged in research in the area for more than a decade now. While this history substantially enabled my research and allowed me to access a deeper contextual understanding, it also influenced how I was perceived as a researcher in the field. There were multiple conversations during which research participants referred to previous interactions that they had with researchers from Oxford and the University of Nairobi.

In some ways, this was advantageous because it supported perspectives of me as a researcher with an academic interest and temporary presence. When I was approached as a potential source of aid, it was helpful to manage expectations by referring to my status as a student. On the other hand, some participants had preconceived notions about what I wanted to focus on in engaging with them, so additional time and explanation was required to differentiate the objectives of my work from the focus of previous research efforts (which largely engaged with functionality and financial sustainability of water supplies). In my questionnaires and interview guides, I included questions to ascertain whether participants recalled receiving information or data pertaining to water safety and the findings indicated that researchers had been a negligible source of such information compared to NGOs, community health volunteers, and health care providers (Chapter 6).

Besides the general history of research in the area, my collaboration with FundiFix in implementing this research substantially influenced my approach. My research assistants, Musenya and Martin, were positioned within FundiFix and in engaging with LWMs they emphasised that the water safety monitoring programme was not being implemented as an established service from FundiFix, but rather as a trial with the intention of understanding data utility on multiple fronts. It is important for the scalability of FundiFix, and the sustainability of user payments towards maintenance services, that their operations be perceived as locally-owned and distinct from foreign initiatives and funding. For this reason, and furthermore to avoid influencing the expression of dilemmas by appearing partisan, I presented myself to stakeholders as an independent student researcher as opposed to a formal affiliate of FundiFix.

Nevertheless, participants will have associated me with FundiFix to varying degrees because of how I was introduced to them (and for the LWMs, I was present during monitoring activity in the training and check-in periods, I was observed by some to be working at the laboratory in Kyuso, and Musenya and Martin supported me during the interviews). Despite these unavoidable associations, however, the interviews provided some assurance that FundiFix was viewed as an undertaking from residents of Kyuso while I was received as a foreigner from further afield – respondents instructed me about FundiFix rather than asking me about it or soliciting my input to resolve any concerns or questions (which they instead directed to Musenya and Martin occasionally).

Researcher and Reactivity Bias

In addition to the implications for FundiFix, my status as a foreign white (*mzungu*), relatively wealthy, female student associated with the ex-colonial power of the UK also influenced my own passive and active biases and reactivity bias on the part of the research participants. In an attempt to better bracket my a priori assumptions, I sought feedback frequently throughout the research process from my supervisors and collaborators in Kenya and the REACH programme more broadly. I also designed my research so that continually developing my understanding of the empirical context was important throughout the process. In particular, I found that going into my interviews with a view to later dilemma analysis was helpful in that I felt no incentive to resist or dismiss contradictory views.

With respect to active bias, a key issue that I had to manage was my reaction to statements where participants had views about water safety that were, to me, misinformed and potentially leading to risky choices. In such instances, I withheld my views (and consciously tried to maintain neutral body language to avoid telegraphing) until the end of the interview when I invited them to ask me questions and we shifted to an intentional two-way information exchange. I welcomed questions from participants because their use of me as a knowledge broker was a relevant finding in itself. I structured the interview so that I encouraged their questions towards the end of the discussion, but if they asked me questions earlier I gave minimal answers and made a note to revisit the topic at the end.

With respect to reactivity bias, I knew based on previous experiences and advice from collaborators that I would need to avoid positioning myself in a philanthropic light, otherwise I would incentivise participants to respond in a way they felt would increase the chances of receiving some form of assistance (the Hawthorne effect: alteration of behaviour due to awareness of an observer). I introduced myself as a student and when asked made it clear that I was not affiliated with any NGO or donor. Generally in interactions with people who approached me, in Kyuso or at water points, as a potential source of assistance, I found that their stance shifted quickly when I identified myself as a student. Nevertheless, some of the research participants ended our interviews with requests for assistance, making it clear that they did view me as a potential source of aid. I made a point of looking for patterns related to this during my qualitative analysis work, but I did not find exaggerated concerns or other outstanding observations to be more strongly linked with participants who did or did not ask for help. I am aware, however, that my position as a *mzungu* will have influenced the interviews that I conducted.

Given that I used dilemma analysis, it was especially important to be aware that some contradiction could be generated by the difference between what respondents think I want to hear (another form of the Hawthorne effect) and what they truly believe. I suspect this was less relevant at the county and national levels because our relative positions meant the participants did not want anything from me. At the local level, I was reassured by the impression that most participants wanted me to understand their view and position, with many of them making a point to differentiate their own perspective and circumstances from what they understood mine to be. Additionally, my use of mixed-methods was advantageous for mitigating the Hawthorne effect (by allowing me to cross-reference findings from the interviews I did myself with other sources of information for which I was not a visible observer).

Reactivity bias in the form of the novelty effect (alteration of behaviour due to a novel stimuli introduced by the data collection process) was also important. I used a phone for recording rather than a dedicated audio recording device to reduce potential awkwardness or self-consciousness (because phones are a more familiar object). But I, myself, was a novelty as a visitor in many of the interviews. In one case, a participant was not forthcoming so that the discussion stayed very superficial. In debriefing with Musenya and Martin after the interview they reflected that the interviewee was uncomfortable because he was not used to speaking with *mzungu* women. More often, however, the novelty effect manifested in that interviewees were very welcoming, offering tea and food and showing interest in me personally. I made room for this by planning a lot of time for each interview and not rushing into the interview guide. But when we did get into the main discussion of the interview, the tone shifted to be more serious and professional, less jovial and sociable.

A final important source of bias to discuss is related to my inability to engage in Kiswahili and Kikamba, therefore, limiting communications to English and reducing nuance and sub-text. I benefited from translation help during interviews, but the choice of language rested with the participants, multiple of whom struggled to communicate in English but made efforts to do so despite our assurance that Kiswahili or Kikamba would be equivalently good. This reduced the quality of some of the interviews. In contrast, for interviews where the participant did speak to Musenya and Martin in Kiswahili or Kikamba, the back-and-forth dynamic between the four of us was helpful to indicate to the interviewees that I wanted to understand on their terms. Fortunately, the LWM survey series and the household surveys and interviews were carried out by Kenyan researchers and enumerators who speak Kiswahili and Kikamba (and are trained in anthropological methods in the case of the household interviews), so once again cross-referencing material was important in my analysis.

Additionally, I had some experience learning about which concepts do and do not translate well by writing the informed consent and results reports in English and then working through translations of them into Kiswahili and Kikamba, sentence by sentence, with my research assistants. Based on this experience I modified some of the terminology that I used in questionnaires and interview guides so that it would be more easily translatable.

# 4

# Overview of Monitoring Results

This first results-focused chapter provides a selective overview of the water safety monitoring programme results – insofar as they inform and provide useful context for the analyses and discussion in subsequent chapters. Sampling was conducted monthly at 79 points of collection (PoCs) from December 2018 to the end of 2019, and quarterly for the 45 equipped PoCs that were registered with FundiFix in 2020 (Section 3.2). A total of 1078 site visits were made during this two year period, and chemical and microbial water quality indicators (specific electrical conductivity and *E. coli*, respectively) were measured during each visit (Figure 4.1). Only six sites (8%) never had a positive *E. coli* sample. Thirty-nine sites (49%) never had conductivity exceeding 2500 $\mu$S/cm, which is the East Africa

Standard (EAS) for natural potable water that is used by the Kenya Bureau of Standards (KEBS reference KS EAS 12:2018).

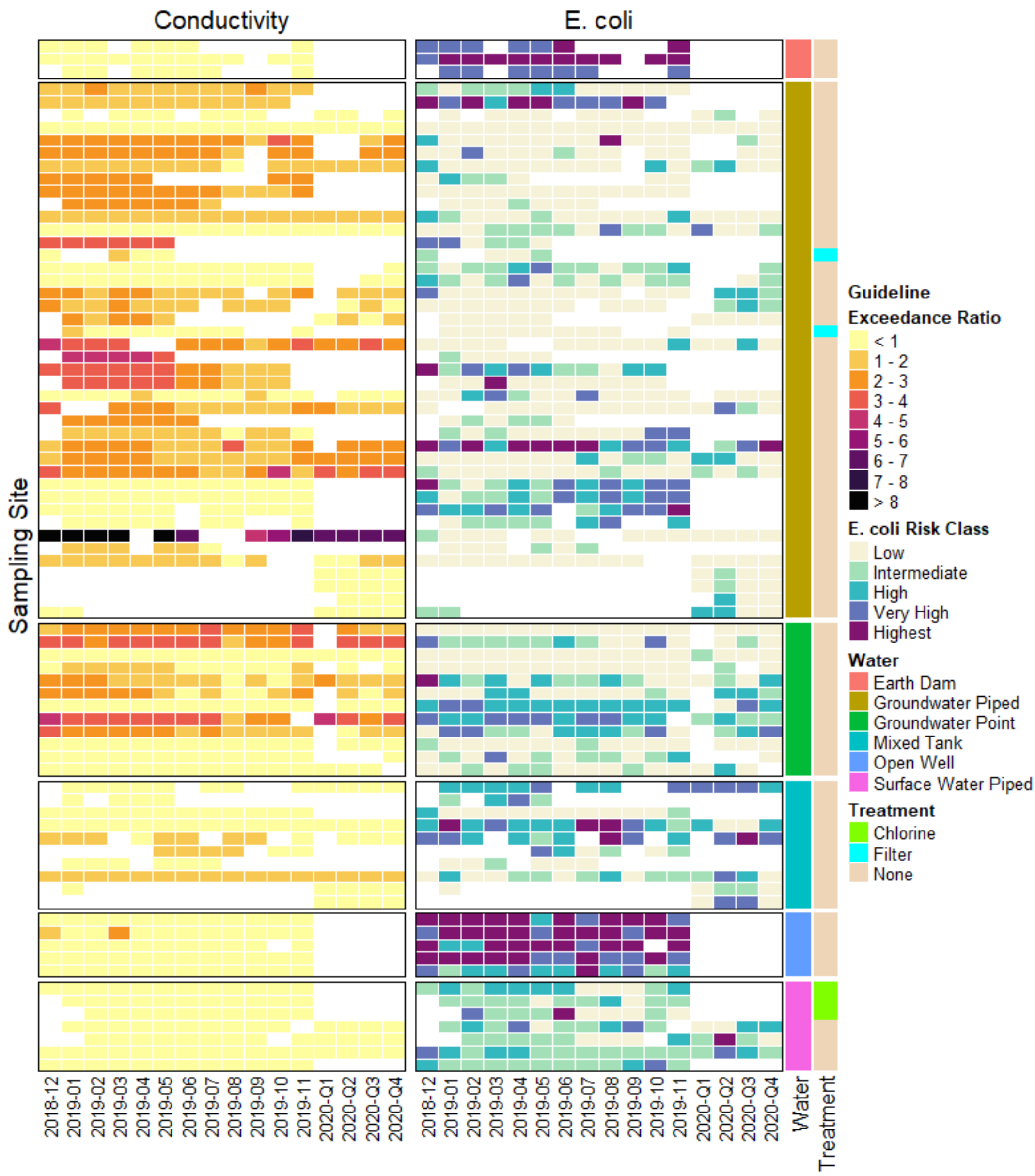



**Figure 4.1:** Heatmap of conductivity and *E. coli* sampling results from 79 PoCs between December 2018 and the final quarter of 2020. *The conductivity guideline used in calculating the exceedance ratio is the EAS for natural potable water, 2500 µS/cm (KEBS reference KS EAS 12:2018). Based on the WHO classification scheme (WHO, 2017a), the E. coli risk classes signal concentrations of <1 (low), 1-10 (intermediate), 11-100 (high), >100 (very high), and >1000 (highest). Missing data are due to sampling being prevented by breakdowns (52%); PoCs being closed usually due to water users moving to surface sources during wet periods(14%); PoCs closing due to school holidays (11%); PoCs drying out (11%); broken piped connections (9%); no power for pumping (3%) or impassable roads (1%).*

Across the monitoring sites, there are key trade-offs observed between turbidity and microbial contamination versus conductivity and fluoride (Figure 4.2).

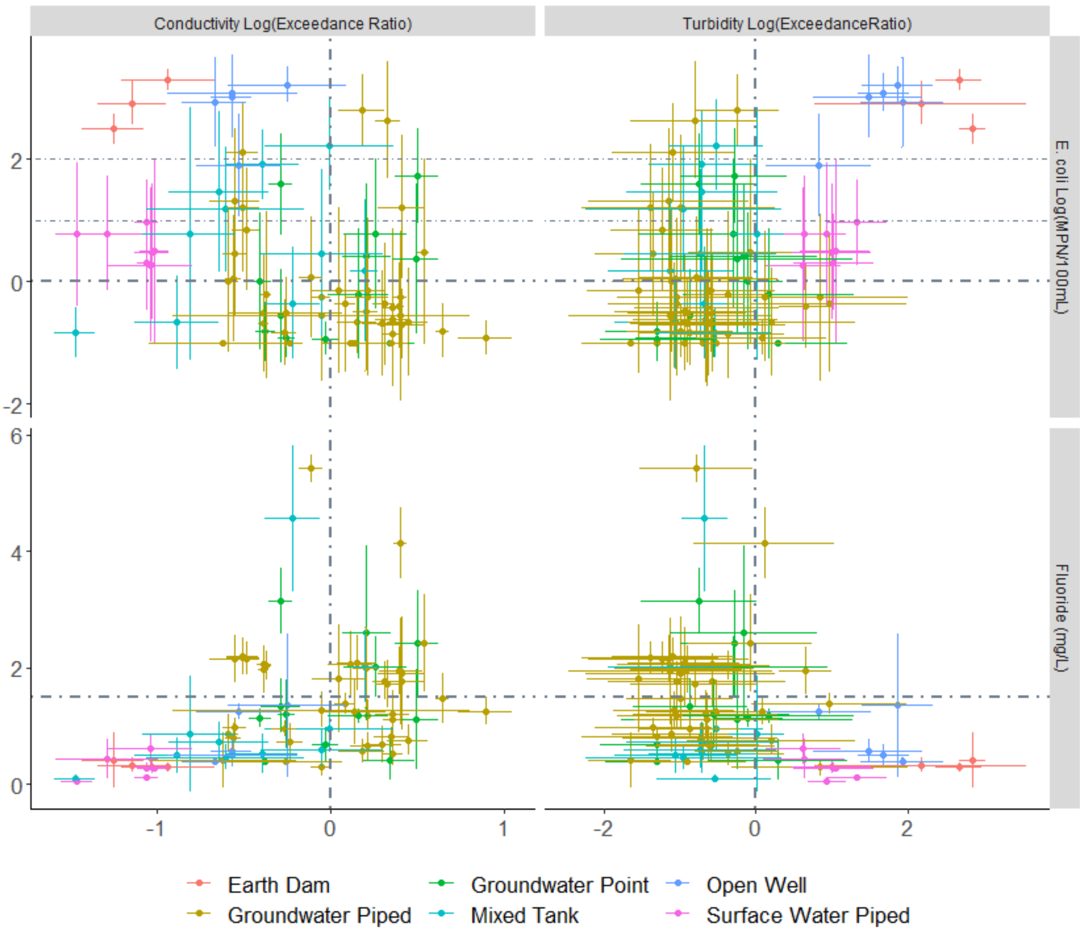



**Figure 4.2:** Water quality scatter plots comparing key threat parameters (*E. coli* and fluoride) with key organoleptic parameters (conductivity and turbidity) at 79 PoCs. *The points show means and the error bars show plus and minus one standard deviation from the mean. To improve readability, $\log_{10}$ values are used for conductivity, turbidity, and E. coli. The conductivity and turbidity results are reported as exceedance ratios, which are calculated by dividing the test result by the standards for conductivity (2500 µS/cm) and turbidity (25 NTU) in natural potable water (KEBS reference KS EAS 12:2018). Since exceedance ratios are used, negative log values indicate results meeting the standard and positive log values indicate results exceeding the standard, as demarcated by the dot-dash lines. For E. coli, the dot-dash lines correspond to the WHO risk classification thresholds: log values below 0 correspond to low risk (<1 MPN/100 mL), values between 0 and 1 correspond to intermediate risk (1-10 MPN/100 mL), values between 1 and 2 correspond to high risk (11-100 MPN/100 mL), and log values above 2 correspond to very high risk (>100 MPN/100 mL). For fluoride, the dot-dash line corresponds to the WHO guideline and KEBS standard of 1.5 mg/L.*

Although I focus in this thesis on the threat of illness from microbial contamination, the chemistry results speak to important context: some users and LWMs have concerns about fluoride and high salinity, and salinity is particularly important because it constrains response efficacy by reducing the usability of microbiologically safer source options. The source types that are preferred for drinking based on the cross-sectional household survey (shallow wells, earth dams; see Chapter 6) have the lowest salinity but the highest microbial risk. The piped surface water supplies have better results but are rarely free of *E. coli*. The groundwater supplies generally have good water clarity, but exhibit a broad range of *E. coli*, conductivity, and fluoride concentration. Finally, tanks with a mixture of groundwater and rainwater had fewer fluoride guideline exceedances but worse microbial quality. These results demonstrate that supply type is an inadequate proxy for water safety or acceptability.

The subsections that follow contain more details of the monitoring results for physicochemical parameters – focusing on fluoride, major ions, and trace elements – and microbial hazard assessment – focusing on *E. coli*, tryptophan-like fluorescence (TLF), and sanitary inspection scores.

## 4.1 Physicochemical Water Quality

Monthly sampling resolution did not capture clear seasonal patterns in physicochemical water quality except for the piped surface water PoCs, which had higher conductivity and pH during the dry season (Figures 4.3 and 4.4). The pH results were generally between 6.5 and 8.5, although some of the piped surface water samples were more strongly alkaline, particularly in the dry season. The deeper groundwater (piped from mechanised boreholes) had higher pH on average than the shallower groundwater (hand-pumped from shallow boreholes or dug wells).

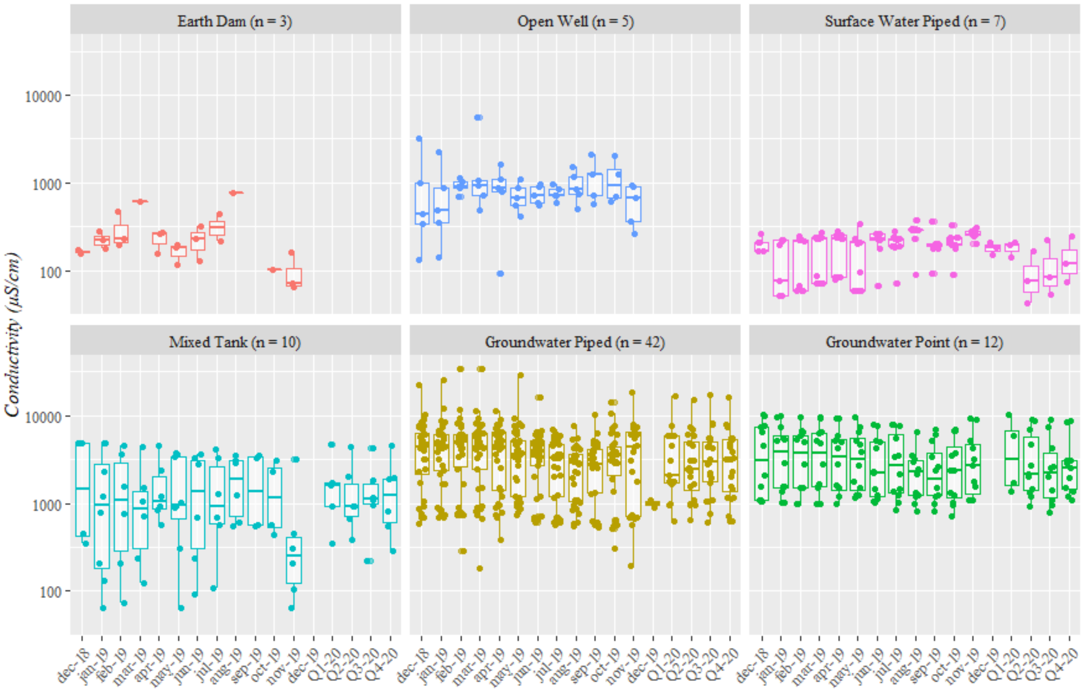



**Figure 4.3:** Summary plots of conductivity results by PoC type. *The presentation overlays box-and-whisker plots with dot plots to better represent the variability in the data.*

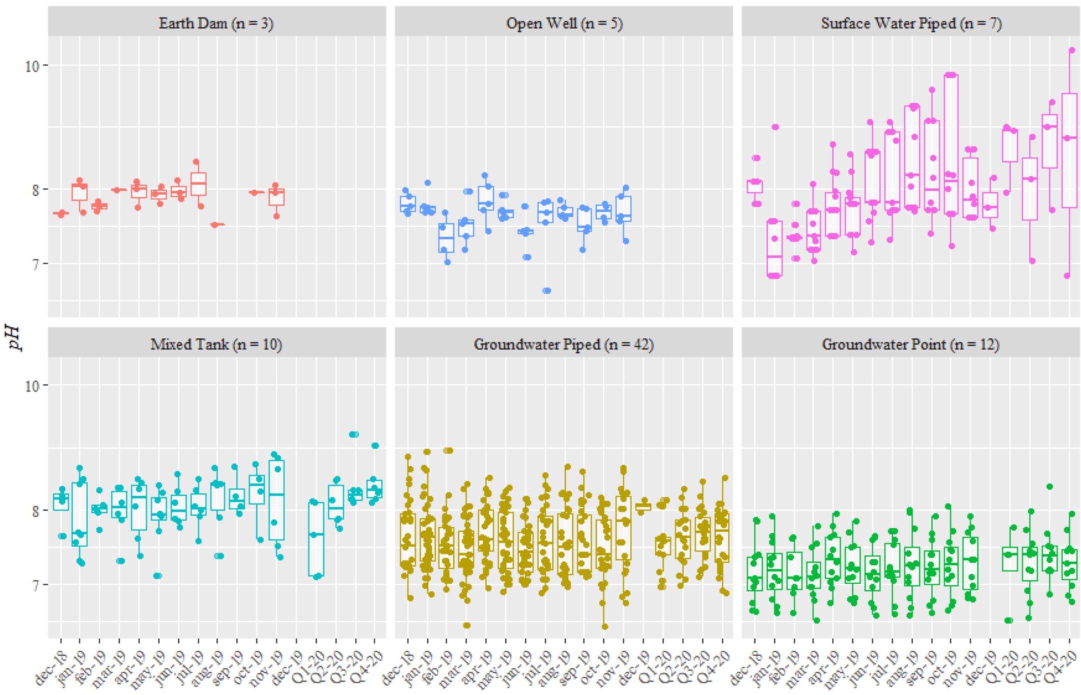



**Figure 4.4:** Summary plots of pH results by PoC type. *The presentation overlays box-and-whisker plots with dot plots to better represent the variability in the data.*

Ion chromatography found that sodium (Na), chloride (Cl), magnesium (Mg), and sulphate ($SO_4$) ions were the primary contributors to conductivity in the groundwater (Figure 4.5). While sodium can have direct impacts on health through blood pressure effects, there is insufficient evidence to establish health-based guidelines for sodium in water (Section 2.1). Nevertheless, an aesthetic guideline of 200 ppm[1] is recommended by the WHO and upheld by KEBS. This guideline reflects a water quality acceptability threshold, which can also have indirect health consequences. In Kitui County, for taste and satiation reasons, people may choose to drink water that has high microbial contamination risk because it is less salty.

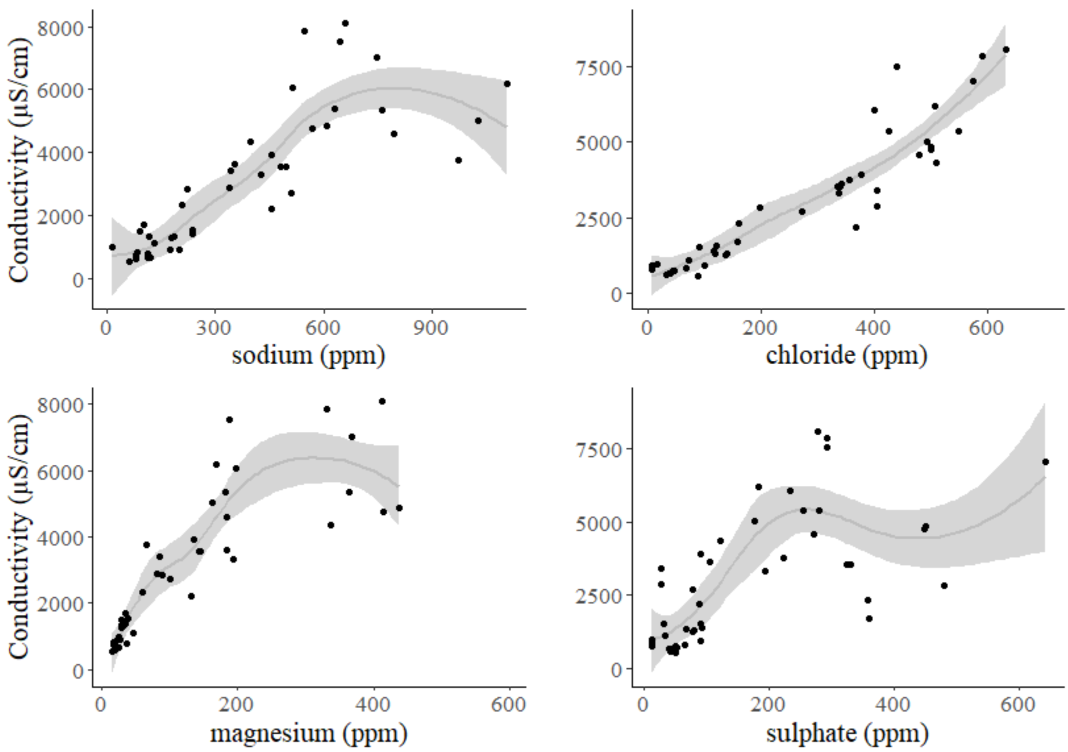



**Figure 4.5:** Scatter-plots of conductivity and major ions in samples from the groundwater PoCs. *The line through the data points shows the fit of a simple linear regression, with the grey shading showing the 95% confidence interval. Correlation coefficients are not reported because of low data accuracy at high concentrations for sodium, magnesium, and sulphate.*

[1]Parts per million (ppm) are equivalent to milligrams per litre (mg/L).

Fluoride was not correlated with conductivity (Figure 4.6), so conductivity measurements cannot be used to screen for supplies with hazardous fluoride concentrations. Furthermore, the fluoride results did not exhibit a spatial pattern across the monitored groundwater sites, so source location is not a good predictor of fluoride concentration. At low concentration (<1.5 ppm), fluoride has beneficial effects for prevention of dental caries, but long-term consumption of higher fluoride concentrations through water and food can cause dental and skeletal damage. Dental fluorosis is a concern when water contains >1.5 ppm of fluoride (which is the WHO guideline and KEBS standard for drinking-water); skeletal fluorosis is a concern above 3 ppm and crippling skeletal fluorosis is associated with concentrations above 10 ppm – although health impacts are driven by cumulative exposure so intake from food and inhalation must also be considered (WHO, 2017a). Most fluoride standard exceedances from the monitoring results were between 1.5 and 3 ppm and concentrations above 6 ppm were not recorded.

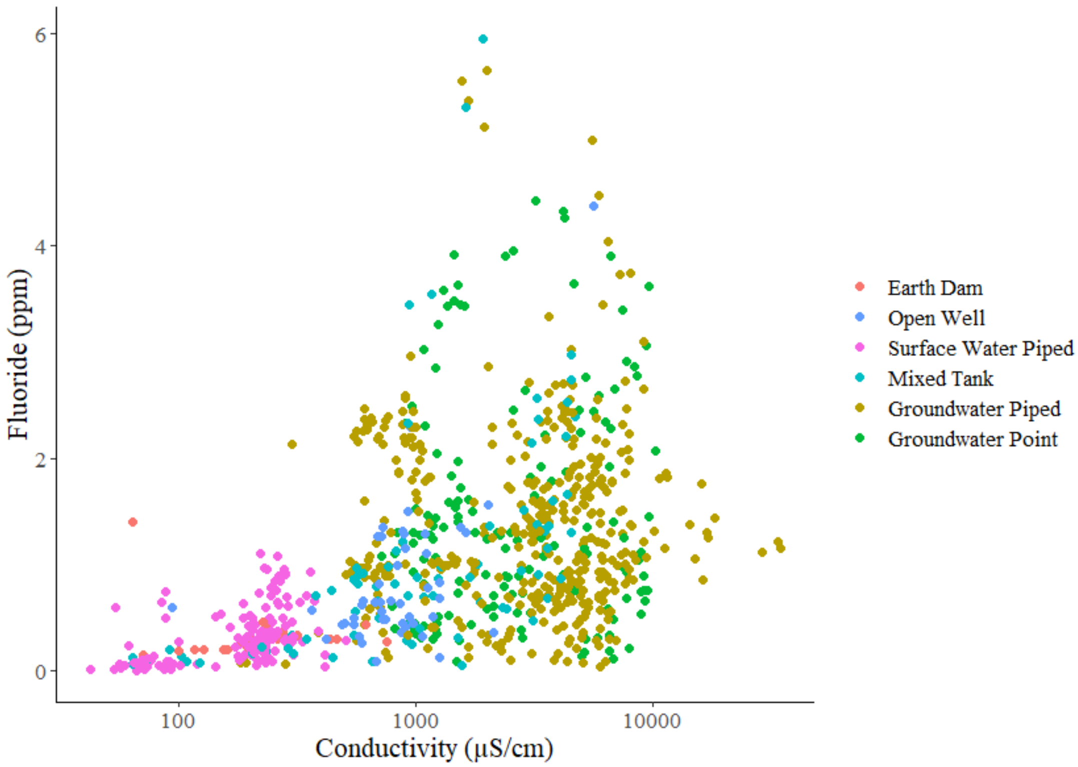



**Figure 4.6:** Fluoride and conductivity results from all sampling of the 79 monitored PoCs.

Fluoride and salinity (Na, Cl, Mg, $SO_4$) issues are well-recognised in Kitui County (by bureaucratic, community, and market-based stakeholders alike), but the major ions and trace elements screening also identified manganese, nitrate, selenium, and uranium guideline exceedances (Figure 4.7). While these contaminants do not appear to be widespread, they potentially complicate health risks from groundwater supplies in the area.

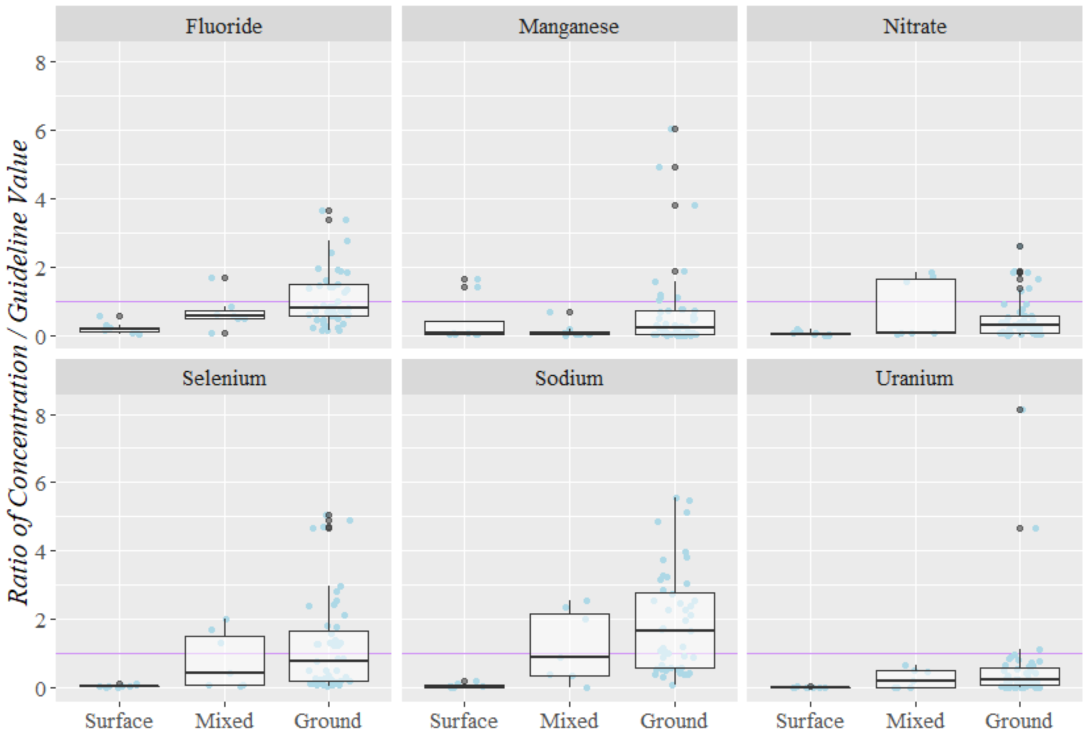



**Figure 4.7:** Box-and-whisker plots of the ratio of F, Mn, $NO_3$, Se, Na, and U concentrations over respective guideline values. *The box-and-whisker plots are underlain with dot plots (faded blue points) to better represent the underlying data. Where sample concentrations equalled guideline values, the ratio equals 1 (purple lines). Samples with ratios >1 were exceeding guidelines. The guideline values used in most of the ratio calculation are the KEBS drinking-water standards (KEBS reference KS EAS 12:2018): 1.5 ppm F, 0.1 ppm Mn, 45 ppm $NO_3$, 0.01 ppm Se, 200 ppm Na. For U, no KEBS standard is specified so the provisional WHO guideline value of 0.03 ppm was used.*

## 4.2 Microbial Water Quality

Focusing on the *E. coli* results, most sites exhibited variable microbial water quality over the study period (Figure 4.8). The least protected sites (earth dams and open wells) most consistently had very high risk results (>100 MPN/100 mL). The other sites had a larger range: 8% never had *E. coli* detected, 38% had *E. coli* detected less than 50% of the time, and 20% always had *E. coli* detected.


**Figure 4.8:** Summary plots of *E. coli* results by PoC type. *The presentation overlays box-and-whisker plots with dot plots to better represent the variability in the data.*

Due to the expense and delays associated with *E. coli* sampling, tryptophan-like fluorescence (TLF) was also measured during the monitoring programme to evaluate its utility for higher frequency sampling (Section 2.1.3). It quickly became apparent, however, that high concentrations of coloured dissolved organic matter (CDOM) in the water supplies (including the groundwater) interfered with the TLF signal to the extent that it could not be reliably associated with microbial contamination (Figure 4.9). Occasional outliers, where TLF was relatively high compared to CDOM were not linked to *E. coli* or total coliform (TC) counts.

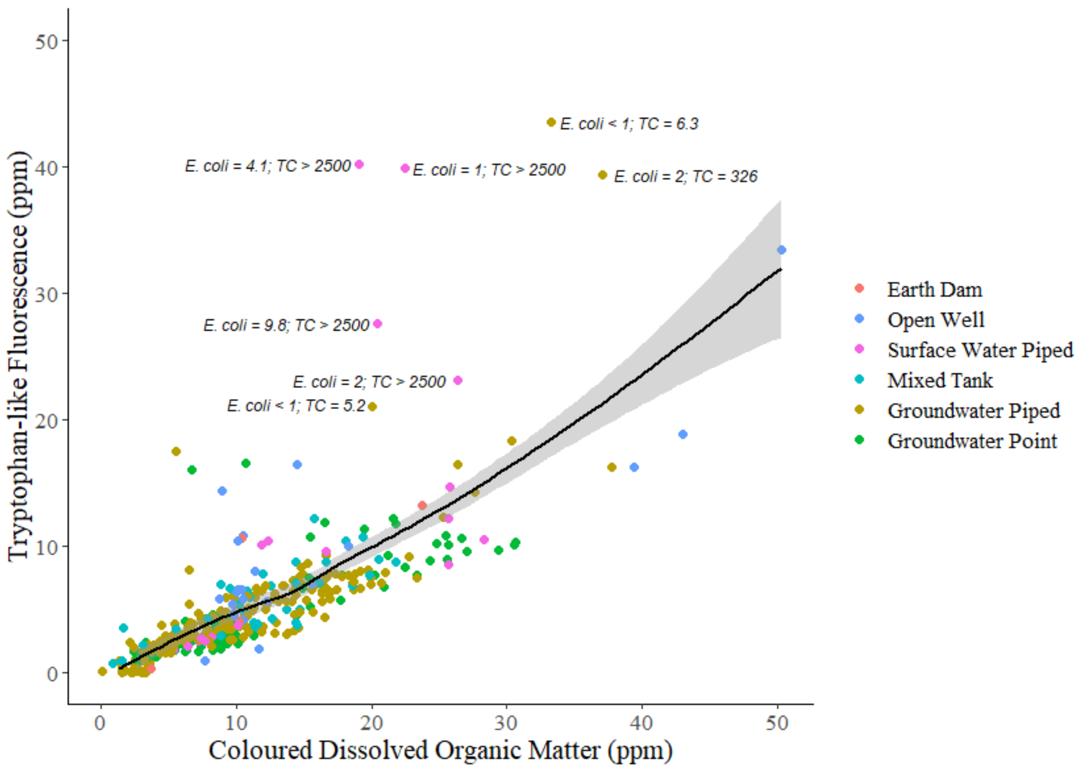



**Figure 4.9:** Concentrations of TLF and CDOM in the monitored PoCs. *The line through the data points shows the fit of a simple linear regression, with the grey shading showing the 95% confidence interval.*

TLF is generally expected to be unreliable for assessing the microbial quality of surface water (due to physicochemical and biological factors: Bridgeman et al., 2015), but in groundwater with low turbidity and pH between 5 and 8 it has more potential as an indicator – assuming that concentrations of CDOM are sufficiently low (Nowicki et al., 2019). The TLF excitation/emission region has overlap with CDOM fluorescence (Lapworth et al., 2009; Stedmon et al., 2011), so water that is naturally rich in CDOM will have a stronger apparent TLF signal that does not correspond to microbial activity from faecal contamination. Earlier efforts to establish TLF as a microbial contamination assessment tool did not explore this complication in-depth (e.g. Sorensen, Baker, et al., 2018; Sorensen et al., 2015), but the results of more recent work, including this thesis, establish it as a key drawback of the method in multiple locations (for example, in addition to the results from Kitui, unpublished data from a TLF pilot study I led in

Matlab, Bangladesh in 2018 demonstrated CDOM interference, and J. S. Ward et al., 2020, also discuss this issue based on their work with TLF in Malawi). I discontinued the TLF sampling in the second half of the monitoring programme in 2019.

In addition to exploring TLF as an option to better characterise microbial water quality variability, my study design incorporated a contrasting approach by including sanitary inspection (SI) as a means to decouple hazard assessment from indicator measurements. Although sanitary inspection scores are not expected to correlate with *E. coli* measurements at any given point in time, I hypothesised that they may be related to the variability of *E. coli* in water supplies over time (Section 2.1.3). I adapted the WHO guidance for sanitary inspections so that two scores were calculated after inspection of each monitored PoC (Section 3.2.4).

The second SI score includes discounting for treatment measures, but comparison of *E. coli* means and SI score means for each PoC found no correlation for either scoring method (Figure 4.10); neither were the mean SI scores related to the magnitude of the standard deviation of the *E. coli* results. Thus, the sanitary inspections were a useful tool for understanding the water supply conditions and discussing hazard control options with LWMs (Chapter 6), but the methods I used did not link the SI results to the variability of microbial water quality in the supplies (as judged by monthly *E. coli* sampling). Insufficient accuracy and precision in the sanitary inspection approach will have contributed to this null result, but the characteristics of *E. coli* as an imperfect indicator of contamination must also be considered (Section 2.1.2). In the next chapter, I explore the utility of *E. coli* as a contamination indicator for rural drinking-water in greater depth.

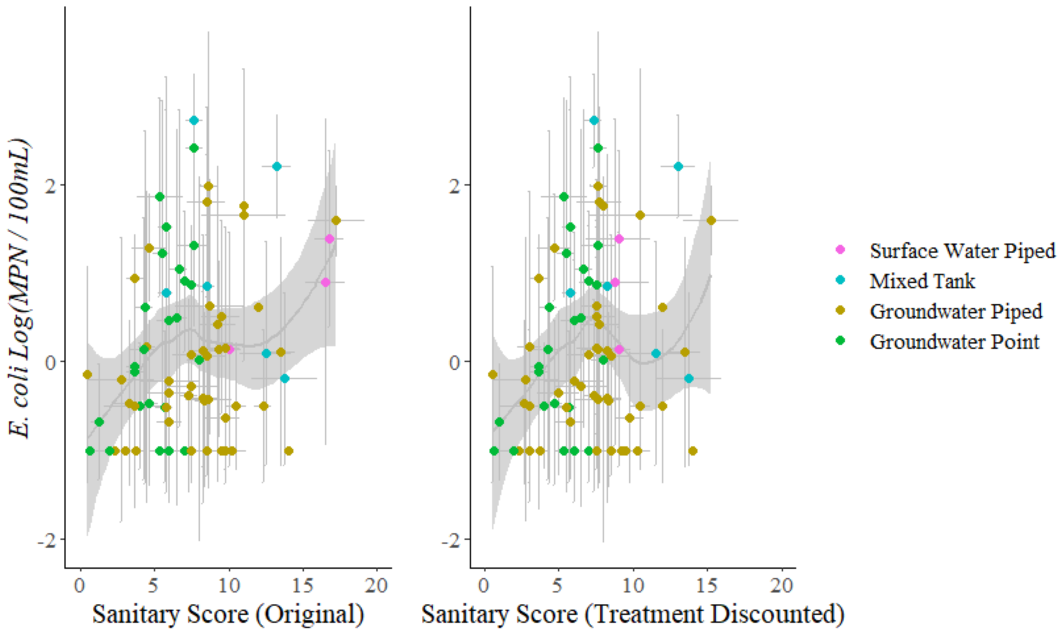



**Figure 4.10:** Comparison of sanitary inspection scores and $\log_{10}$ *E. coli* results. *The points show mean values and the error bars show plus and minus one standard deviation from the mean. The line through the data points shows the fit of a simple linear regression on the mean values, with the grey shading showing the 95% confidence interval. The E. coli and sanitary inspection means were not correlated for either score 1 (Kendall's $\tau$ = 0.17 for all sites and 0.13 for the groundwater sites) or score 2 ($\tau$ = 0.13 for all and 0.09 for groundwater only).*

*...the role of [Bacillus] coli as an indicator of excretal contamination*
*is as old as the bacteriology of water itself;*
*yet it is a matter of considerable doubt*
*whether the perfect bacterial indicator of faecal pollution exists even today.*
— Burke-Gaffney, 1932

# 5

# Genomic Characterisation of *E. coli*

The first guiding question of this thesis asks how uncertainties in understandings of hazard flows based on monitoring data influence the potential effectiveness of monitoring as a feedback mechanism. Based on the findings of my literature review, I narrowed the focus of my response to this question to engage specifically with the utility of *E. coli* as a contamination indicator (Section 2.1). The indicator-based approach for microbial contamination assessment, which is of particular significance for linking rural water quality monitoring to health concerns, contends with two key uncertainties in the relationship between pathogens and *E. coli* (Section 2.1.2). First, to what extent is *E. coli* at point of collection (PoC) linked to recent faecal contamination? Second, what are the health hazard implications of changes in *E. coli* concentration between PoC and point of use (PoU)? These long-standing (Burke-Gaffney, 1932) and strongly context dependant uncertainties are not easily resolved.

In this chapter, I present the findings of my work to better understand and account for these uncertainties. I isolated and comparing *E. coli* strains from nine of the water supplies that were included in the monitoring programme. I used whole genome sequencing to characterise each isolate to investigate the diversity of phylogroups, multi-locus sequence types (MLSTs), and virulence and antimicrobial resistance (AMR) genes within and between water supplies and household water storage (Section 3.3). The results contribute to characterisation of non-clinical *E. coli* populations in Kenya and, more specifically, provide insight into the occurrence of *E. coli* in rural water systems. They inform comparison between PoC and PoU conditions and enable reflection on the utility of *E. coli* as a faecal contamination indicator in rural mixed-infrastructure settings.

The results and discussion presented in this chapter are published in a peer-reviewed paper on “The utility of *Escherichia coli* as a contamination indicator for rural drinking water: Evidence from whole genome sequencing” (Nowicki et al., 2021). The co-authorship of this article reflects my collaboration with my supervisor and researchers from KEMRI as detailed in Chapter 3. I led the design, execution, and writing of the work as specified in the co-authorship statement in Appendix A. In this chapter, the work is presented in three main sections, which explain the sampling site selection (Section 5.1); present and discuss the phylogeny, virulence and AMR, MLST, and allelic diversity results (Section 5.2); and provide summary recommendations and directions for further research (Section 5.3).

## 5.1 Site Selection

The nine water systems in the *E. coli* sequencing study were chosen to include multiple supply types with varying degrees of protection against contamination (piped schemes sourcing water from boreholes or reservoirs and point sources including boreholes and hand-dug wells with or without handpumps). As explained in Section 3.3.3, the number of selected systems was constrained by the distances between sites and the allowable time between sampling and DNA extraction.

To be selected, a system had to be a main or alternative source of drinking-water with above zero median *E. coli* concentration from the monitoring programme results. Most of the selected systems are managed by LWMs and are either point sources or small (<5 km) piped distribution systems (Table 5.1), which include one or more storage tanks.

Only one of them is managed by a formal water service provider (FWSP). The water in this system is clarified and chlorinated in a water treatment facility and then piped through a 66 km distribution network. The local manager reported that dosing levels varied with chlorine availability and chlorine residual testing at PoCs was rare. The FWSP produces about 3000 $m^3$/day on average, but due to the size of the distribution system and high demand for water, the supply at the PoC is intermittent (approximately two days per week).

Two key factors constrained my total sample size: 1) I was limited to sampling one set per day because of the long distances between sites and the need to walk to many of the homesteads for collecting PoU samples, and 2) the field lab was not equipped for freezing samples nor doing clean DNA extractions, thus limiting the window of time available to me before samples had to be transported to a better-equipped lab to proceed with DNA extraction.

**Table 5.1:** Water systems included in the *E. coli* genomic characterisation study.

| Set Label | System Type | Source | Management | Protection | Treatment |
|---|---|---|---|---|---|
| S1 | piped | reservoir | community | no entrance advisory | none |
| S2 | piped | borehole | community & school | fenced | none |
| S3 | piped | borehole | community & school | not fenced | chlorine |
| S4 | piped | borehole | community | fenced | none |
| S5 | piped | reservoir | FWSP | fenced | chlorine |
| S6 | point | borehole | community | not fenced | none |
| S7 | point | borehole | community | fenced | none |
| S8 | point | dug well | private owner | not fenced | none |
| S9 | point | borehole | school | fenced | none |

With the help of my two research assistants, for each system, I sampled one or more PoCs (Table 5.2). For each PoC, I sampled multiple PoUs (Table 5.3). We asked water system managers and users to help us find homes with stored water. The goal was to sample at least three PoUs per PoC, but it was sometimes difficult to find households with stored water from the PoC of interest due to multiple source use and mixing water from multiple sources in home storage. Additionally, PoCs in schools (n = 3) were not associated with PoU storage because students drank directly from the standpipes or tank taps. A total of 44 sites were sampled including 14 PoCs and 30 PoUs. In this chapter, I refer to a system and its associated PoCs and PoUs as a set, and each sampling site is labelled according to its corresponding set, PoC and PoU (S#C#U#). Sites within a set were sampled on the same day.

During the sampling visits for this study, household water managers (as distinct from household heads who are not always aware of the details of water management in the home) reported that PoU water was transported by donkey, motorbike, wheelbarrow, or self-carry to be stored in either plastic drums (approx. 200 L) or 20 L jerrycans located either inside the main house, a separate shelter, or outside in a private or communal area. At the time of sampling, the water was reported to have been stored between zero and four days, with one or two days being most common (Table 5.3).

**Table 5.2:** PoC sites in the *E. coli* genomic characterisation study.

| Set Label | PoC Label | Type | Protection | Monitoring Sample Size |
|---|---|---|---|---|
| S1 | C1 | standpipe tap | n/a | 30 |
| | C2 | standpipe tap | n/a | 5 |
| S2 | C1 | standpipe tap | n/a | 7 |
| | C2 | standpipe tap | n/a | 7 |
| | C3 | standpipe tap | n/a | 5 |
| S3 | C1 | standpipe tap | n/a | 7 |
| | C2 | tap from concrete tank | unsealed | 7 |
| S4 | C1 | tap from plastic tank | well-sealed | 7 |
| | C2 | tap from concrete tank | unsealed | 25 |
| S5 | C1 | tap from plastic tank | well-sealed | 24 |
| S6 | C1 | handpump | n/a | 7 |
| S7 | C1 | handpump | n/a | 7 |
| S8 | C1 | bucket draw | n/a | 7 |
| S9 | C1 | tap from concrete tank | unsealed | 5 |

Respondents said that jerrycans were occasionally cleaned with sand; they did not approximate a washing schedule but said the decision to clean depends on the colour inside the jerrycan. Although the first household in set 8 reported occasional boiling and the third in set 6 reported occasional chlorination, none had treated the water that I sampled. PoU water was sampled in line with standard practice by asking the respondent to provide me with a cup of water that they would normally drink from.

The PoC sites had been sampled either weekly[1] or monthly for seven months (with some gaps due to breakdowns and dry periods). The median pH for each site ranged from 6.6 to 8.6 (Figure 5.1) and median conductivity ranged from 90 to 1600 $\mu$S/cm except for Sets 4 and 7, which had median conductivity of 5000 and 10,500 $\mu$S/cm, respectively (Figure 5.2)[2].

[1] Three of the monitoring sites were sampled weekly due to their proximity to the FundiFix office and initial intentions to assess the utility of frequent TLF samples. This weekly data was not useful due to the CDOM interference issue explained in Chapter 4, so in all other presentations of the results only monthly data from these three sites are used (to maintain comparability with the other sites).

[2] The managers reported that water from the saline sites is only used for drinking when better alternatives are unavailable due to dry periods, breakdowns, affordability, and intermittent FWSP supply.

**Table 5.3:** PoU sites in the *E. coli* genomic characterisation study.

| Set | PoC | PoU | Type | Days Stored | Transport | Storage | Location |
|---|---|---|---|---|---|---|---|
| S1 | C1 | U1 | homestead | 2 | motorbike | jerrican | main house |
| | | U2 | homestead | 1 | donkey | drum | separate shelter |
| | | U3 | homestead | 2 | donkey | drum | separate shelter |
| | | U4 | compound | 1 | donkey | jerrican | separate shelter |
| | | U5 | homestead | 1 | donkey | jerrican | outside |
| | | U6 | homestead | 1 | donkey | jerrican | main house |
| | C2 | U1 | homestead | 1 | donkey | drum | main house |
| | | U2 | homestead | 1 | donkey | jerrican | outside |
| | | U3 | homestead | 1 | donkey | jerrican | outside |
| S2 | C1 | U1 | town compound | 1 | wheelbarrow | drum | communal area |
| | | U2 | town compound | 2 | self-carry | jerrican | outside |
| | | n/a | no other stored | n/a | n/a | n/a | n/a |
| | C2 | U1 | homestead | 4 | motorbike | jerrican | main house |
| | | U2 | homestead | 2 | motorbike | drum | main house |
| | | U3 | town shop | 2 | wheelbarrow | drum with tap | storage room |
| | C3 | n/a | drink from tap | n/a | n/a | n/a | n/a |
| S3 | C1 | U1 | town compound | 1 | self-carry | jerrican | communal area |
| | | U2 | town home | 2 | self-carry | drum | main house |
| | | U3 | homestead | 1 | donkey | drum | outside |
| | | U4 | town home | 1 | self-carry | jerrican | main house |
| | C2 | n/a | drink from tap | n/a | n/a | n/a | n/a |
| S4 | C1 | U1 | homestead | 0 | self-carry | jerrican | outside |
| | | U2 | homestead | 0 | wheelbarrow | jerrican | separate shelter |
| | | n/a | no other stored | n/a | n/a | n/a | n/a |
| | C2 | n/a | no stored water | n/a | n/a | n/a | n/a |
| S5 | C1 | U1 | homestead | 2 | donkey | jerrican | outside |
| | | U2 | homestead | 1 | donkey | drum | main house |
| | | U3 | homestead | 1 | donkey | jerrican | main house |
| S6 | C1 | U1 | homestead | 1 | donkey | jerrican | main house |
| | | U2 | homestead | 1 | donkey | drum | outside |
| | | U3 | homestead | 1 | donkey | jerrican | separate shelter |
| S7 | C1 | U1 | homestead | 5 | donkey | jerrican | main house |
| | | U2 | homestead | 0 | self-carry | jerrican | outside |
| | | n/a | no other stored | n/a | n/a | n/a | n/a |
| S8 | C1 | U1 | homestead | 1 | donkey | jerrican | main house |
| | | U2 | homestead | 0 | donkey | jerrican | separate shelter |
| | | n/a | no other stored | n/a | n/a | n/a | n/a |
| S9 | C1 | n/a | drink from tap | n/a | n/a | n/a | n/a |

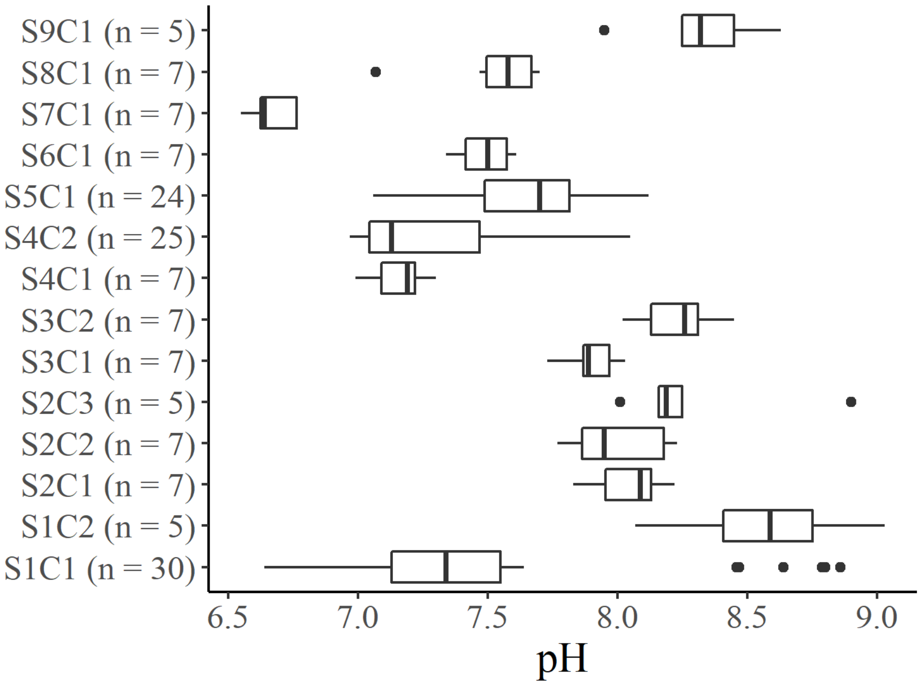



**Figure 5.1:** Box-and-whisker plot of pH results for the selected PoCs. *The boxes show median values and span lower to upper quartiles, the whiskers show the lowest and highest datums within 1.5 times the interquartile range.*

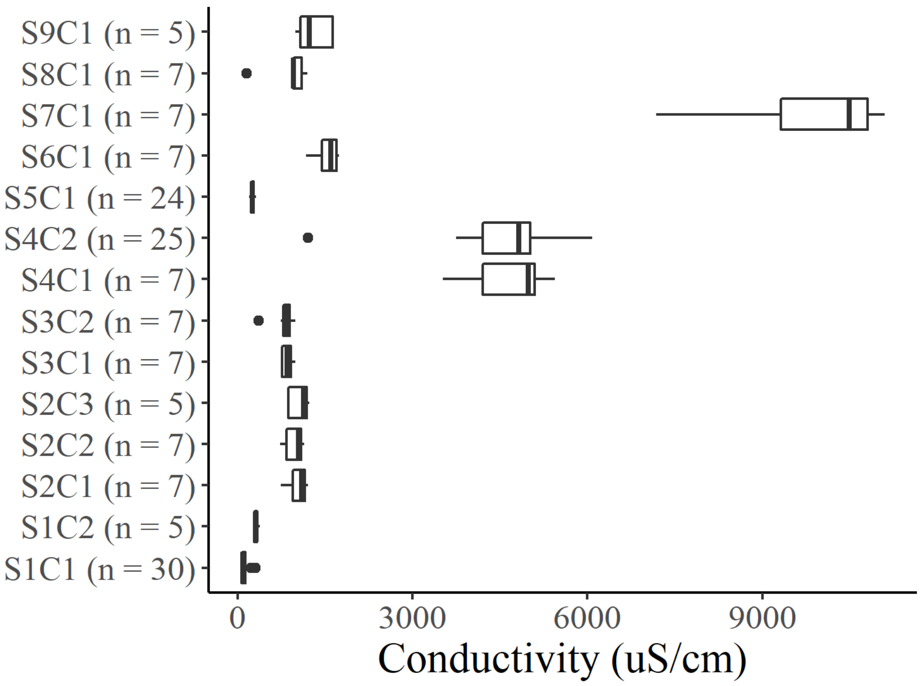



**Figure 5.2:** Box-and-whisker plot of conductivity results for the selected PoCs. *The boxes show median values and span lower to upper quartiles, the whiskers show the lowest and highest datums within 1.5 times the interquartile range.*

The median *E. coli* concentrations ranged from 1 to 920 MPN/100 mL, with all PoCs having variable results over the monitoring period (Figure 5.3).

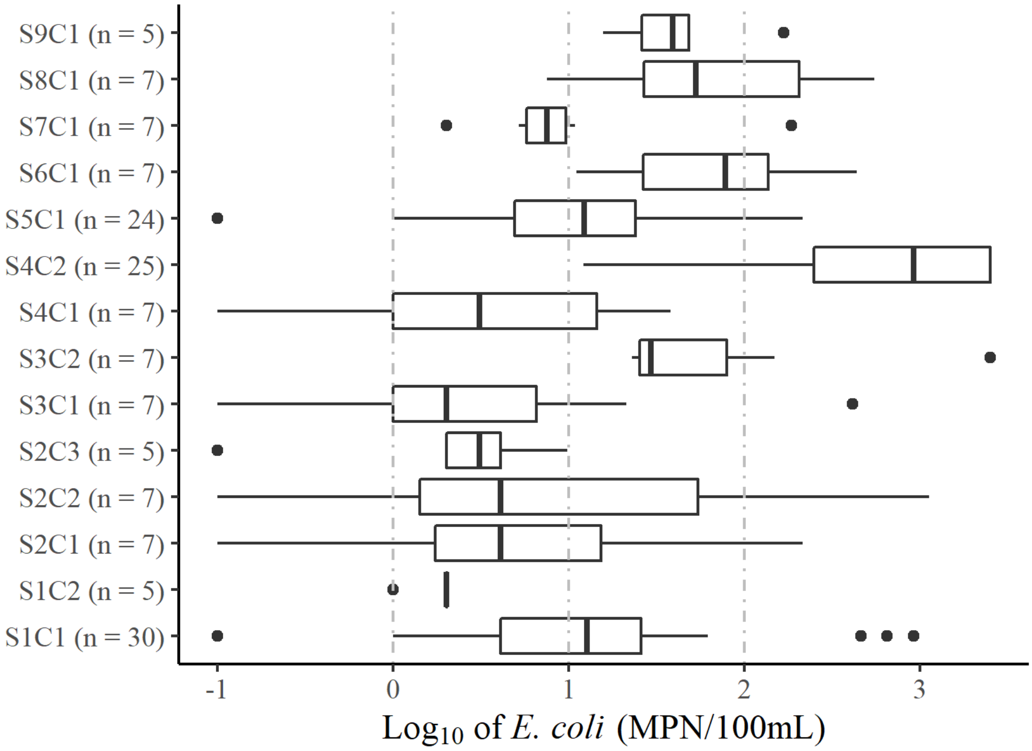



**Figure 5.3:** Box-and-whisker plot of $\log_{10}$ transformed *E. coli* results for the selected PoCs. *The boxes show median values and span lower to upper quartiles, the whiskers show the lowest and highest datums within 1.5 times the interquartile range. Data are censored by a lower bound of 0 MPN/100 mL and an upper bound of > 2419.6 MPN/100 mL. Results at the lower bound were converted to 0.1 (log = -1) and results at the upper bound were converted to 2500 (log = 3.4). Vertical dashed grey lines show the WHO recommended risk category cut-offs (WHO, 2017a) with E. coli equal to 1, 10, and 100 MPN/100 mL (corresponding to log values of 0, 1, and 2). The risk categories are low (<1), intermediate (1-9), high (10-99), and very high (>99).*

## 5.2 Overview and Discussion of Results

The sampling effort targeted six isolates for each of the 44 sites, but fewer were sequenced for 16 sites and none were sequenced for 20 sites. This was because of low or no concentration of *E. coli* in the sample water (S1C1, S1C1U1/U3-6, S1C2, S1C2U2-3, S2C2U1, S2C3, S3C1, S3C1U1-2/4, S4C1, S4C1U1-2, S5C1, S5C1U1, S6C1, S7C1) or high concentration of thermotolerant coliforms (TTCs) preventing clean selection of six colonies (S1C2U1, S2C2U3, S3C1U3, S4C2-A, S5C1U2, S5C1U3, S6C1U2, S7C1U2). Other issues preventing sequencing of isolates included thermotolerant coliform (TTC) contamination of the agar plate (one isolate each from S3C2 and S7C1U1); limited growth on the agar plate (one isolate from S2C1U2); inadequate DNA extraction (one isolate from S4C2-B); and sequencing library preparation failure (one isolate from S2C1U1).

A total of 125 libraries were successfully sequenced, including four duplicates. The raw sequence reads are publicly available, having been deposited in the European Nucleotide Archive under study accession number PRJEB40218[1]. A full list of the sequenced isolates with sequencing, assembly, phylogroup, MLST, virulome, and resistome results is available in the supplementary material[2] of the paper that I published on this study (Nowicki et al., 2021).

The duplicates were consistent in phylogroup and sequence type. They are not otherwise included in the results. Six of the libraries were contaminated with non-*Escherichia* DNA, five from S1C1U2 contained *Cronobacter sakazakii* and one from S5C1U2 contained *Klebsiella pneumoniae*. These libraries were removed from further analysis. The remaining 115 libraries had 628,219 reads per library on average (SD = 145 199), with mean read length of 177 bp (SD = 7), mean PHRED quality score of 31 (SD = 0.7), and mean depth of 23 (SD = 6). BUSCO assessment of the genomes assembled from these 115 libraries identified 12 chimeric genomes. Excluding the chimeric genomes, the reads from each library assembled into an average of 246 contigs (SD = 141), with mean genome size of 4.8 Mbp (SD = 0.2).

Four of the chimeric genomes have multiple perfect allele matches for at least one of the Achtman MLST genes, confirming them as chimeras of multiple MLSTs. A further three of them have imperfect identity matches for multiple

[1]http://www.ebi.ac.uk/ena/data/view/PRJEB40218
[2]https://doi.org/10.1371/journal.pone.0245910.s006

alleles (ranging from 86.5% to 99.8% identity match) and do not correspond to known sequence types. These seven chimeras with multiple MLSTs or imperfect allele matches were excluded from further analysis. The remaining five chimeric genomes contain only one match for each MLST gene with perfect identity matches for each allele. These single MLST chimeric genomes are included in the ClermonTyping and MLST results (total of 108 isolates) but I excluded them from the pangenome and virulence and AMR analyses (total of 103 isolates).

### 5.2.1 Pan-genome and Phylogeny

The pan-genome of my isolates and the 14 references strains that were included for comparison has a total of 25,526 genes, including 1794 core genes (in $\geq$ 99% of the genomes), 1201 soft core genes (in $\geq$ 95%), 2152 shell genes (in $\geq$ 15%), and 20,379 cloud genes (in $<$ 15%). The phylogenetic tree generated from the core genes (Figure 5.4) reflects the ClermonTyping characterisation of my isolates except for isolate 2-8B (MLST 3519), which the in silico assays classified as phylogroup A but was closer to B1 isolates in the Mash estimation and the phylogenetic tree. I note that the MLST 3519 entries in the Warwick Enterobase database are also classified as phylogroup A with AxB1 lineage (Zhou et al., 2020). When the phylogenetic tree nodes are colour-coded by set (Figure 5.5), the evolutionary similarity of the isolates is observed to be unrelated to the water system that they came from.

The ClermonTyping analysis classified 69 isolates from 21 sites as belonging to phylogenetic group B1, making B1 the most represented group in the sample set. The second-most prevalent is group A with 15 isolates from 8 sites, followed by group B2 with 14 isolates from 3 sites, group D with 6 isolates from 4 sites, and group E with 3 isolates from 3 sites.

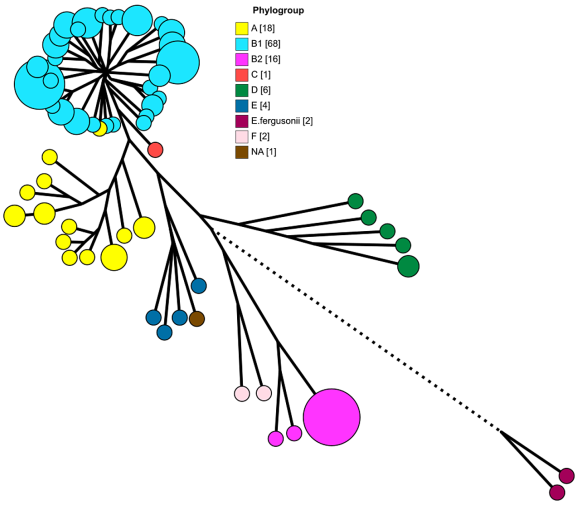



**Figure 5.4:** Phylogenetic tree with nodes coloured by phylogroup as determined by ClermonTyping. *The bracketed numbers in the image keys indicate the number of isolates in each category. The tree is scaled to 125%. Branches with length less than 0.0006 nucleotide substitutions per site were collapsed and the size of the nodes is scaled to indicate the number of isolates each one encompasses. The branch length for E. fergusonnii was shortened from 0.05 to 0.03 substitutions per site.*

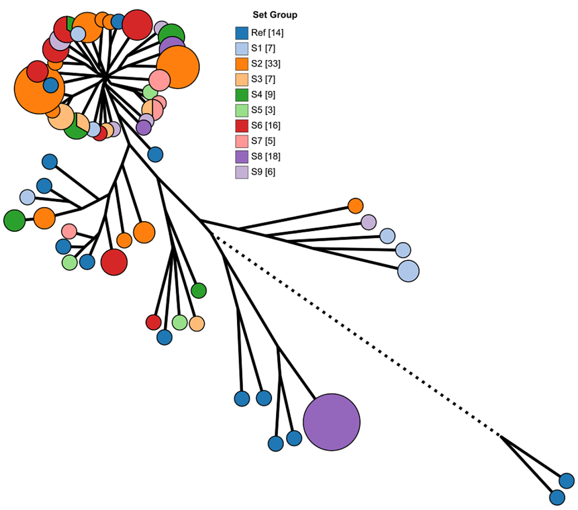



**Figure 5.5:** Phylogenetic tree with nodes coloured by sample set.

One isolate from S3C2 could not be classified by ClermonTyping, but the phylogenetic tree indicates that it belongs in phylogroup E (Figure 5.4). Cryptic clade *E. coli*, the group most strongly associated with environmental origins (Devane et al., 2020; Ingle et al., 2011), were not identified.

The association between phylogroup and strain origin varies based on diet, hygiene, animal domestication status, and morphological and socioeconomic factors (Tenaillon et al., 2010). Some localised studies have found differences in the relative frequency of phylogroups by strain origin (Smati et al., 2015), but others have not (Julian et al., 2015). A review of results from both higher and lower income countries in Europe, Africa, the Americas, Asia, and Australia (Tenaillon et al., 2010) found that phylogroup B1 strains were dominant in animals (41% of the reviewed B1 isolates were from animals or animal faeces), followed by A (22%), B2 (21%), and D strains (16%); whereas A strains were most common in humans (40.5%), followed by B2 (25.5%) and then B1 and D strains (17% each). Phylogroup B1 strains, which may be more common in animal faeces than in humans, comprised 78% of my PoC isolates and 50% of my PoU isolates. In contrast, A strains, which may be more common in humans, comprised 4% of my PoC isolates and 22% of my PoU isolates.

The dominance of phylogroup B1 and A strains in my samples does not necessarily indicate recent faecal contamination. Strains from B1 and A are better generalists and are more prevalent in freshwater samples than other strains (Donnenberg, 2013). B1 strains, especially, have been found to survive best in the environment (Bergholz et al., 2011; Walk et al., 2007), and in freshwater specifically (Berthe et al., 2013; Orsi et al., 2007; Ratajczak et al., 2010; Touchon et al., 2020), and phenotypes linked to environmental survival are relatively prevalent in B1 isolates (Méric et al., 2013; A. P. White et al., 2011). In contrast, B2 and D isolates do not survive well and are under-represented in freshwater (Donnenberg, 2013; Touchon et al., 2020). Less is known about phylogroup E, which is a small set of formerly unassigned strains that are relatively uncommon, historically difficult to cluster phylogenetically, and generally understudied (Clermont et al., 2013; Wirth et al., 2006) – except for the O157:H7 serotype, which is clinically important but is excluded by typical culture methods that rely on $\beta$-glucuronidase activity.

### 5.2.2 Virulence Genes

For the 103 non-chimeric isolates, a total of 184 virulence genes were identified with 100% identity and coverage[1]. These genes represent eight functional groups including secretion (67 genes), adherence (54 genes), iron uptake (46 genes), chemotaxis and motility (6 genes), invasion (5 genes), immune evasion (3 genes), autotransport (2 genes), and toxin production (1 gene). Most of the genes occur with low frequency across the isolates, and the number of genes possessed by any one isolate ranges from 34 to 94, with most having between 40 and 60 (Figure 5.6). Isolates from phylogenetic group A have the least virulence genes (mean = 43, SD = 6.7), and isolates from groups B2 (63, 0.5), E (67, 1.7), and D (75, 9.2) have higher numbers than most B1 isolates (55, 10.1).

Due to the plasticity of the *E. coli* genome, it can be challenging to define and identify pathovars, but some combinations of virulence genes have been linked to different *E. coli* pathotypes (Chen et al., 2016; Kaper et al., 2004). Genes for Shiga toxin production were not identified, ruling out presence of enterohemorrhagic *E. coli* (EHEC) or Shiga toxin-producing *E. coli* (STEC). Eight isolates from phylogroup B1 have multiple enteropathogenic *E. coli* (EPEC) associated virulence genes for adherence, autotransport, invasion, iron uptake, motility, secretion, and toxin production, but they lack key bundle-forming pili (*bfp*) and intimin (*eae*) genes, suggesting that they are neither typical nor atypical EPEC

[1]The complete list per isolate can be found at https://doi.org/10.1371/journal.pone.0245910.s006

(Robins-Browne et al., 2004). Similarly, all twenty isolates from phylogroups D or B2 have multiple genes that are associated with uropathogenic *E. coli* (UPEC) and / or neonatal meningitis-associated *E. coli* (NMEC), but all are missing key genes such as *fdeC* for adherence or *cnf1* for toxin production.

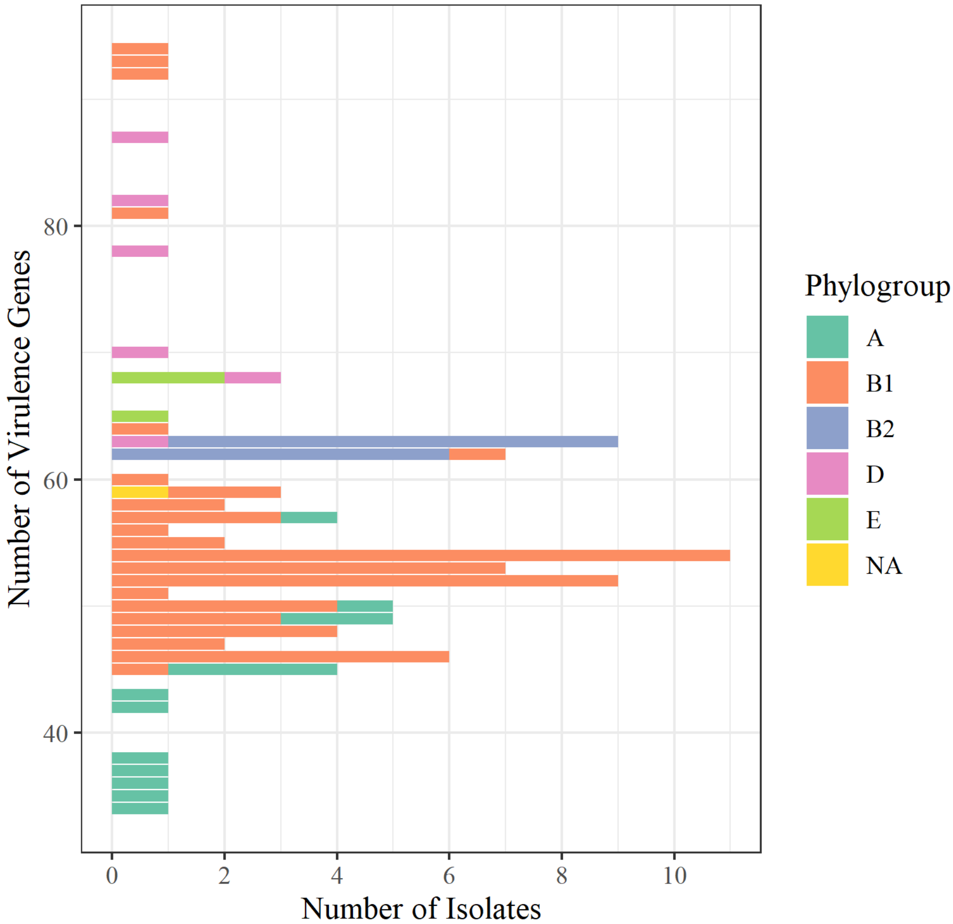



**Figure 5.6:** Stacked bar chart displaying the number of virulence genes per isolate by phylogroup.

None of my isolates were identified as complete pathovars, but the presence of virulence genes is informative, nonetheless, since virulence genes are more prevalent in strains isolated from humans and the trend is conserved within phylogroups (Tenaillon et al., 2010; Touchon et al., 2020). Four phylogroup B1 isolates have exceptionally high numbers of virulence genes (>80), suggesting that they are human derived. All four were isolated from PoU sites (S3C1U3, S6C1U1, S6C1U3). Furthermore, the phylogroup B2 and D isolates possessed more virulence genes than most of the A and B1 isolates. Taken together with evidence of their relatively poor survival in the environment (Donnenberg, 2013; Touchon et al., 2020), this further supports that the PoC and PoU sites that had B2 or D isolates were subject to recent contamination. This applies to three PoC sites that were poorly protected from contamination (S1C1, an open reservoir; S8C1, an open dug well; S9C1, an unsealed concrete tank) and four household sites (S1C2U1, S2C1U2, S8C1U1, S8C1U2).

### 5.2.3 Antimicrobial Resistance Genes

For the 103 non-chimeric isolates, a total of 24 AMR genes were identified with 100% identity and coverage, with every isolate having at least one AMR gene associated with resistance to aminoglycosides, beta-lactams, erythromycin, quaternary ammonium compounds, sulphonamides, tetracycline, or trimethoprim. Additionally, arsenite resistance gene *arsB-mob*, which codes for an arsenite efflux pump, was found in 82 isolates. Arsenic resistance can develop in response to use of arsenicals in antimicrobial drugs or in response to naturally occurring arsenic in the environment (Ferrie, 2014). Concentrations of arsenic were low at the PoC sites, ranging from 0.04 to 0.95 ppb. As such, geogenic arsenic is unlikely to explain the prevalence of the *arsB-mob* gene. Furthermore, the absence of additional arsenic resistance genes suggests that the presence of *arsB-mob* may not be related to drug use or geogenic arsenic, rather research into broad arsenic resistance in prokaryotes points to ancestral gene clusters as a likely explanation (Fekih et al., 2018).

Excluding *arsB-mob*, at least one AMR gene was found in each of the 103 isolates. Most occur with low frequency across the isolates[1], with 88 isolates having only one gene. AMR genes are transferable between bacteria via plasmids,

[1] See https://doi.org/10.1371/journal.pone.0245910.s006 for a list of AMR genes per isolate

and environmental reservoirs of resistance genes are widely recognised, including freshwater and drinking-water systems (Davies & Davies, 2010; Haberecht et al., 2019). Nevertheless, multiple AMR genes may be more common in *E. coli* strains sourced from human as opposed to animal or naturalised populations (Devane et al., 2020; Iramiot et al., 2020; Mainda et al., 2019). Four PoU sites had isolates with multiple AMR genes including three phylogroup D isolates (7 to 12 genes each; S1C2U1) and six phylogroup B1 isolates (4 to 7 genes each; S2C2U1, S3C1U3, S7C1U1). Additionally, two PoC sites (S4C2 and S9C1, both unsealed concrete tanks) had phylogroup B1 isolates with 4 to 7 AMR genes each.

### 5.2.4 Multi-Locus Sequence Types

Using the Achtman MLST scheme, I identified a total of forty previously known sequence types among my isolates (Table 5.4). The number of entries for these MLSTs in the Warwick Enterobase database (as of May 2020) ranged from 1 to 7763; ten of the MLSTs had not previously been identified in Kenya; and six of the isolates have MLST allele combinations that were not represented in the database, I have labelled them New1 to New6[1].

I refer to a system and its associated PoCs and PoUs as a set. The main discriminating factor between the sequence types is the set that the isolate came from (Figure 5.7). The sequence types generally do not overlap between sets, except in the cases of ST10, SW180, ST345, and ST216. I also looked at the overlap in sequence types between matched PoC and PoU sites. There was no overlap for set 1, but sets 2, 6, and 8 did have overlap. For sets 3 and 5, no *E. coli* was isolated from the PoCs (except S3C2, which is an unsealed concrete water tank at a school that is unrepresentative of the wider distribution system). For sets 4, 7, and 9, *E. coli* was only isolated from one site each.

[1]See https://doi.org/10.1371/journal.pone.0245910.s006 for the new allele combinations.

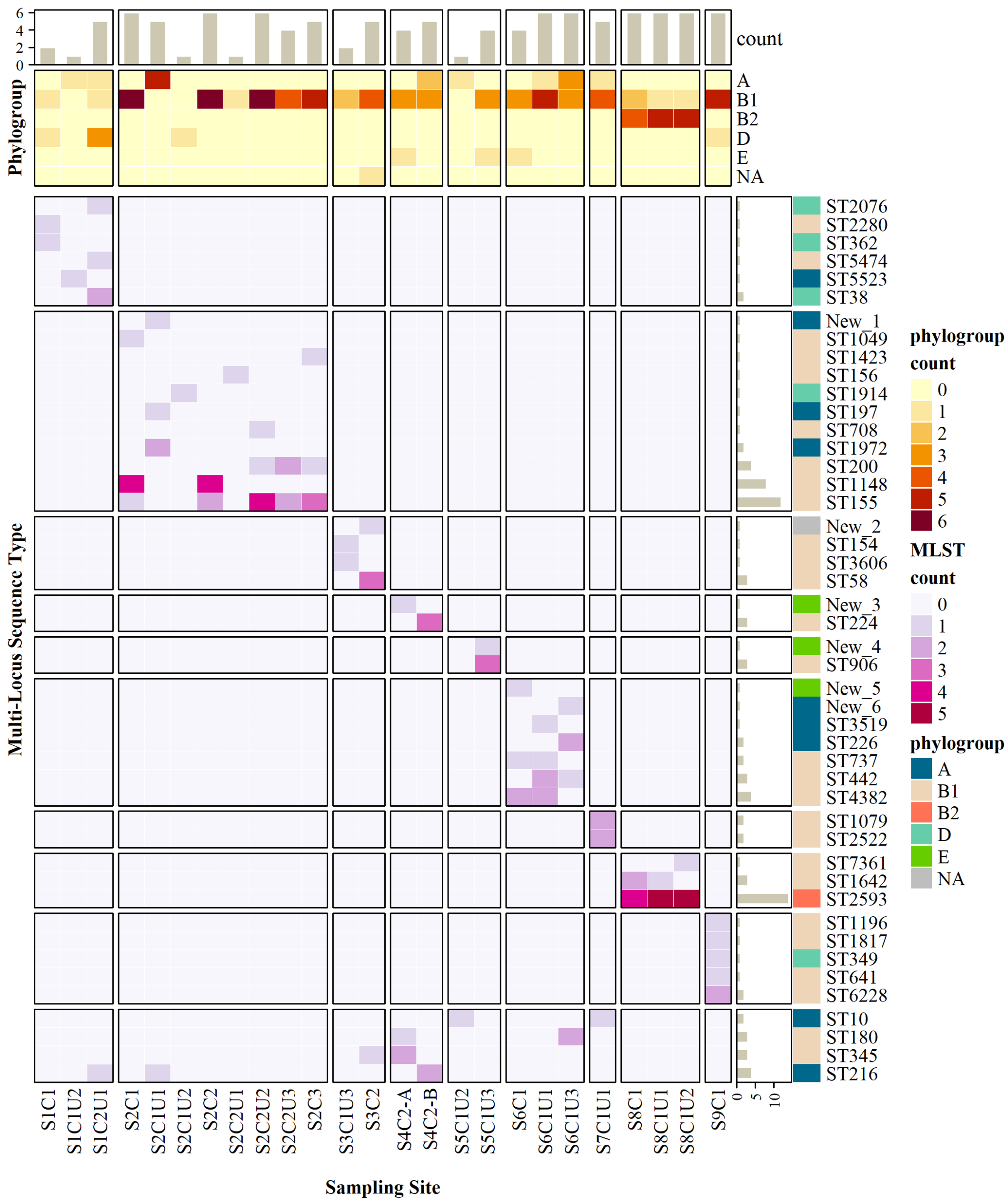



**Figure 5.7:** Heatmap of phylogenetic groups and MLSTs identified for each sampling site. *Colour gradients indicate number of isolates. Bar chart annotations show total counts of isolates per MLST (right) and per site (top). The heatmap was created with R package 'ComplexHeatmap' (Gu et al., 2016).*

Logically, five scenarios may dictate the population of *E. coli* in PoU water, these are permutations of three factors: presence or absence of *E. coli* in the PoC water, whether PoC strains retain culturability in PoU water, and whether post-collection hygiene conditions introduce new strains. The scenarios are:

1. mixed contamination
2. post-collection contamination
3. water system strain survival
4. abatement of *E. coli*
5. *E. coli* free water is maintained

Although the isolates analysed in my study allow only a partial view of the diversity of *E. coli* strains at each sampling site, comparison of the MLSTs isolated from matched PoC and PoU sites suggests that multiple PoUs exemplified each of the five scenarios (Figure 5.8).

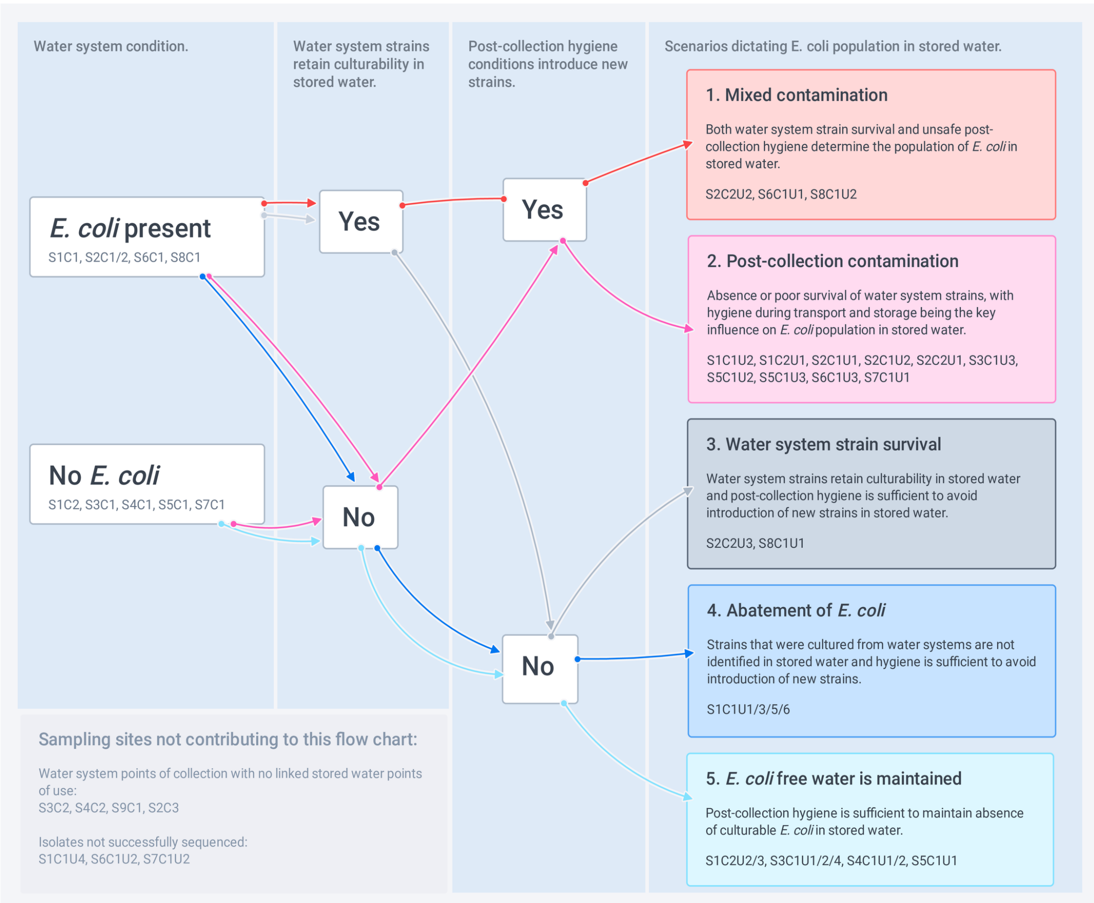



**Figure 5.8:** Five scenarios theorised to explain the population of *E. coli* in stored water at point of use. *Scenarios are based on sustained presence of strains that were isolated from the water supply system and addition of new strains during post-collection transport and storage.*

In scenarios 3, 4, and 5 no additional health hazard is introduced at the household level: *E. coli* in PoU water is determined by PoC water quality and persistence or abatement of strains in storage containers. Abatement of *E. coli* does not equate to abatement of pathogens (decreased health risk), so PoC results should be prioritised in these scenarios. In scenarios 1 and 2, inadequate hygiene at the household level does influence PoU *E. coli* population, either as the exclusive driver (scenario 2) or in combination with persistence of PoC *E. coli* strains (scenario 1).

Only five of the households that I sampled had overlap in MLSTs between PoC and PoU (scenarios 1 and 3), this points to strain persistence but is not evidence of regrowth. Nevertheless, the results are interesting in light of research that a) found increase in *E. coli* between PoC and PoU was unrelated to household-level sanitary or hygiene factors (Trevett et al., 2004) and b) demonstrated regrowth in household storage containers within 48 hours (Momba & Kaleni, 2002). Conversely, scenario 2, post-collection contamination, appears to be the most common for the households that I sampled, which is consistent with studies that relate PoU water quality deterioration to unsafe storage (Levy et al., 2008; Sobsey, 2002).

The health implications of post-collection contamination are debated. In households like those in my study area, with low levels of access to sanitation and hygiene facilities, *E. coli* and other faecal indicators and pathogens are widespread on surfaces and in food produce (Pickering et al., 2012) and it is likely that strains circulate between humans, animals, and the domestic environment (Montealegre et al., 2020; Tenaillon et al., 2010). Large-scale randomised control trials investigating the impact of water, sanitation, and hygiene interventions on health outcomes for communities in Kenya, Bangladesh and elsewhere have demonstrated the importance of considering multiple faecal exposure pathways (B. Arnold et al., 2018). In a household setting, where there are multiple pathways for exposure to pathogens that are circulating in the household environment, focusing on only one of these pathways (stored water) is unlikely to reduce the burden of enteric disease in the household (Feachem et al., 1978; Robb et al., 2017). In contrast, a contaminated water distribution system may pose a unique threat as a pathway for spreading disease between households and, in some cases, between communities.

**Table 5.4:** Identified MLSTs grouped by water system and counts of corresponding Enterobase database entries as of May 2020.

| Set | MLST | Phylogroup | Isolates | Enterobase total | Enterobase Kenya |
|---|---|---|---|---|---|
| S1 | ST5523 | A | 1 | 10 | 1 |
| | ST5474 | B1 | 1 | 6 | 0 |
| | ST2280 | B1 | 1 | 21 | 6 |
| | ST2076 | D | 1 | 15 | 3 |
| | ST362 | D | 1 | 198 | 2 |
| | ST38 | D | 2 | 1616 | 4 |
| S1 \| S2 \| S4 | ST216 | A | 4 | 131 | 14 |
| S2 | ST1972 | A | 2 | 9 | 1 |
| | ST1914 | D | 1 | 35 | 0 |
| | ST1423 | B1 | 1 | 38 | 0 |
| | ST1148 | B1 | 8 | 36 | 1 |
| | ST1049 | B1 | 1 | 75 | 4 |
| | ST708 | B1 | 1 | 13 | 1 |
| | ST200 | B1 | 4 | 167 | 3 |
| | ST197 | A | 1 | 6 | 1 |
| | ST156 | B1 | 1 | 301 | 9 |
| | ST155 | B1 | 12 | 1059 | 76 |
| | New1 | A | 1 | 0 | 0 |
| S3 | ST3606 | B1 | 1 | 1 | 0 |
| | ST154 | B1 | 1 | 238 | 1 |
| | ST58 | B1 | 3 | 1333 | 38 |
| | New2 | NA | 1 | 0 | 0 |
| S3 \| S4 | ST345 | B1 | 3 | 166 | 4 |
| S4 | ST224 | B1 | 3 | 293 | 16 |
| | New3 | E | 1 | 0 | 0 |

Continued on next page...

**Table 5.4 – continued from previous page**

| Set | MLST | Phylogroup | Isolates | Enterobase Total | Enterobase Kenya |
|---|---|---|---|---|---|
| S4 \| S6 | ST180 | B1 | 3 | 6 | 1 |
| S5 | ST906 | B1 | 3 | 199 | 5 |
| | New4 | E | 1 | 0 | 0 |
| S5 \| S7 | ST10 | A | 2 | 7763 | 123 |
| S6 | ST4382 | B1 | 4 | 13 | 0 |
| | ST3519 | A | 1 | 16 | 1 |
| | ST737 | B1 | 2 | 26 | 1 |
| | ST442 | B1 | 3 | 599 | 5 |
| | ST226 | A | 2 | 150 | 4 |
| | New5 | E | 1 | 0 | 0 |
| | New6 | A | 1 | 0 | 0 |
| S7 | ST2522 | B1 | 2 | 68 | 7 |
| | ST1079 | B1 | 2 | 207 | 5 |
| S8 | ST7361 | B1 | 1 | 2 | 0 |
| | ST2593 | B2 | 14 | 1 | 0 |
| | ST1642 | B1 | 3 | 36 | 0 |
| S9 | ST6228 | B1 | 2 | 2 | 0 |
| | ST1817 | B1 | 1 | 18 | 0 |
| | ST1196 | B1 | 1 | 151 | 7 |
| | ST641 | B1 | 1 | 348 | 11 |
| | ST349 | D | 1 | 337 | 2 |

### 5.2.5 Allelic Diversity

In addition to directly comparing MLSTs, I queried the differences between sites further by using the MLST genes to analyse differences in the diversity of the isolates from the lower (<50 CFU/100 mL) and higher (>50 CFU/100 mL) concentration PoC and PoU sites. I found that all loci are polymorphic in all groupings (Table 5.5) and the diversity of alleles ($h_j$) ranges from 0.32 to 0.91. A permutation test comparing all four of the sub-groups (PoU-H, PoU-L, PoC-H, and PoC-L) found that the grouping has an effect on diversity (z = 2.47, p = 0.0499);

more specifically, pairwise tests found that the PoC-L group is less diverse than both the PoC-H group (z = 2.12, p = 0.03) and the PoU-H group (z = 2.29, p = 0.02). No other pairwise differences are significant, including comparisons of the PoU sites versus the PoC sites (z = 1.13, p = 0.26), the high concentration sites versus the low concentration sites (z = 1.82, p = 0.07), or the PoU-L sites versus the PoU-H sites (z = 1.4, p = 0.17).

**Table 5.5:** Genetic diversity of alleles ($h_j$) and average genetic diversity ($H$) for groupings based on source type (PoC vs PoU) and *E. coli* concentration level (higher or lower than 50 MPN/100 mL)

| **Groups** | **H** | **Diversity of Alleles ($h_j$)** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | ***adk*** | ***fumC*** | ***gyrB*** | ***icd*** | ***mdh*** | ***purA*** | ***recA*** |
| All | 0.8 | 0.63 | 0.83 | 0.9 | 0.87 | 0.85 | 0.7 | 0.81 |
| PoU | 0.8 | 0.72 | 0.88 | 0.88 | 0.89 | 0.86 | 0.7 | 0.82 |
| PoC | 0.8 | 0.51 | 0.76 | 0.9 | 0.84 | 0.81 | 0.71 | 0.76 |
| Higher | 0.8 | 0.74 | 0.84 | 0.89 | 0.87 | 0.84 | 0.77 | 0.8 |
| Lower | 0.7 | 0.44 | 0.78 | 0.84 | 0.82 | 0.8 | 0.54 | 0.64 |
| PoU-H | 0.8 | 0.79 | 0.84 | 0.85 | 0.85 | 0.82 | 0.8 | 0.74 |
| PoU-L | 0.7 | 0.52 | 0.85 | 0.81 | 0.87 | 0.78 | 0.44 | 0.76 |
| PoC-H | 0.8 | 0.65 | 0.8 | 0.91 | 0.89 | 0.86 | 0.73 | 0.81 |
| PoC-L | 0.6 | 0.32 | 0.67 | 0.76 | 0.77 | 0.75 | 0.62 | 0.45 |

That the allelic diversity of *E. coli* isolates from low concentration PoCs is significantly less than from high concentration sites is interesting in light of studies that found lower allelic diversity and greater genome similarity in samples from environmental sources compared to samples from faecal sources (Devane et al., 2020; McLellan, 2004; Perchec-Merien & Lewis, 2013). The comparison suggests that PoC sites with low concentration of *E. coli* may be more associated with naturalised *E. coli*. Although not significantly different from the high concentration sites, the low concentration PoU sites also had lower allelic diversity and, therefore, may have been less affected by recent contamination. This interpretation of allelic diversity supports use of *E. coli* risk categories (WHO, 2017a) and aligns with research findings that indicate a threshold effect, with significant increase in diarrhoeal disease burden only associated with high concentrations (>1000/100 mL) of *E. coli* (Moe et al., 1991).

Interpretations of *E. coli* results, however, should not rely exclusively on concentration: the health implications of differences in *E. coli* concentrations are context dependent and naturalisation is not the only process that confuses the relationship between *E. coli* and health hazard. For example, the water for set 1 is sourced from an open reservoir system, which has animal and human activity in the catchment area and does not include treatment. Thus, the low concentration of *E. coli* in S1C1, and absence in S1C2, may be better interpreted as indicating poor survival of *E. coli* in the reservoir – likely due to a combination of predation, competition, UV radiation, and absence of surfaces for biofilm formation (Berthe et al., 2013; Ishii & Sadowsky, 2008) – rather than absence of faecal contamination. Furthermore, one of the isolates from S1C1 was from phylogroup D with numerous virulence genes, a likely indicator of recent human faecal contamination. Additionally, for sets 3 and 5 the water is chlorinated in the distribution system, which gives more assurance of safety, but some pathogens are more resistant to chlorine than *E. coli* (WHO, 2017a).

Generally, concentrations of *E. coli* do not correlate with concentrations of pathogens. The transport and survival patterns of *E. coli* vary considerably from those of faecal pathogens, particularly viruses and protozoa which tend to be more robust (Charles, Nowicki, & Bartram, 2020). So, the likelihood that water has been contaminated with faecal matter must be prioritised over *E. coli* sampling results.

## 5.3 Summary and Recommendations

Although definitive attribution is not possible, the strains that most likely originated from human and/or recent faeces were found in poorly protected PoC water (four sites including an unfenced open reservoir, unfenced open dug well, and two unsealed concrete tanks) or PoU water (12 out of 30 PoU sites). These were the

34 isolates from phylogroups A, B2, and D, and the 16 from phylogroup B1 with >80 virulence genes or multiple AMR genes. The other B1 isolates with fewer virulence genes account for almost half of my sample (48%), likely because B1 strains are generally better adapted to the freshwater environment. Allelic diversity comparisons suggest that naturalised *E. coli* may be particularly relevant at PoC sites with lower *E. coli* concentrations (<50 / 100 mL). And for PoU sites, analysis based on five theorised PoU *E. coli* population scenarios underscores the difficulty of interpreting health risk from grab samples.

Placing my findings in relation to the literature, I developed two sets of recommendations. Firstly, I emphasise the inadequacy of judging hazard based on single *E. coli* samples at either PoC or PoU. Tracking sanitary conditions and *E. coli* concentrations over time can inform a more reliable understanding of hazard. In addition to *E. coli* sampling, rapid, on site measurements such as turbidity or TLF may be useful for high frequency tracking of water quality variability. Under certain conditions, these measures can indicate process changes in water systems (Carstea et al., 2020; Nowicki et al., 2019), which may help differentiate between naturalised *E. coli* and contamination events. In Kitui County, however, and in other locations where groundwater contains substantial coloured dissolved organic matter, interference from CDOM fluorescence prohibits the use of TLF for this purpose (Section 4.2). But regardless of water quality measures, sanitary inspection is needed to confirm the current and prospective safety of a system. Studies have found weak or no correlations between sanitary inspection scores and microbial water quality as measured by faecal indicator bacteria (FIB) (Kelly et al., 2020), but this does not diminish the importance of the inspections given what we know of FIB results having multiple possible explanations.

Secondly, I recommend that PoC and PoU *E. coli* samples should not be compared directly in terms of their health hazard implications. PoCs with high *E. coli* concentrations should be prioritised for interventions with a focus on water safety management. On the other hand, PoU samples are more difficult to interpret because uncertainty is introduced by variability in: PoC quality, persistence of strains, and post-collection hygiene. Positive *E. coli* samples at household level could indicate no additional health hazard but, conservatively, they should be interpreted as indicating a hazardous household environment, generally. Effective intervention at the household-level requires a multi-pathway approach that goes beyond water treatment and safe storage.

### 5.3.1 Limitations and Further Research

The growth of *E. coli* is influenced by physicochemical characteristics of water such as nutrient levels, salinity, and temperature, as well as microbiome characteristics such as competition and predation (Berthe et al., 2013; Ishii & Sadowsky, 2008). Given the sample size of my study, I was not able to query the impact of these factors on the balance between growth and die-off of *E. coli* strains. Similarly, my study did not focus on temporal change in *E. coli* populations. Only one site was sampled twice: S4C2 had no overlap in MLSTs between the two samples taken two weeks apart. This suggests that continual contamination is driving the population dynamics at this site rather than persistent dominance of strains in biofilms or otherwise. The site is a poorly protected concrete tank with multiple openings situated in a market square. Furthermore, the water at the site is saline (median 4.1 mS/cm), and salinity is known to inhibit *E. coli* survival in water (Rozen & Belkin, 2001). Thus, the conditions at this site seem to enable ongoing input of new *E. coli* whilst discouraging *E. coli* survival and growth, which could explain the lack of overlap in the time-separated samples.

A larger study incorporating a temporal dimension would improve insight into *E. coli* population dynamics in water systems over time – including the impact of sanitary conditions and physiochemical and microbiome characteristics. Additionally, a larger study would enable better characterisation of strain diversity within samples if more isolates per sample were analysed (Figure 3.10).

Another avenue for further work is prompted by the prevalence of phylogroup B1 isolates in my samples, given their association with animal faeces (Tenaillon et al., 2010). Multiple studies have now emphasised the importance of animal management as a key sanitary factor influencing drinking water safety (Daniel, Diener, et al., 2020; Dufour et al., 2012; Hamzah et al., 2020); however, the importance of zoonotic transmission is not well established in the WASH literature and recent models relating health outcomes to WASH factors have excluded zoonotic pathways in part due "to data scarcity on animal faeces and animal presence" (Wolf et al., 2019, p.279). Further work in this space would be valuable.

Finally, the limitations of genomic characterisation for informing on strain origin is a key constraint of this study – I can comment on the likelihood of isolates being naturalised or recently sourced from faeces but cannot definitively identify them as such. To-date there have been few studies focusing on genomic characterisation of *E. coli* from drinking water supplies, but as the collective data set grows, it will enable meta-analyses and more robust statistics that will improve our ability to distinguish naturalised strains and better understand the origins, diversity, and dynamics of *E. coli* populations in water supplies.

*In the end, humans make their own health,*
*but not in the conditions of their choosing.*
— Anthony Gatrell & Susan Elliott, Geographies of Health, 2015

*Straightway then practice saying to every harsh appearance,*
*You are an appearance, and in no manner what you appear to be.*
*Then examine it by the rules which you possess,*
*and by this first and chiefly,*
*whether it relates to the things which are in our power*
*or to the things which are not in our power:*
*and if it relates to anything which is not in our power,*
*be ready to say,*
*that it does not concern you.*
— Epictetus, Enchiridion

# 6 Threat, Efficacy, and Data-Driven Decisions

The second guiding question of this thesis asks how understandings of data interact with other drivers of decision-making to influence the actions of water users and LWMs. In response to this question, and based on the findings of my literature review, I developed an integrated fear appeal conceptual framework to guide my analysis of the potential effects of sharing water quality monitoring data with rural water users and LWMs (Figure 2.3 in Section 2.2). This framing conceptualises monitoring reports as fear appeals (risk communications that describe a hazard with the purpose of motivating behaviour change) and draws from the extended parallel process model (EPPM) and the precaution adoption process model (PAPM). It directs attention to key aspects of cognitive and affective message processing while encouraging a longitudinal study design and inclusion of concept-driven qualitative inquiry – to retain time and situational differences as crucial and under-researched dimensions of behaviour change in response to fear appeals.

Using this framework, I have layered insight from the monitoring programme, cross-sectional and longitudinal surveys, and semi-structured interviews to a) assess user perceptions of drinking water quality hazards and b) evaluate an information intervention through which microbial water quality monitoring results were shared with LWMs over a 1.5-year period (as detailed in Chapter 3). The findings emphasise that water quality results should be reported with sensitivity to self-efficacy limitations and the threatscapes that recipients navigate. While withholding information is not recommended, the baseline assessment discourages sampling at household level for the purpose of motivating behaviour change. The monitoring intervention demonstrates, however, that specific and repeated messaging can encourage long-term engagement with water safety precautions among LWMs. Thus, LWMs are potentially effective change-agents for safe rural water supply, especially if their self-efficacy is supported through infrastructure design and ongoing resourcing. Further, the results highlight that reporting strategies should account for variability in microbial water quality such that individual tests are well-contextualised to promote proactive management.

The results and discussion presented in this chapter are submitted for publication in a paper titled: "Fear, efficacy, and environmental health risk reporting: complex responses to water quality test results in low-income communities", which is under review at the time of writing. The co-authorship of this article reflects my collaboration with my supervisor, my research assistants, and researchers from the Universities of Nairobi and Oxford through the REACH programme (Chapter 3). I led the design, execution, and writing of the work as specified in the co-authorship statement in Appendix A. In this chapter, the work is presented in two parts. First, I focus on the household-level assessment (Section 6.1), presenting results from the cross-sectional and longitudinal household surveys and complementing these with deductive thematic analysis from interviews with water users. Second, I evaluate the effects of reporting water quality monitoring results to LWMs (Section 6.2). I focus on change over time with sub-sections dedicated to baseline awareness, the evolution of stages of change, and patterns of response. To conclude, I discuss the results of the study (Section 6.3) and highlight key conclusions and limitations of the work (Section 6.4).

## 6.1 User Perceptions of Water Safety

Results from the cross-sectional and longitudinal household surveys and the semi-structured interviews provide insight into water user perceptions and decision-making around water safety. The following subsections discuss perceptions of threat and efficacy (Section 6.1.1) and problem-focused and defensive responses to water quality hazards (Section 6.1.2).

### 6.1.1 Perceptions of Threat and Efficacy

The household survey respondents judged water safety most frequently on the basis of either general knowledge about pathogens from faecal contamination (n = 554) or not attributing any health problems to drinking water quality (n = 559). Their judgements were also influenced by attribution of illness to water quality, organoleptic factors, and advice from experts (Figure 6.1). General knowledge about risk of teeth damage from contaminated water was localized, with most responses (96%) coming from eight villages in Tseikuru and Tharaka wards.

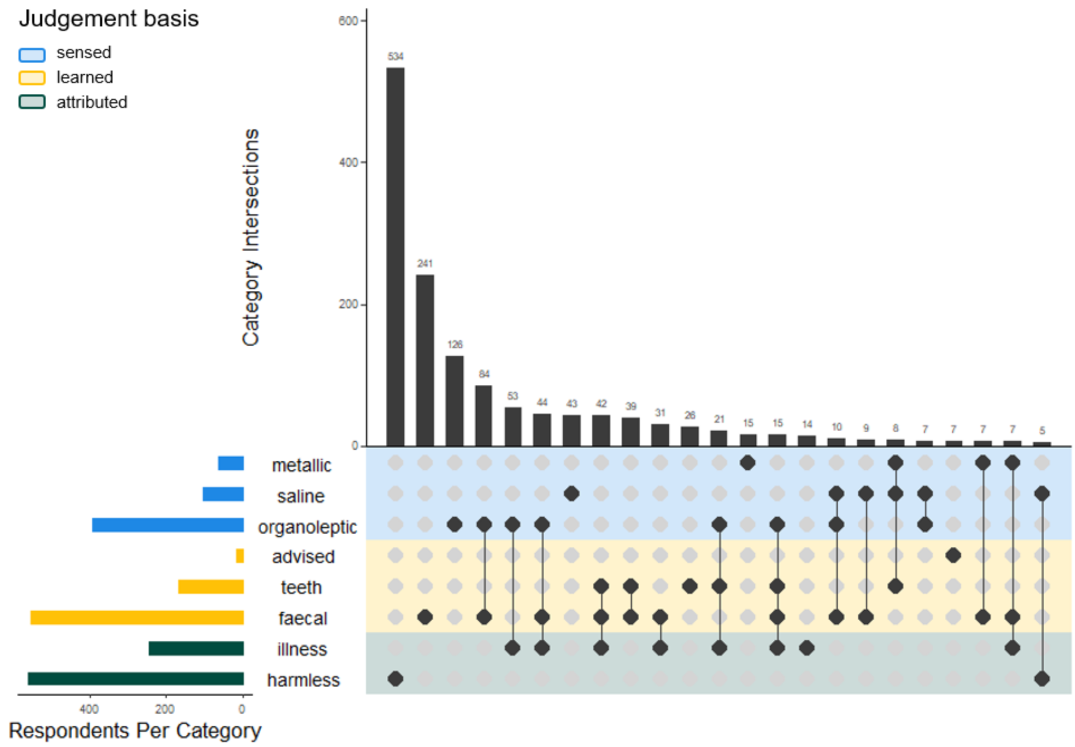



**Figure 6.1:** Intersecting sets visualisation showing the factors influencing household survey respondents' judgements of drinking water safety. *The vertical bars show frequencies of judgement combinations in decreasing order; the horizontal bars on the left show the number of respondents that answered positively for each category (Conway et al., 2017). Blue corresponds to sense-based judgements including metallic taste, saline taste, or other organoleptic observations for taste, smell, and visual. Yellow corresponds to learning-based judgements including advice from others, knowledge about damage to teeth, or knowledge about faecal contamination hazards. Green corresponds to attribution-based judgements including whether respondents have attributed illness to drinking water or not.*

More than half of the 1457 household survey respondents recognized that their drinking-water is not always safe (58%). Of those respondents, 13% reported their water is always unsafe but the majority recognized variability and said that their water is rarely safe (43%) or sometimes safe (44%). Only six respondents (<1%) admitted uncertainty and said they do not know if their water is safe. Welfare quartile and level of education did not predict perception of water quality threats, except that respondents from households with no adults having at least primary education (n = 136) were less likely to perceive variability in water safety and more likely to say that their water is always safe ($\chi^2 = 14.6$; p <0.001).

Recognition of water quality threat was strongly related to water source type. Respondents from households that were mainly using surface water sources for drinking during the time of the survey were less likely to say that their water is always safe ($\chi^2 = 84.7$; p <0.001; Figure 6.2).

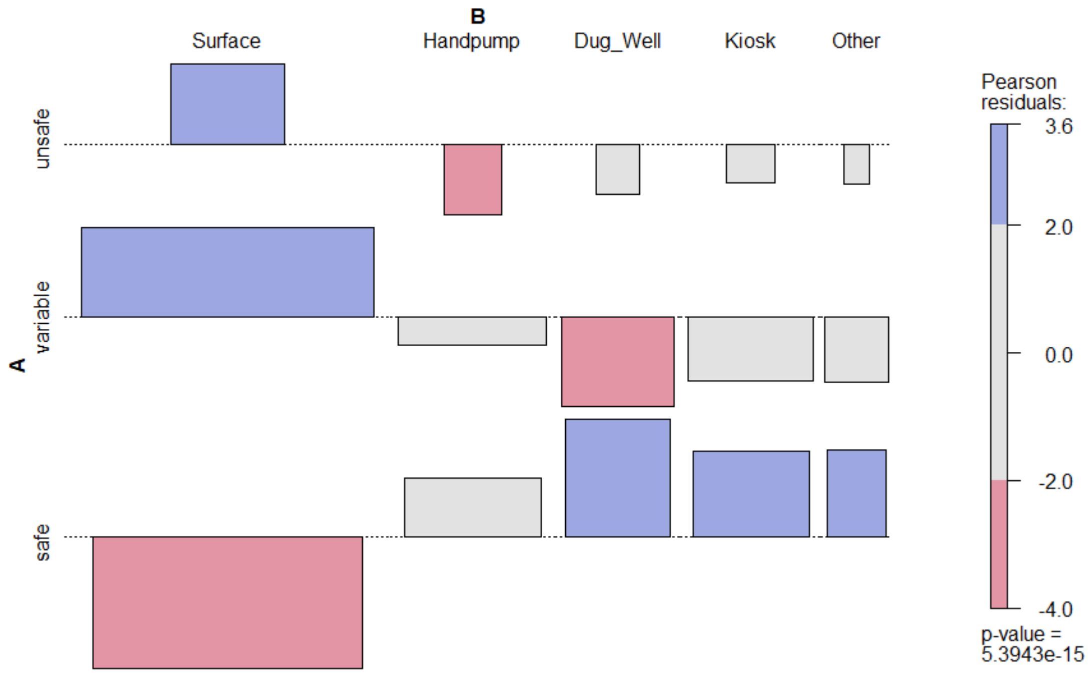



**Figure 6.2:** Association plot for perceived water safety by main drinking-water source type. *Blue shading indicates that the observed value is higher than expected if the data were random, and red shading indicates that the observed value is lower than expected. The 'Other' category includes rainwater, bottled water, vended jerrican water, and water that is piped into a compound or household, delivered by a tanker truck, or borrowed from a neighbour.*

Only 10% of the survey respondents said 'yes' when asked if they had ever received information about the safety of their drinking-water. Those who did recall receiving information received it from doctors, health officers and community health volunteers (69%), an NGO (13%), a chief or sub-chief (6%), a water service provider (5%), or other (7%). In the water diary households, respondents who reported cases of stomach pain and diarrhoea were often uncertain of the cause, or linked it to waterborne disease, food poisoning, growing teeth, or other causes such as pregnancy complications, malaria, salinity, stress, or ulcers (Figure 6.3).

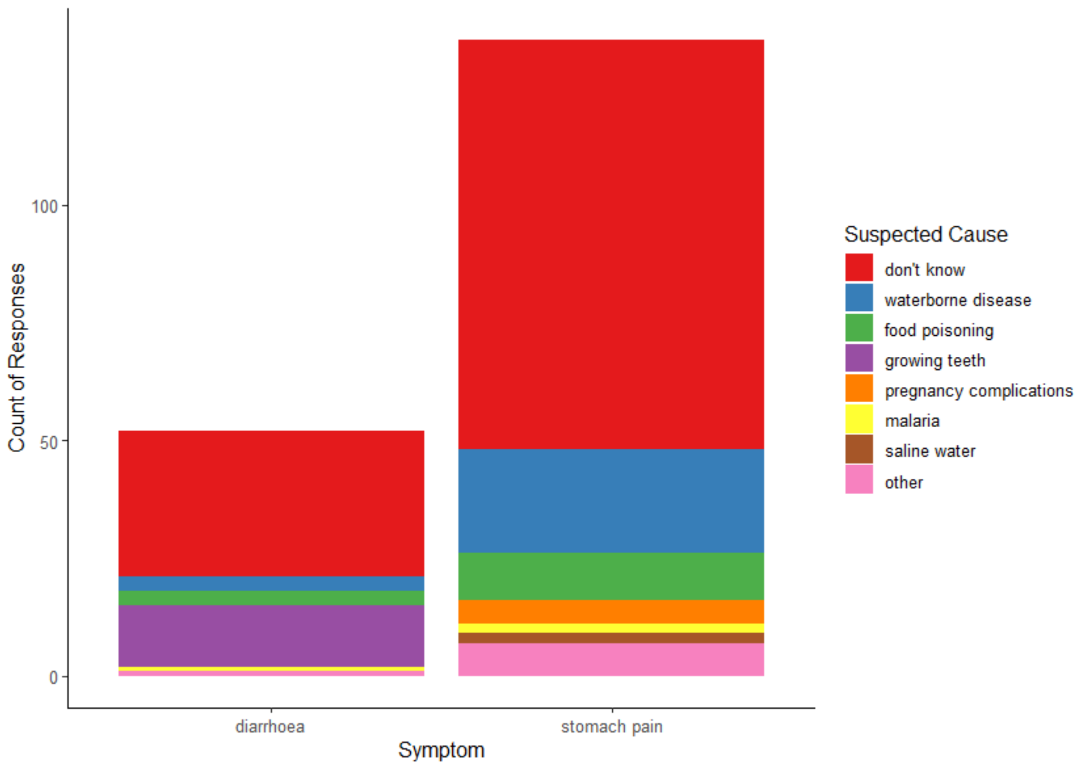



**Figure 6.3:** Counts of reported stomach pain and diarrhoea symptoms by suspected causes from the water diaries surveys. *Stomach pain was reported at least once from 59 households with each household reporting between 1 and 6 times (mean = 2.3, median = 2). Diarrhoea was reported from 31 households with each household reporting between 1 and 6 times (mean = 1.7, median = 1).*

The interviews provided richer insight into perceptions of threat from unsafe drinking-water. The perception of surface water being especially unsafe was prominent (Table 6.1 theme 1). This awareness was expressed either as common sense or as a result of learning from health facility staff, community health volunteers, and NGOs. Groundwater, in contrast, was discussed with reference to trade-offs between chemical and microbial quality (Table 6.1 theme 2).

In accordance with the survey findings on low access to water safety information and high uncertainty about the causes of illness, interview participants also highlighted that their appraisal of water safety is influenced by the absence of specific information (Table 6.1 theme 3). Their views on the severity of water-related disease were expressed in terms of fears for themselves and others (Table 6.1 theme 4).

**Table 6.1:** Key threat perception themes from the interviews. *Max case count is 35.*

| Theme | Case Count | Coding Coverage | Description | Example Quote |
|---|---|---|---|---|
| (1) Surface water is especially unsafe | 31 | Avg 4.0%<br>Max 8.3%<br>Min 1.3% | Participants pointed to the openness and stagnation of water as hazardous, and they linked the threat of disease (speaking of typhoid, amoebiasis, cholera, dysentery, stomach problems and diarrhoea) to inadequate separation of water from livestock, wildlife, latrines, and open defecation, with 'dirt' or 'faeces' carried into the water by rain (overland flow), on people's shoes, or on containers and ropes that are used to draw water. | "There are places where people have not dug pit latrines, there are animals that have died and decayed in the bushes, and other bad things. When it rains, then all that dirt is swept by the rainwater and drained in the earth dam. . . . Even now, the rain is not here but whatever dirt was brought before is still in the water source." – P35F |
| (2) For groundwater, there is a trade-off between microbial vs. chemical quality | 20 | Avg 1.6%<br>Max 4.2%<br>Min 0.5% | Participants recognising the benefits of superior protection from faecal contamination but highlighted that the suitability of many groundwater sources for drinking and cooking purposes is limited by salinity and bitterness, especially during drier seasons. Participants linked salty water to unquenched thirst, constipation, bloating, and pain, which one woman described as "slashing your intestines into pieces". Participants also expressed concerns about health impacts of salinity on livestock. | "Water from the boreholes is safe for human consumption since it is well covered and protected from all sources of contamination. However, . . . it is limited in use due to its saltiness." – P07M |
| (3) Lack of specific external stimuli limits judgement of water safety | 19 | Avg 1.7%<br>Max 5.4%<br>Min 0.2% | General knowledge about water contamination is widespread, but none of the participants had received test results for the water sources that they relied on. Participants discussed the limitations of assessing water quality based on organoleptic properties. On the one hand they may have a bad reaction from drinking water even if it appears clean but, on the other hand, when they become sick they usually cannot be confident of the cause. | "You have to realize that even if the water is dirty, we cannot tell because we don't have a professional to check its quality or treat it. We just take the water the way it is, even when you get sick you can never tell whether it was the water or something else." – P06M |
| (4) Water quality threats induce fear for oneself and others in one's care | 25 | Avg 1.8%<br>Max 3.9%<br>Min 0.2% | Participants spoke of prolonged stomach pain and needing to seek medical relief. Death and the contribution of waterborne illness to malnutrition were not directly discussed, but participants said that they fear dirty water and that infants are more susceptible to hygiene-related illness, including from unclean water. This view of heightened susceptibility extended to adults who are already weakened from illness. | "We have a lot of fears because, personally, I have stomach problems and if I take the water without boiling then the problem escalates. I also fear for my children because some of them have similar stomach problems." – P04F |

Interview participants also shared views on their ability to respond to water quality threats. Perceived response efficacy was uniformly high, with nobody questioning the existence of effective protection and treatment measures. Self-efficacy, however, was strongly limited by poverty, gender norms, collective action challenges, and rural isolation (Table 6.2).

**Table 6.2:** Key efficacy perception themes from the interviews. *Max case count is 35.*

| Theme | Case Count | Coding Coverage | Description | Example Quote |
|---|---|---|---|---|
| (1) Despite knowledge of threats, poverty constrains safe water practices | 20 | Avg 3.5% Max 12.0% Min 0.3% | Participants differentiated know-how, will, and capability to act. They discussed access and affordability issues that prevent them from acting on knowledge about water safety practices. They also highlighted the inability of communities to maintain NGO projects without ongoing support, especially in the face of difficult environmental conditions, vandalism, and theft. | "We were trained about the earth dam water and told that it is not clean, but due to our low-income levels and other problems we have here you may find people drinking the earth dam water just the way it is knowing very well it is not good for drinking." – P35F |
| (2) Gender norms especially limit the self-efficacy of women | 31 | Avg 4.8% Max 13.7% Min 0.7% | Gender norms within families and the wider community limit opportunities for women to lead and participate in water management committees. Further, many water sources have flexible payment structures that require users to strike an agreement with the owner or management committee. In most cases, the household head (usually men) makes these agreements, they also decide what portion of household income can be spent on water; consequently, they largely determine source selection even if other household members (usually women) fetch water and manage its use within the household. | "I cannot say I have anything I do for livelihood, maybe a business or anything. I like the idea and I would very much want to do that, but my husband refuses... And this happens for most women. This really affects us in terms of provision for our children... you will find that [I] am the most knowledgeable person about the needs of the children and the household... Even when they are aware that we know all these, they say it is not possible to allow us to go sell their produce." – P04F |
| (3) Water source protection is a collective action challenge | 25 | Avg 2.4% Max 6.6% Min 0.4% | Participants emphasised that self-efficacy is eclipsed by the need for collaboration and leadership from committees or owners in protecting water sources. They discussed examples where protective measures have failed due to lack of cooperation, presenting them as testament to the difficulty of sustaining protective measures despite strong motivation – water quality is only part of the motivation, participants were also concerned about drowning accidents, water shortages, and functionality issues. | "Like now the water is only used to water the animals as it is very dirty, people have allowed them to enter the earth dam and urinate among other things... The thing is if you go and complain, no one listens to you. So, after a while you stop worrying and do what others are doing. If the consequences come, they affect you all." – P06M |
| (4) Self-efficacy is limited by rural isolation | 19 | Avg 2.0% Max 5.3% Min 0.4% | Participants noted the lack of follow-through on campaign promises and expressed a sense of isolation both by physical distance and political hierarchy. None of them were positive about their ability to attract or mobilise support from NGOs or the government (neither through the pre-devolution system of chiefs nor the post-devolution system of village administrators). | "I think we are very deep in the rural areas, I don't even know how you've reached here (chuckles), because nothing ever gets here. People only get to this area when they are in need of votes." – P29F |

### 6.1.2 Household-level Water Management Choices

Despite the self-efficacy limitations discussed in the interviews, some participants did say that they take source-selection and treatment measures to improve water safety, and this was reflected in the cross-sectional and longitudinal surveys as well. The water diaries showed that households use between one and four sources over the year, with the most common sources being dug wells, temporary open wells in river-beds, earth dams, and piped water kiosks (Figure 6.4). Interview participants explained source selection as a result of many interrelated factors (Table 6.3 theme 1).

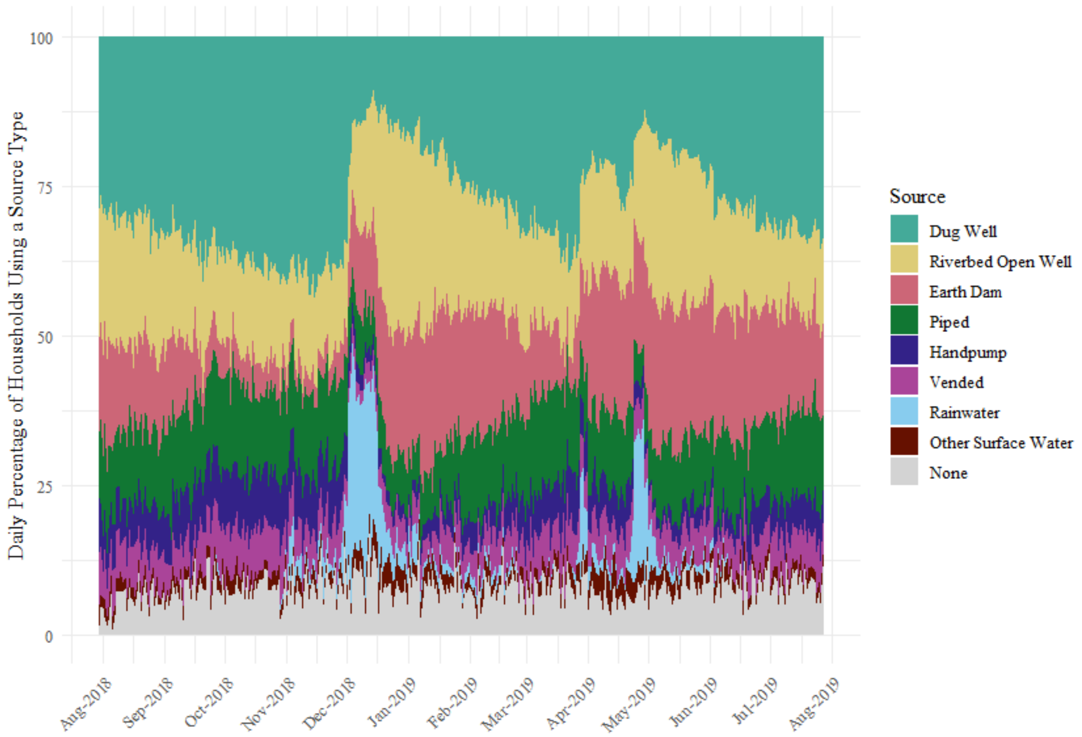



**Figure 6.4:** Daily percentage of water diaries households using a given water source type as their main source for drinking and cooking over a year starting 30 July, 2018.

Interview participants also discussed intermittent use of water safety measures in response to specific stimuli (Table 6.3 theme 2). The insight from these discussions is consistent with the survey results. In the cross-sectional survey, 49% of respondents said that they never treat their drinking water but 19% of respondents said that the water they drank on the day of the survey had been treated, mostly by boiling (74%) and/or adding chlorine-based disinfectant (30%). In the water diaries surveys, the 115 households reported doing water treatment 327 times over the year:

- Boiling was the most common method, with 61 households (53%) reporting boiling drinking-water in at least one survey. Households also reported using chlorine-based disinfectants (27%), filtration (6%), and alum or 'purifying stones' for sedimentation (4%). There were also 74 reports of bottled water purchases from 37 households (32%).

- Only six households reported taking measures consistently (in more than 90% of the surveys in which they participated), 21 households took measures 50 to 90% of the time, 24 households took measures 25 to 50% of the time, 33 households took measures up to 25% of the time, and 31 households never reported doing treatment or buying bottled water.

- The proportion of reported treatment was not related to wealth index ($p = 0.4$); in open-ended responses, the reasons participants gave for doing treatment or buying bottled water were because clean drinking-water was not otherwise available (159 responses from 62 households); to avoid previously experienced illness (102 responses from 27 households); to kill germs/bacteria (63 from 31) or visible worms and insects (14 from 11); to protect a sick person (21 from 14), young child (10 from 3), or visitors (6 from 4); because it was advised by a doctor (12 from 6) or NGO (11 from 4); to avoid salinity (2 from 2); or out of habit (1 from 1).

The inconsistency in applying water safety measures reflects the wider threat landscape and self-efficacy constraints that water users navigate. In the household survey, 68% of respondents listed drinking-water services (including quality, quantity, and reliability) in their top three concerns, which also included education (53%), healthcare (32%), agricultural support (28%), transportation and roads (25%), financial services (20%), employment (19%), and electricity (19%) among others. When asked about their top three concerns for water services specifically, 31% of respondents had no concerns, but others said sources were too far (51%), insufficient in quantity of water (47%), unsafe for drinking (39%), too costly (25%), dirty for domestic use (20%), and unreliable (14%). In the interviews, participants emphasised that in adopting problem-focused responses, they must balance water quality threats with many others (Table 6.3 theme 3).

**Table 6.3:** Key response themes from the interviews. *Maximum case count is 35.*

| Theme | Case Count | Coding Coverage | Description | Example Quote |
|---|---|---|---|---|
| (1) Source selection is influenced by multiple dynamic factors | 35 | Avg 11.0% Max 28.8% Min 4.0% | Source selection varies in response to rainfall, distance, queuing, security, labour, monetary cost, livestock needs, personal relationships, functionality, and quality. Distance and cost present less flexible constraints on choice compared to preference and acceptability of different water qualities. Payment structure is also important: where people can borrow, pay with food, or offset monetary payments by providing labour for the maintenance of a water point, they can more consistently access a cleaner source. Sources that require upfront payment in cash without exception are more challenging. | "When it gets very dry, the water gets saltier, but when it rains well, the salt is reduced - though not all the times... [In the dry season,] people have to buy fresh water from the market kiosks which amounts to being very expensive for some of the community members...Unless one buys water from the salt-less wells, which are very few like three wells in this area." – P11F |
| (2) Problem-focused water safety measures are employed intermittently | 20 | Avg 1.5% Max 3.0% Min 0.3% | Boiling, adding chlorine disinfectant, filtering water, or buying bottled water is done intermittently in response to specific stimuli including advice from doctors, to provide for new infants, or to protect people who are already ill. The key reason for not consistently maintaining measures to protect against water quality threats is that time, energy, and money must be put towards problem-focused responses to many different threats, some of which are more immediately severe than waterborne diseases. | "When a person fetches water and takes it home, most of them use it without doing anything to it not even treating it or even boiling it; but when they are told they have amoeba or typhoid, they start boiling the water or even use WaterGuard to treat the water." – P13M |
| (3) Resources must be balanced for problem-focused responses to multiple threats | 29 | Avg 2.7% Max 7.3% Min 0.3% | In adopting problem-focused behaviours, participants balanced water quality threats against many others including attacks from people, hyenas, snakes, and *majini* (spirits) when walking to fetch water; thirst and fatigue from inadequate access to water supply; unreliable rainfall and crop production; flooding; falls into wells or reservoirs; chest problems from cooking fires; and a variety of communicable diseases including HIV/AIDs. Participants also worried about keeping children in school. For girls, this intersected with concerns including gender-based disempowerment, sexual assault, early pregnancy, and abusive marriages. For boys there was heightened concern about drug and alcohol abuse. | "People are having problems finding money to buy water. At the same time, they are also scared of selling their food to leave the children with nothing to eat. The fear is also because no one is sure that it will even rain." – P30F |
| (4) Cognitive re-appraisal, particularly resignation, is a common defensive response | 25 | Avg 1.9% Max 6.4% Min 0.3% | Participants framed their circumstances as uncontrollable; they were resigned to "use patience" and "persevere with the situation at hand." One participant linked feeling a heavy burden to using resignation to "try navigate the challenges." Other forms of cognitive re-appraisal were also expressed including religiosity (circumstances are in God's hands), downward comparison (unsafe water is better than no water), self-exemption (the hazard is real, but I am not susceptible), and humour as reframing (suggested through tone and laughter when discussing threats). | "For lack of alternative a woman can even start having labour pains when she is on her way from the water point... Some even suffer backaches up to now. But then how can we help them? This is how the world is." – P20F |

According to my integrated fear appeal framework (Figure 2.3), the combination of substantial perceived threat and limited self-efficacy should result in defensive processing, cognitive responses that help individuals mitigate the negative emotions that arise when they are confronted with a health threat. Defensive responses can take a variety of forms, and they often occur on a sub-conscious level, which makes them difficult to assess. Avoidance and suppression by their nature are most subconscious, and reactance (dismissing a threat because engaging with it would inhibit one's behavioural freedom) did not feature in the interviews. Interview participants' reflections on water safety and other threats did, however, demonstrate cognitive re-appraisal (wherein a hazard is acknowledged but additional beliefs frame it as futile to engage with and/or not personally threatening) (Table 6.3 theme 4).

Compared to cognitive reappraisal, denial of water quality threats was uncommon in the interviews, being expressed by only three participants: one speaking on behalf of himself and the others reflecting on attitudes in their communities more broadly. Denial took the form of dismissing hazards and "just decid[ing] that water is clean" despite contrary observations and learning. One participant also pointed to lack of specific information and difficulty attributing consequences to water quality as denial-enabling.

## 6.2 Messaging Intervention with LWMs

The longitudinal survey series and semi-structured interviews provided insight into LWM responses to the monitoring results. In the following sub-sections, I discuss the starting conditions of the study (6.2.1), changes in perceived susceptibility (6.2.2), the evolution of stages of change (6.2.3), and the main patterns in LWM responses (6.2.4).

### 6.2.1 Baseline Awareness

Only one LWM said that they had received microbial water quality test information prior to the study (from an NGO that tested once and reported the water was safe). Six others (12%) said that the borehole drillers (contracted by the government) or an NGO tested the water and told them it was either good for drinking (4%) or very saline and should be used for livestock (8%). Most said the water had not been tested (35%), or that they did not know if it had been tested (29%). Others said that they never received any information after the water was tested by researchers (14%), drillers (8%), or an NGO (2%).

In my initial survey, five LWMs (10%) indicated that they were unaware of potential water quality hazards, relying on the assumption that groundwater is safe (this assumption also featured in the results of the household-level baseline assessment). Most LWMs (81%), however, were grouped in the uninvolved stage, saying that they were uncertain about the water quality, recognising the potential for the water to be unsafe, but not considering taking precautionary measures. Two LWMs were undecided about whether to do something, two were already acting (using chlorine, advising users to boil), and one perceived high threat but had decided against trying to act due to low self-efficacy.

### 6.2.2 Changes in Perceived Susceptibility

Perceived susceptibility is the key fear appeal message processing variable that was influenced by the monitoring results reporting (Section 3.5.3). The associations between perceived susceptibility, affect display, and stage of change were assessed using correspondence analysis (CA) with contribution biplots. Comparison of perceived susceptibility and affect display found that positive affect is associated with low perceived susceptibility ($X^2 = 227$, p $< 0.001$, dim1: 92%, dim2: 8%). Further analysis found that change in perceived susceptibility (relative to the preceding timeline step) discriminates better between the other affect display categories (Figure 6.5; $X^2 = 315$, $p < 0.001$, dim1: 76%, dim2: 14%). Negative affect display was associated with increased and sustained high perceived susceptibility. Other strong associations (Pearson residuals >2) were for:

- positive affect display with sustained low susceptibility;
- surprise with increased susceptibility;
- uncertainty with sustained medium susceptibility; and
- disinterest and undetermined affect display with sustained high susceptibility.

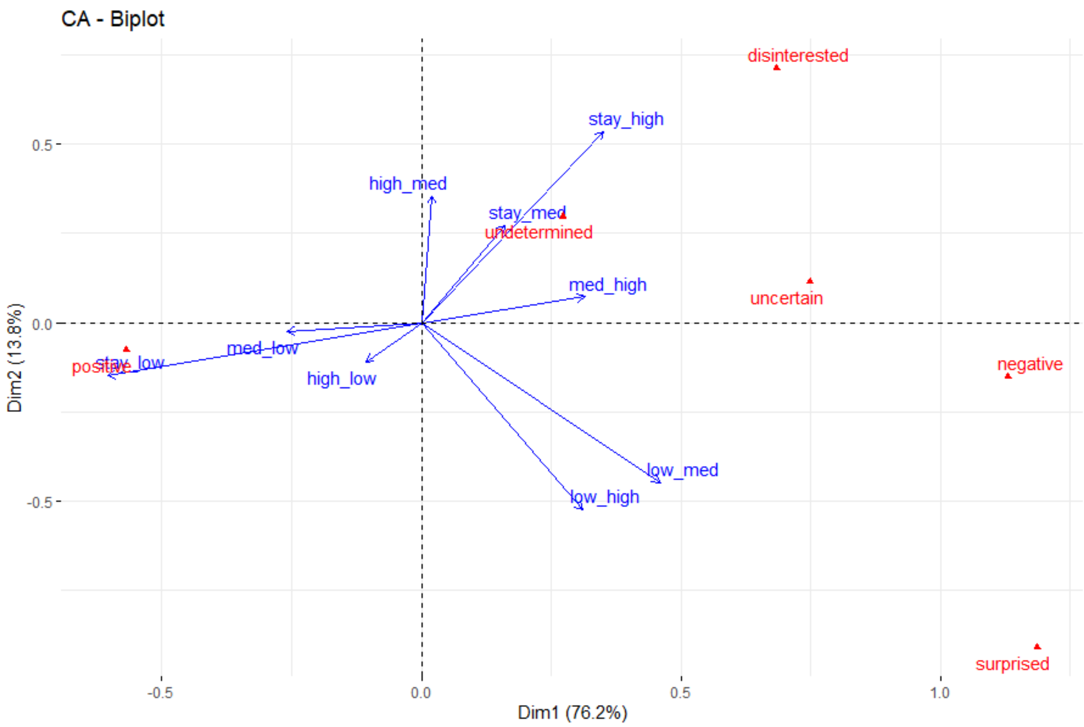



**Figure 6.5:** Contribution biplot of affect display by change in perceived susceptibility. *The dependent variable categories (red points) are positioned further from the centre of the chart if they contribute more strongly to the correspondence analysis solution (if they are more strongly associated with categories of the independent variable). Likewise, the independent variable categories are represented by blue arrows that are longer if they contribute more to the solution (if they are more predictive of the dependent variable). The angular distances between the arrows and the axes shows how much the independent variable categories contribute along each axis: the closer the arrow is to an axis, the stronger the contribution to that axis relative to the other one. If an arrow is midway between the two axes, it contributes to them equally.*

Comparing affect display with stage of change, intention to act is least associated with affective state, whereas intending no action is associated with disinterest; indecision is associated with uncertain, negative, and surprised affect displays; and the uninvolved stage is associated with positive affect display (Figure 6.6; $X^2 = 339$, $p < 0.001$, dim1: 69%, dim2: 21%). Comparing change in perceived susceptibility with stage of change directly, the correspondence solution is dominated by the sustained low susceptibility observations which are strongly associated with the uninvolved stage (Figure 6.7; $X^2 = 396$, $p < 0.001$; dim1: 90%, dim2: 8%). Other substantial associations (with Pearson residuals $>2$) were between: indecision and increase in susceptibility and between intending no action and sustained medium or high susceptibility. Intending to act is inversely associated with sustained low susceptibility.

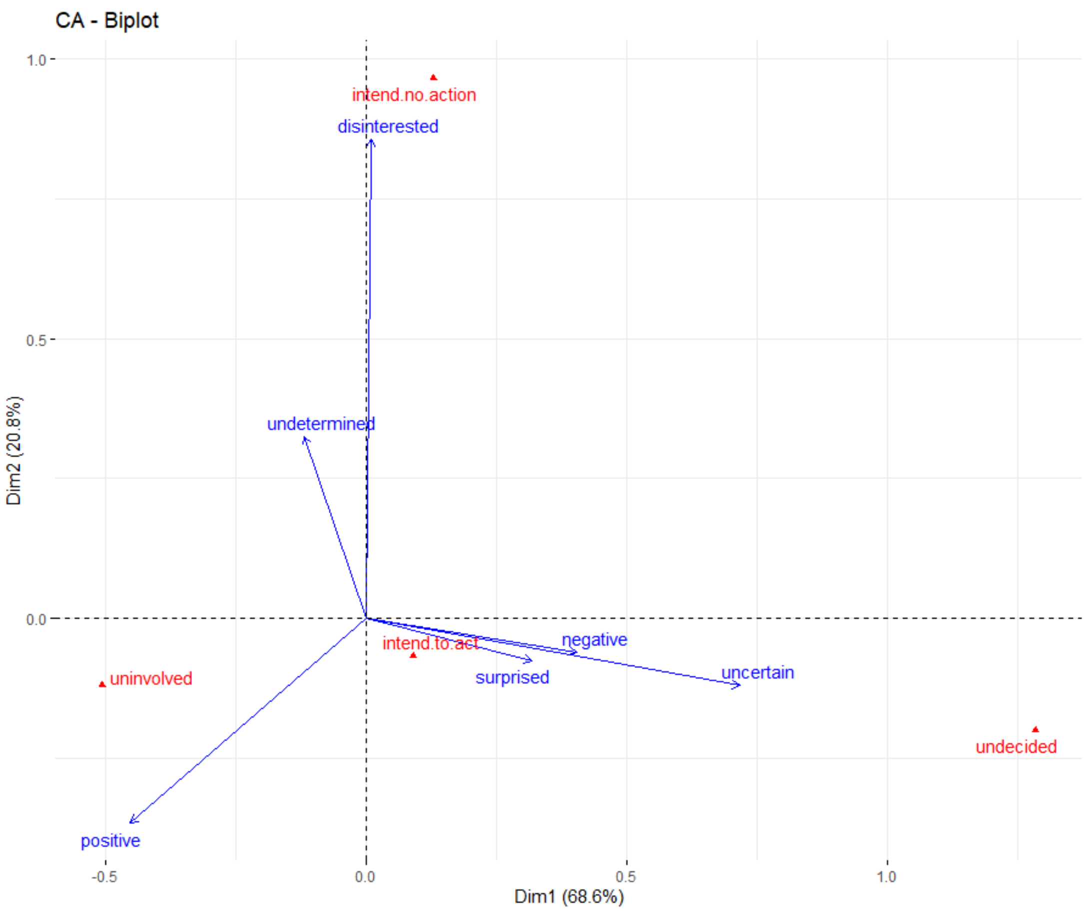



**Figure 6.6:** Contribution biplot of stage of change by affect display.

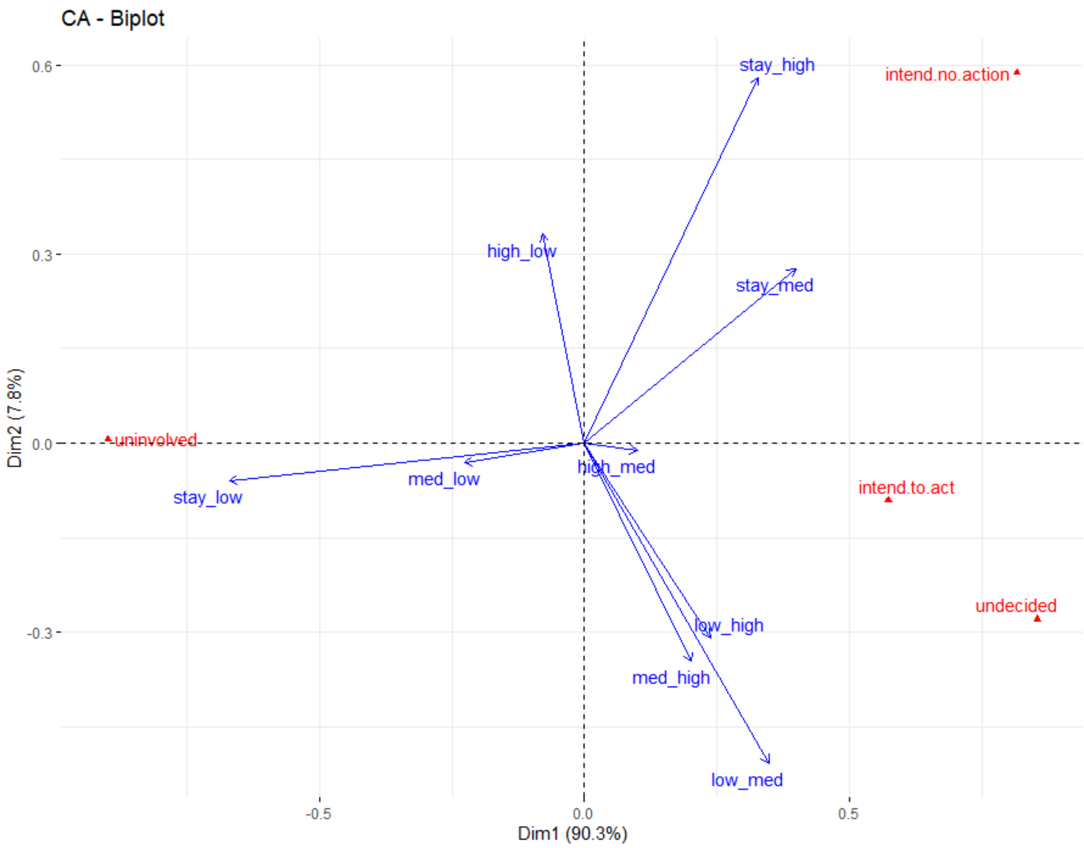



**Figure 6.7:** Contribution biplot of stage of change by change in perceived susceptibility.

### 6.2.3 Evolution of Stages of Change

The first reporting of monitoring results produced the most uniform shift in stage of change across the participants (Figure 6.8). Of the thirty-one LWMs who perceived medium or high susceptibility to microbial hazards after the first report, twenty-one expressed intention to act, nine sought further information and therefore stayed in the message processing undecided stage, and one continued to intend no action due to low self-efficacy. Of the LWMs who perceived low susceptibility, nine stayed in the uninvolved stage, but two became undecided and ten expressed intention to act based on the information accompanying the results (despite the tests being *E. coli* negative).

With further reporting in the following months, the response patterns be-

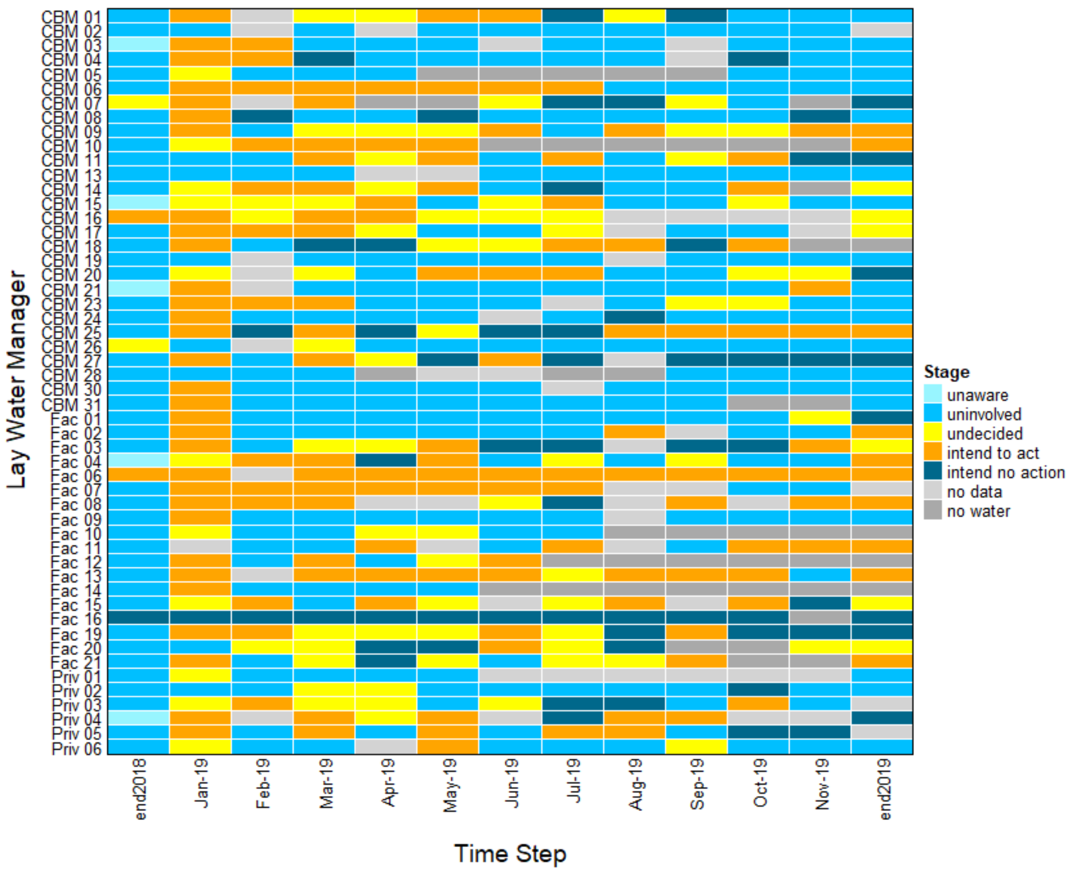



**Figure 6.8:** LWM stages of change at each time step.

came more complex (Figure 6.9). Most LWMs (85%) expressed an intention to act at least once during the study period. The choice of different activities was largely guided by a) the water supply design and starting condition and b) the water supply usage patterns (whether serving a facility or the general community). The most common intended measures were disinfection-based treatment, tank cleaning, advising HHWT, and fencing, although reported actions were consistently fewer than expressed intentions (Table 6.4). Unlike for household level managers, the range of responses under consideration by the LWMs included seeking support from the government (n = 6) or NGOs (n = 6). This was moderated by level of isolation, with LWMs in facilities or community management committees being more likely to consider it a viable option, especially if they were based nearer to population centres (as opposed to individual owners or committees in more remote locations).

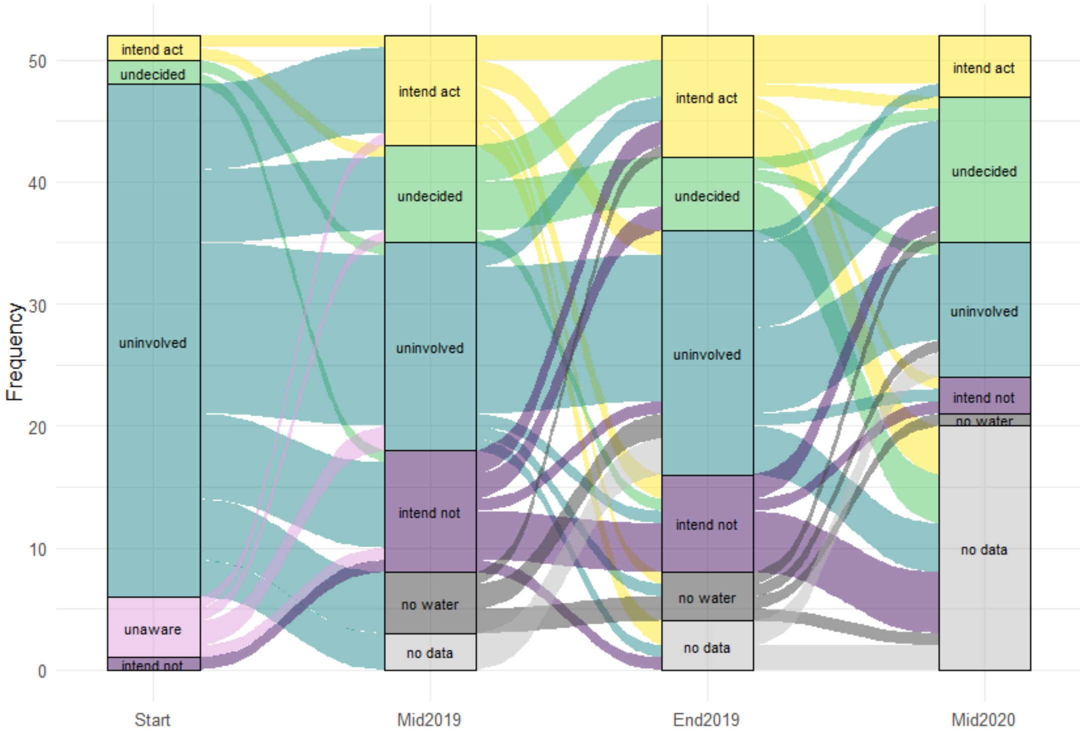



**Figure 6.9:** Evolution of LWM stages of change at biannual intervals.

**Table 6.4:** Percentages of community-based management (CBM) committee, school or health facility, and private owner LWMs reporting intentions and actions at least once.

| **Approach** | **Activity** | **CBM** | | **Facility** | | **Private** | |
|---|---|---|---|---|---|---|---|
| | | **Intended** | **Acted** | **Intended** | **Acted** | **Intended** | **Acted** |
| Taking direct action | Treat water | 25 | 11 | 87 | 60 | 50 | 17 |
| | Clean tank(s) | 39 | 18 | 53 | 40 | 0 | 0 |
| | Install fencing | 36 | 25 | 7 | 7 | 33 | 17 |
| | Other source protection | 18 | 14 | 27 | 20 | 50 | 33 |
| | Implement source switching | 0 | 0 | 40 | 33 | 0 | 0 |
| Requesting support | Seek government support | 18 | 11 | 7 | 7 | 0 | 0 |
| | Seek NGO support | 0 | 0 | 40 | 27 | 0 | 0 |
| | Inform activism | 4 | 0 | 0 | 0 | 0 | 0 |
| Advising users to act | Instruct source protection | 18 | 7 | 20 | 20 | 33 | 17 |
| | Instruct HHWT | 46 | 25 | 7 | 0 | 50 | 33 |
| | Instruct source switching | 0 | 0 | 7 | 7 | 0 | 0 |
| | Instruct HHWT for other sources | 18 | 11 | 40 | 20 | 17 | 17 |
| **Any** | **All** | **82** | **71** | **93** | **87** | **67** | **67** |

Perceived efficacy was not manipulated with each reporting of monitoring results, but it was commonly found to decrease over time. After the first reporting, 92% of the LWMs expressed confidence that, if necessary, they could execute response measures to resolve microbial water quality threats. Towards the end of the study, however, 87% of the LWMs expressed that an effective response requires external support. This was influenced by experience with trying to act on intentions and recognising challenges in the process that were not fully appreciated initially. Limited access to resources (including financing and local supply chains) and low confidence or know-how in implementing response measures were the main barriers. In response to realisations of limited response and self-efficacy, thirty LWMs indicated defensive processing at least once, including downward comparison, fatalism, resignation, denial, and avoidance (Table 6.5).

**Table 6.5:** Defensive responses indicated at least once by LWMs following monitoring reporting.

| Defensive response | Description of expression. | No. of LWMs |
|---|---|---|
| Downward comparison | Contextualising the reported monitoring results with reference to less protected drinking water sources and other more severe threats. | 21 |
| Fatalism | Expressed by statements indicating that microbial contamination is natural or God's will, and that it is outside of the LWM's responsibility and ability to control. | 11 |
| Resignation | Indicated by statements of patience and waiting for self-efficacy to change through receipt of external support. | 11 |
| Reframing | Used for justification of inaction, for example by framing *E. coli* presence as a consequence of short-term, anomalous events like breakdown repairs. | 10 |
| Denial | Expressed by characterising test results as false alarms and presenting reasons why they may not be reliable, including no consequent cases of illness or no convincing pathway for *E. coli* ingress into the system. | 8 |
| Avoidance | One LWM withdrew permission for sampling to continue into 2020. Six other LWMs indicated avoidance by a combination of purposefully not sharing results with other committee members or administrators, low responsiveness to phone calls and meeting requests, and voicing that test results without solutions are unhelpful. | 7 |

Defensive processing arose in response to limited self-efficacy, but the LWMs demonstrated that danger and fear control processing are not mutually exclusive. They voiced intentions to take actions that they knew would partly but not fully control the threat. Different appraisals of self-efficacy were applied to different actions, and system design moderated response efficacy. For example, one-time measures like building a fence were more attractive than ongoing measures like routine chlorination, some tanks are easier to clean than others, batch chlorination was more feasible for systems with longer stored water residence times, and *barazas* (community meetings) to promote household water treatment and safe storage were associated with high self-efficacy on the part of the organisers but limited response efficacy due to mixed behaviour of community members in following recommendations. In this way, efficacy was often partial and, as was observed in the household-level analysis, problem-focused and defensive responses were expressed contemporaneously. For example, one LWM described water treatment (via automatic chlorine dispenser) being implemented for part of their water system but said that multiple standpipes (which were used for drinking) were not receiving chlorinated water. In their timeline, they demonstrated intention to act, maintenance of action, and then concurrent defensive responses (including downward comparison, resignation, and reframing) with respect to the untreated part of the system.

### 6.2.4 Patterns of Response

LWM reactions to monitoring information over the study period demonstrated six main patterns of response. These are characterised by differences in perceived threat and efficacy, extrapolation of information over time or to other sources, and extent of defensive processing. Table 6.6 reports the number of LWM response timelines best described by each pattern. Perceived threat was insufficient to motivate formation of intentions in seven cases, but the most common pattern was long-term variable engagement with microbial water quality threat, with LWMs moving between stages in response to changing perceptions of susceptibility and partial efficacy. For 29 LWMs, there was overlap in the patterns, so Table 6.6 also reports how many times each was observed as a secondary pattern. The patterns with the most frequent secondary expression were: reverting to the uninvolved stage when perceived susceptibility reduced or voicing intentions to act despite *E. coli*-negative results based on extrapolating information in time or to other sources.

Descriptions of Response Patterns

1. Reporting does not motivate formation of intentions. This pattern is associated with positive affect displays in response to sustained low perceived susceptibility (consistent absence of *E. coli* when the water was in regular use).

2. Reporting prompts intention to act proactively (based on potential future threat but not current threat) or intentions to act are extended to other sources. Despite *E. coli* negative results, accompanying information and/or prior test results prompt intention to act and information seeking (specifically, requesting test results from nearby alternative sources for comparison). This pattern is associated with positive affect displays in response to low perceived susceptibility, but it is unclear what separates uninvolved LWMs (pattern 1) from those who extrapolate threat information and are motivated to engage with water safety measures despite *E. coli*-negative test results.

3. Reporting of a reduction in contamination prompts reversion from intention to act to uninvolved. This pattern is associated with positive affect displays in response to reduced perceived susceptibility relative to a previous report.

4. Reporting of sustained threat prompts initial variable engagement that evolves to uninvolved. This pattern is associated with regular concentrated *E. coli* contamination and the highest expected efficacy gaps, meaning the difference between the number of intentions voiced and the number of actions taken was largest for these LWMs. Defensive processing was most common for these LWMs, presumably supporting their return to the uninvolved stage, wherein they no longer consider adopting control measures.

5. Reporting of variable threat prompts long-term engagement with LWMs moving between indecision, intentions to act, and intentions to not act. This pattern is associated with changing perceptions of susceptibility and partial efficacy (actions do not fully control the threat). Defensive processing is indicated but respondents continue to acknowledge and want to address the threat. Respondents looked to test results for confirmation of the impact of their actions.

6. Sustained intention to act. This pattern is associated with regular concentrated *E. coli* contamination and is differentiated by higher self-efficacy and implementation of consistent chlorine disinfection (with support from NGOs in four out of the seven cases).

**Table 6.6:** Patterns of LWM response to monitoring results reports.

| No. | Main Cases | Secondary Cases | Intentions* | Actions* | Efficacy Gap** | Defensive Responses* |
|---|---|---|---|---|---|---|
| 1 | 7 | 0 | 0 (0 – 0) | 0 (0 – 0) | 0 (0 – 0) | 0 (0 – 2) |
| 2 | 7 | 10 | 2 (1 – 3) | 1 (0 – 2) | 1 (0 – 2) | 0 (0 – 2) |
| 3 | 8 | 14 | 2.5 (0 – 3) | 1 (0 – 2) | 1 (0 – 3) | 0 (0 – 2) |
| 4 | 7 | 0 | 4 (1 – 5) | 1 (0 – 2) | 2 (1 – 4) | 3 (2 – 4) |
| 5 | 16 | 5 | 3.5 (1 – 5) | 3 (1 – 4) | 1 (0 – 1) | 2 (0 – 4) |
| 6 | 7 | 1 | 3 (2 – 8) | 2 (2 – 5) | 1 (0 – 4) | 1 (0 – 3) |

*Values are medians (with range in brackets) of the number of intentions, actions, and defensive responses recorded at least once for each LWM.
**Values are medians (with range in brackets) of the expected efficacy gap for each LWM, with gap calculated as the number of actions subtracted from the number of intentions.

## 6.3 Discussion of Key Findings

I conducted this study to understand whether, and under what conditions, water quality data is useful for community-level water management. In doing so, I differentiated the activities of household-level management (by water users) and water system management (by LWMs). My analysis, founded on an integrated fear appeal conceptual framework, emphasises the advantages of specific personalised threat information and well-contextualised repeated messaging, but also draws focus to efficacy constraints and poverty threatscapes (complex threat landscapes). In the following subsections, I discuss the household-level and LWM findings concurrently, noting that while LWMs do not systematically have more training than users on water safety threats, they are often in positions of relatively greater efficacy due to community hierarchies and gender roles (79% of the LWM participants were male, reflecting the strong gender norms that were evident in the results of the household-level assessment).

### 6.3.1 Specific External Stimuli

Based on my integrated fear appeal framework, specific personalised threat information (like a test result) that triggers an affective response is expected to motivate behaviour change better than general awareness. This is supported by my results, and by other research (Doria, 2010), which show that water quality is judged by a combination of factors such that the intended effects of general messages about water quality hazards may be counteracted by stability of other judgements, like organoleptic perception and experience. Additionally, in behavioural economics literature, unrealistic optimism about one's own situation relative to a general context is a recognised cognitive bias that "can explain a lot of individual risk taking, especially in the domain of risks to life and health" (Thaler & Sunstein, 2009, p35). The effectiveness of health communications that proffer general information about risks without personally specific data, which are common in research and practice, are hampered by this optimism bias.

Baseline general awareness of water quality threat was high among the participants in this study. More than half of the household survey respondents recognised water safety risks and 90% of the LWMs were aware of potential microbial water quality hazards before the monitoring programme began. Nevertheless, few respondents reported consistently acting to improve water safety at household level and most LWMs were uninvolved (not considering adopting water safety precautions). In interviews, participants reflected that, in the absence of specific water quality information, attribution of illness to water becomes more difficult and trade-offs involving water safety and time, monetary expense, effort, and other risks are more difficult to evaluate. Upon first receiving *E. coli*-positive test results, however, the LWMs in this study universally engaged with the threat (none remained uninvolved) and 77% acted at least once to improve water safety.

### 6.3.2 Repeated Messaging

In noting the motivational advantages of specific threat information, I also emphasise the importance of framing test results to encourage proactive risk management. In this study, monthly results-reporting showed benefits from reinforcing consideration of water safety, particularly for LWMs who were inclined to prolonged indecision and information seeking. This is consistent with previous research on persuasion in marketing (van't Riet & Ruiter, 2013) and WASH messaging (Pickering et al., 2019). But I caution that the variability of *E. coli* results led some LWMs to disengage from considering or using water safety measures when tests were *E. coli*-negative. This highlights the importance of contextualising variability in results-reporting. Rather than focusing as much on individual results as I did in this study, monitoring reporting should direct attention to proactive risk management, making use of sanitary inspection information and avoiding overemphasis on any one sample.

Repeated messaging initiatives must also recognise that affective message processing and resulting motivation is likely to shift over time. The initial sharing of results would be most associated with rapid affective processing, whereas subsequent sharing is likely to be more associated with conscious affective processing wherein people have more opportunity to influence their emotions through cognitive means (van't Riet & Ruiter, 2013). Thus, as I observed in this study, the success of repeated messaging efforts strongly depends on the balance between threat and efficacy; where efficacy is insufficient, defensive cognitive processing is likely to have increasing influence over time. This trend combined with reductions in self-efficacy over time (as discussed in the next subsection) means that links between data and decisions should be expected to weaken if self-efficacy limitations remain unaddressed.

### 6.3.3 Efficacy Constraints

The users and LWMs in this study demonstrated that problem-focused responses and defensive cognitive processing are not mutually exclusive, particularly when problem-focused responses involve taking partial measures due to efficacy constraints. Low self-efficacy driven by structural constraints outside of individual control is widespread in the study area, and similarly in many lower-income rural regions. Under these conditions, users and LWMs make use of partial efficacy to improve water safety through limited (as opposed to multi-barrier) controls and/or action at discrete intervals when threat is relatively high (e.g. when someone is already ill).

In contrast to general water users, LWMs often have higher self-efficacy as signalled by their positions within committees and facilities or as owners. They have access to pooled user fees and have more scope to apply cost-effective centralised treatment measures and seek support from governments, NGOs, or service providers. Nevertheless, my temporal analysis shows that, while changes in perceived threat and related affective state motivate LWMs to engage with water quality threat, the effect is less productive and reduces over time in the absence of sufficient efficacy.

I find that, for water safety management, LWM efficacy is strongly moderated by water system design, which highlights the importance of building water safety controls into the initial design phase of water projects. Furthermore, LWMs require ongoing support to maintain water supplies (Lockwood & Smits, 2011) and exclusively local financing of safe water supplies is widely unachievable (Libey et al., 2020). I note that response and self-efficacy were overestimated by LWMs before they had attempted to engage in problem-focused responses and realised, in the process, the extent of the challenges involved. Considering this, I suggest that many behaviour change studies overestimate the influence of single information interventions by measuring the development of intentions to act over a short duration – usually no more than two weeks in evaluations of fear appeal messages (Tannenbaum et al., 2015) and no more than a month or two in evaluations of responses to water quality test results (Section 2.2.2).

### 6.3.4 Poverty Threatscapes as Key Situational Differences

Fear appeal research has noted interaction effects between multiple perceived threats; for example, in studying the threat of skin cancer, Cho and Salmon, 2006, discuss perceived threat to behavioural freedom in the sun. Generally, however, the consequences of managing complex poverty threatscapes needs to be more thoroughly considered in public health research, including in the WASH domain (Ray & Smith, 2021). The findings of my research with LWMs and water users suggest that the disconnect between water safety threat perception and problem-focused action in low income areas is due largely to challenges arising from the "everyday complexity of poverty" (Ray & Smith, 2021, p1). And this can apply to other environmental exposures beyond drinking-water safety, for example cooking smoke or pollution from manufacturing activity (Lora-Wainwright, 2017).

Efforts to promote behaviour change by communicate information about environmental exposures must recognise that people living in poverty constantly navigate high-consequence financial trade-offs (A. Banerjee & Duflo, 2011) and work with reduced cognitive bandwidth especially for processing hazards that have chronic or delayed effects (Mullainathan & Shafir, 2013). Furthermore, extending the idea that information about a threat is less influential when people are already fearful of that threat (Muthusamy et al., 2009), my findings suggest that when individuals face many threats within a challenging risky environment, a message aimed at increasing fear about one component of that environment has limited affective influence.

Thus, while constraints on resources, know-how, and effective response options are central to the core concept of self-efficacy, the impact of poverty on processing and response to fear appeals is broader than these most apparent constraints. Poverty threatscapes encompass key situational differences that information interventions should consider.

## 6.4 Conclusions and Further Research

The baseline assessment of user perspectives discourages sampling at household level for the purpose of motivating behaviour change. It indicates that further emphasising threat without improving efficacy would motivate limited behaviour change for improving drinking water safety and may potentially be counterproductive by reducing demand for safely managed water if defensive reasoning is reinforced. Furthermore, as explored in Chapter 5, household-level *E. coli* results are more complex to interpret than source water results. Thus, a messaging campaign that presents severity and response efficacy information based on household-level *E. coli* sampling and household water treatment measures would be subject to substantial uncertainty in terms of health outcomes. Interventions that focus on behavioural settings (Curtis et al., 2019) and align with One Health approaches for improving household environmental conditions are likely to be better investments. While setting up the monitoring programme, I also discovered that sharing water quality results at household level would have lowered the acceptability of the monitoring programme for government and LWMs, in part due to concerns about the self-efficacy of water users (as elaborated in Chapter 7).

I am not suggesting that information be withheld from water users. If testing is done at household-level for other purposes, households should have the option of receiving the results — access to information is a dimension of empowerment (Dery et al., 2020) and they have a right to this information (de Albuquerque et al., 2014). But results should be shared with sensitivity to self-efficacy limitations and the threatscape that household members are navigating, which may mean expectations of promoting behaviour change should be low. In particular, recognition of complex poverty threatscapes has important implications for interpreting willingness to pay and choice patterns.

Studies in varying socioeconomic contexts have explored willingness to pay for clean water (e.g. Dey et al., 2019; Dupont & Jahan, 2012; Makwinja et al., 2019; Rodríguez-Tapia et al., 2017; Vásquez et al., 2009). This approach is useful to understand the potential of community-based financing to support ongoing management of water supplies, but the findings presented in this chapter discourage extending it to conclusions about how much people value safe water. Similarly, in low-income contexts the value of information about water safety should not be assessed through 'value of clairvoyancy' / 'willingness to pay for information' methods that are often used in applications of decision-theory, as discussed by (Shepherd et al., 2015) with reference to the SDGs.

Neither should continued use of risky water sources in lieu of better managed ones be interpreted as indifference to health issues. This conclusion accords with the findings of research conducted elsewhere in Kenya that: "While water-health links are understood to varying degrees within the community, contextual (physical environment), compositional (individual) and collective (community) factors interact to influence health. Community challenges, such as lack of unity, lack of education and lack of control were identified as the main barriers to initiating change, despite a desire for increased access to safe water and sanitation" (Levison et al., 2011, p103). The discussion of water-source selection in the *Drawers of Water* study areas in Uganda, Tanzania, and Kenya further demonstrates that resigned use of water sources that are known to be sub-optimal is a long-standing and widespread issue that arises from constraining circumstances not indifference (G. F. White et al., 1972).

To conclude, specific water safety information can motivate engagement with water quality threats, but the use of fear appeals to promote behaviour change around rural water safety should be accompanied by sustained support to improve decision-makers' self-efficacy. LWMs may be positioned to be effective change-agents for safe rural water supply if they are supported. In addition to training, rural water supplies need ongoing resourcing (including financing and development of local supply chains and services).

Furthermore, in this chapter I noted that water supply designs and starting conditions influence response efficacy and LWM self-efficacy, but my sample size is too small to observe an effect of scale. The scale of supplies managed by LWMs varies considerably from wells that serve a few households to piped distribution schemes that serve hundreds. Further research might usefully consider how scale influences LWM perceptions and behaviour in response to water quality monitoring. Additionally, I've noted that perceptions of threat have personal and interpersonal dimensions (interview participants spoke of their own health and the health of others) at both source- and household-level, but my analysis did not explore this dimension in detail. This may be a worthwhile undertaking for further work, potentially drawing insight with respect to collectivist and individualist orientations from cultural theory.

*Nowhere did we find widespread casual or indifferent evaluations of water sources...if they appeared to act contrary to the judgement of an expert it was for reasons convincing to them. The gap between the two judgements does not seem to rise from lack of motivation to gain healthful supplies, it comes from differences in information and assessment.*

— White, Bradley & White, Drawers of Water, 1972

*postulates [of the sociological conception of contradiction]: that social organisations at all levels (from the classroom to the State) are constellations of (actual or potential) conflicts of interest; that personality structures are split and convoluted; that the individual's conceptualisation is systematically ambivalent or dislocated; that motives are mixed,*
*purposes are contradictory, and relationships are ambiguous;*
*and that the formulation of practical action*
*is unendingly beset by dilemmas.*

— Richard Winter, 1982

# 7

# Data Use and Stakeholder Cooperation

The third guiding research question of this thesis focuses on the key institutional enablers of and constraints on monitoring activity and data use. In responding to this question, and based on the findings of my literature review, I noted that institutional arrangements in the rural water sector in Sub-Saharan Africa are becoming increasingly pluralistic (Section 2.3). And I focused on the need for for insight into how water quality data sharing and use may influence trust-building and cooperation between stakeholder groups in bureaucratic, market, and community domains (Section 2.3.2). In particular, rural water service providers (RWSPs) may be positioned to include water safety monitoring in their post-construction support (PCS) activities, but they operate within a pluralistic governance structure so it is important to consider how their activities and the resulting data may influence cooperation with other stakeholder groups.

By collaborating with a RWSP, FundiFix, in carrying out the water quality monitoring programme and by engaging 56 LWMs and 36 bureaucratic and market-based stakeholders in interviews, I created an institutional experiment and conducted a dilemma analysis to elucidate the factors that enable and limit sharing and use of water quality monitoring information in the rural water sector (Section 3.6). The results of the dilemma analysis point to strategies that can better align rural water service provision with the global agenda for universal access to safe drinking water. They emphasise the importance of contextualising monitoring information; the need for external support to address water safety at the local level; and the value of designing institutional and technical capacity for ensuring water safety into projects at their onset.

The results and discussion presented in this chapter are published in a peer-reviewed paper on "Including water quality monitoring in rural water services: why safe water requires challenging the quantity versus quality dichotomy" (Nowicki et al., 2020). The co-authorship of this article reflects my collaboration with my supervisor and input from a fellow researcher at Oxford with whom I discussed the institutional context of the work. I led the design, execution, and writing of the work as specified in the co-authorship statement in Appendix A. In this chapter, the work is presented in three main sections. The first provides an overview of the dilemma analysis findings (Section 7.1). I then discuss the significance of an identified quality versus quantity dichotomy and relate the findings to the Water Safety Planning approach (Section 7.2). To conclude, I highlight key conclusions and point to directions for further work (Section 7.3).

## 7.1 Overview of Results

The analysis resulted in 111 described dilemmas that revolve around minimising perceived risks and adhering to moral principles. The dilemmas are reflections of conflicting viewpoints, within individuals or within each institutional group (market, bureaucracy, or community). There were no instances of an institutional group expressing unilateral agreement with one side of a dilemma in opposition to another group; however, in many cases dilemmas are formed around the assumptions made by individuals in one group about the impact of choices on and by another group. Conflicting viewpoints persists within and between stakeholders because the dilemmas consist of comparisons between different types of risk and present choices that require the favouring of one moral principle over another. How does one compare the threat of disease to the threat of reputational damage or the threat of maladaptive behaviour change? Or weigh the right to information against the moral imperative to avoid causing undue distress? The dilemmas are grouped by their relevance to nineteen topics, as described in Table 7.1.

**Table 7.1:** Summary of dilemma groupings by stage and topic. *Count refers to the number of dilemmas per group. Applicability indicates whether the dilemma group is relevant to community (C), market (M), or bureaucratic (B) stakeholders. Type indicates whether the dilemmas in each group are predominantly classed as ambiguities (A), judgements (J), or problems (P).*

| Stage | ID | Topic | Count | Appl. | Type | Topic Explanation |
|---|---|---|---|---|---|---|
| Generate info | G1 | Access priority | 14 | CMB | P | The relative importance of quantity versus quality, with water safety perceived as distinct from concerns of access to basic water services. |
| | G2 | Allow monitoring | 7 | CB | J | Approve of, versus object to, monitoring being done by RWSPs. |
| | G3 | Include monitoring | 12 | MB | J | Include or exclude monitoring from regular activities, with perceptions of responsibility to monitor of central importance. |
| | G4 | Monitoring design | 8 | MB | J | Sampling design choices such as what parameters and locations to include and frequency of sampling. |

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**Table 7.1 – continued from previous page**

| Stage | ID | Topic | Count | Appl. | Type | Topic Explanation |
|---|---|---|---|---|---|---|
| | G5 | Lab certification | 5 | MB | J | Use of government certified (usually centralised) labs versus use of field kits and minimalistic field labs. |
| Share info | S1 | Share to users | 11 | CMB | J | Rationale for and against sharing water quality monitoring information with users (perspectives of users are not included). |
| | S2 | Share to LWMs | 2 | MB | J | Rationale for and against sharing water quality monitoring information with LWMs. |
| | S3 | Share to bureaucracy | 4 | CM | J | Rationale for and against sharing water quality monitoring information with bureaucracy. |
| | S4 | Share to sector partners | 4 | CMB | J | Rationale for and against sharing water quality monitoring information with NGOs and donors (perspectives of partners not included). |
| | S5 | Communication mode | 2 | CM | A | A full-programme educative approach to sharing with LWMs and/or users versus a paternalistic approach of partial sharing. |
| | S6 | Entitlement to results | 1 | C | P | Rationale for and against the assertion that LWMs are entitled to the results of water quality monitoring. |
| Engage with info | E1 | Utility | 5 | CB | J | Rationale for dismissing new information versus engaging with and consequently changing beliefs, assumptions, or workplans on the basis of it. |
| | E2 | Power vs bliss | 1 | C | A | Rationale for whether or not knowledge is empowering (when and how), articulated by many as 'knowledge is power' and conversely that without ability to respond to threats, being informed of them causes unwarranted distress so ignorance is preferable (or 'bliss' as in the English idiom). |
| | E3 | Responsibility to use | 13 | CMB | P | Taking versus attributing responsibility for responding to the results of water quality monitoring. |
| Respond to info | R1 | Urgency | 2 | M | A | Rationale for and against immediate, localised response versus developing strategic large-scale solutions over the long-term, as articulated by service providers on the basis of meeting expectations of community versus government stakeholders. |
| | R2 | Source choice | 6 | CMB | J | Weighing options for sourcing water. |
| | R3 | Protection choice | 3 | C | J | Weighing options for protecting source water. |
| | R4 | Treatment choice | 9 | CM | J | Weighing options for treating water at the source, point of collection, and or in the household. |

Continued on next page...

**Table 7.1 – continued from previous page**

| Stage | ID | Topic | Count | Appl. | Type | Topic Explanation |
|---|---|---|---|---|---|---|
| | R5 | Empowerment | 2 | CB | P | Wanting to act versus not having the financial resources and knowledge with which to act (as articulated by LWMs) OR debate about the relative importance of financial versus knowledge barriers to action (as articulated by the bureaucracy). |

The topics are strongly interrelated and Figure 7.1 depicts sixty-nine of the most substantive links between them. The topics are disaggregated by stakeholder group: bureaucracy (blue), community (magenta), and market-based (green).

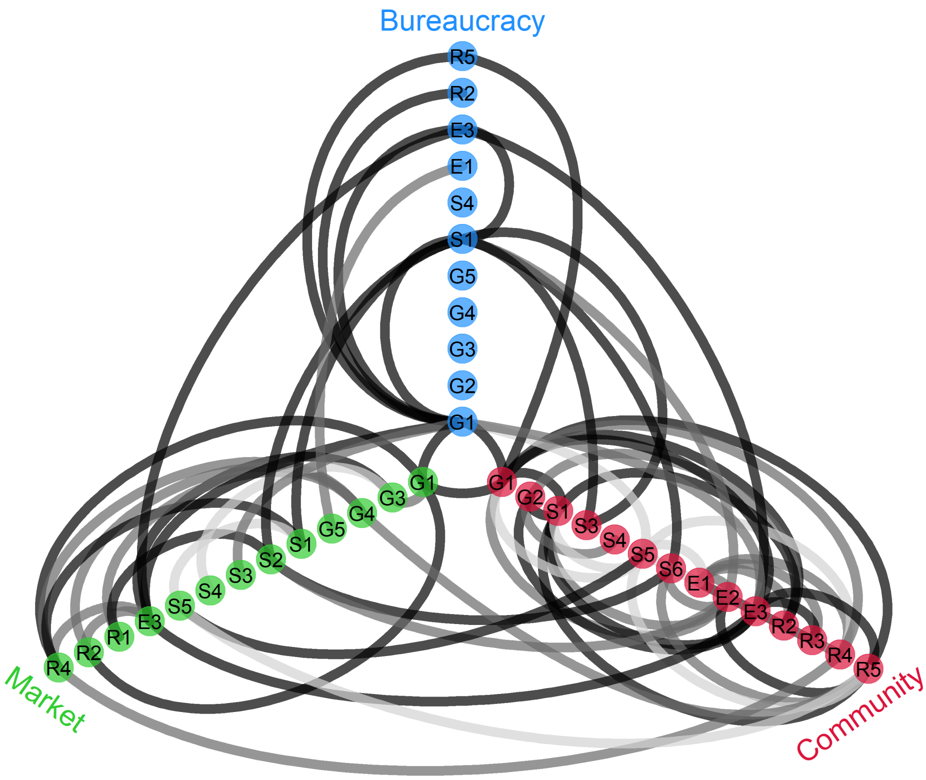


**Figure 7.1:** Axial hive network visualisation of links between dilemma topics. *Axes represent stakeholder groups with blue = bureaucracy, magenta = community and green = market. Nodes refer to the topics described in Table 1 and are organised by stage (generate, share, engage, respond). Black line indicates a barrier, discouraging monitoring. Medium grey indicates neutral influence. Light grey indicates enabling monitoring.*

The darkness of the links between topics in Figure 7.1 indicates their type of influence on generating, using and sharing monitoring information. Only nine links are monitoring enablers. Eight of these relate to communication mode (topic S5 in Table 7.1), and more specifically the advantages of a full-programme educative approach to sharing water quality monitoring information with LWMs and users. The ninth enabler relates to RWSPs, whose enthusiasm for including monitoring in their service package (G3) is increased by anticipating attracting investment by sharing monitoring results with sector partners (S4).

In contrast, just over half (36) of the links depicted in Figure 7.1 represent barriers to effective monitoring. Twenty-three of these barrier links are within-group. Within the community group, for example, there is a barrier between responsibility to use (E3) and allowing monitoring (G2). Generally, LWMs were wary of allowing monitoring when responsibility for responding to results was unclear. When LWMs perceived that they were responsible for the quality of the water, however, they were less wary of monitoring but placed more emphasis on confidentiality of results (S1).

In addition to the within-group barrier links, there were thirteen barrier links between stakeholder groups. Two of these were related to difficulty on the part of RWSPs in judging whether and how to share information with users (S1) and LWMs (S2) given government concerns around confidentiality. A third barrier arose due to differential preferences from RWSPs and communities regarding meaningful versus feasible modes of communicating results (S5). The remaining ten barriers were related to the problem topics of access priority (G1), responsibility to use (E3), empowerment (R5), and entitlement to results (S6). In general, access priority (G1) is one of the most influential topics. It is applicable for all three stakeholder groups, being comprised of 14 dilemmas in total, and is a component of 22 links between topics (as emphasised by thicker lines in Figure 7.2). It is further unpacked in the following sections.

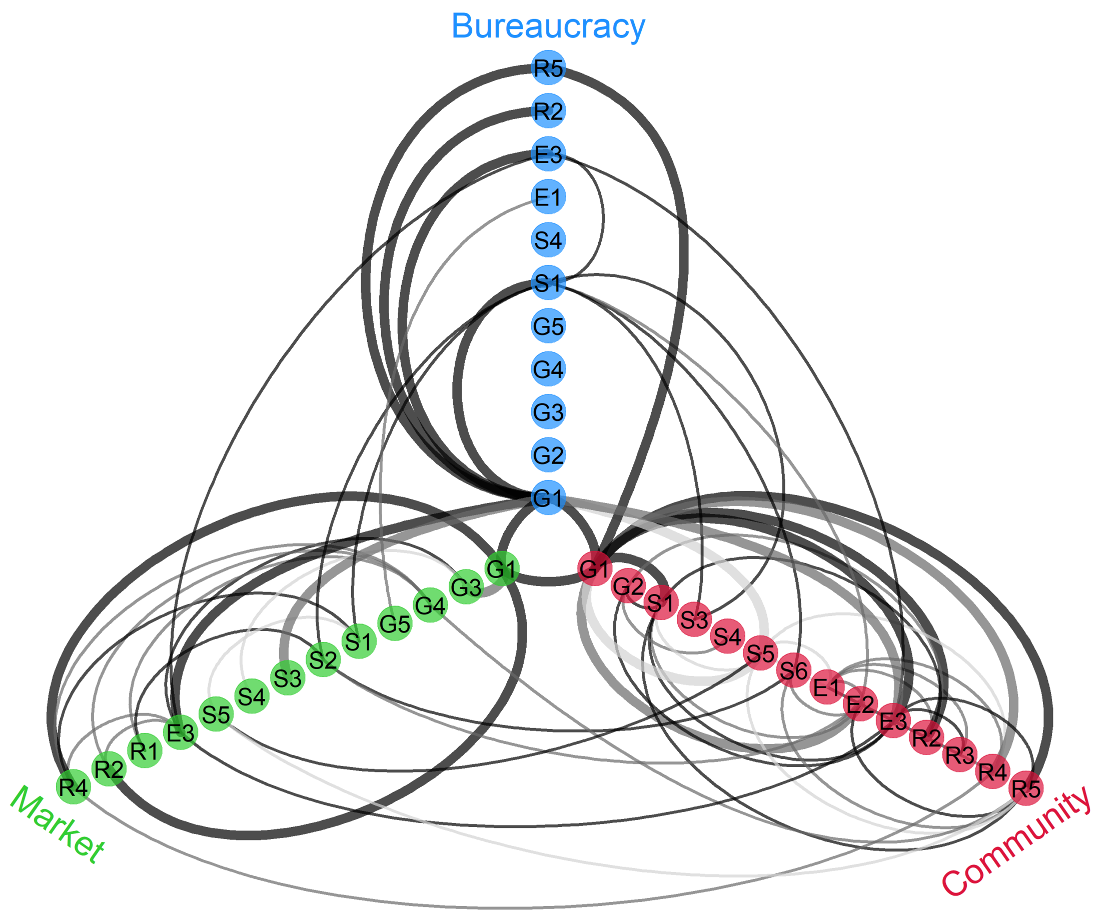


**Figure 7.2:** Axial hive network visualisation of links between dilemma topics with links to 'access priority' (topic G1) emphasised by thicker lines.

### 7.1.1 Unpacking Access Priority Dilemmas

The following three subsections explore the access priority dilemma analysis results around three key emergent themes: contradictory assumptions about the importance of quality, perceptions of water quality monitoring as a threat to supply sustainability, and complications arising from unclear allocation of responsibility. Subsequently, in Section 7.2, I discuss the implications of these results for efforts to implement monitoring and use water quality data.

***Contradictory Assumptions***

From the bureaucratic perspective, national policy mandates that county governments supply safe drinking water. But these national directives are non-binding and open to interpretation. Budgets are allocated at county-level, where they are heavily influenced by election politics. Water supply is an important campaign issue, but quality only becomes politically important when people are focused on problems with it. There is an important link between access priority (G1) and allowing sharing with the public (S1 and S2) that is explained by the prevalence of two contradictory assumptions: first that users do not care about water quality, and second that revealing water quality problems to users will distress them and cause political backlash. This theme, that users don't care about water quality although it is important to them when they believe it to be a threat, persists in the market perspective as well.

> "*Across the board, rural water users do not really care about water quality unless you're in a place that has been affected by a cholera outbreak in recent memory... Whether it's the government side or users, there's little demand for water quality.*" – RWSP 5

While the community LWMs did express that water safety is a lower priority than having water at all, their access priority dilemmas are centrally related to a lack of empowerment (R5). Here the dilemma can be expressed as:

- **On the one hand**, LWMs would like to adopt the multibarrier approach with protection, cleaning and disinfection measures. And they are amenable to separating and treating a smaller volume of water specifically for drinking.

- **On the other hand**, they don't have funds for necessary infrastructure, equipment and/or consumables; don't know how to seek or raise funds; or are not experts and don't feel confident in whether, or how, to carryout measures.

The above dilemma conceptualises empowerment in terms of both resources and knowledge. The importance of knowledge is further elaborated in the power versus bliss topic (E2), i.e. whether knowledge is empowering or ignorance is bliss, where many LWMs articulated the importance of knowledge for enabling consideration of previously unrecognised issues.

> "*people are dying because of lack of knowledge. You know, they may prefer that one because it is fresh, but it's risky. But unless somebody comes in and does some testing, we just assume [it is good to use] — our grandfathers used it. So, we continue with that problem. And you might find, a community like this one, having a chronic issue because of lacking people to bring them to light.*" — Committee 6

> "*if we shall be able to know, we can ask [the government]: how far have you reached in solving this problem? But when we don't know whether there is a problem then we cannot ask them because we think everything is okay.*" — Facility 9

### ***Monitoring as a Threat to Supply***

Across all institutional groups, the access dilemmas include fears that water quality monitoring threatens basic supply by splitting resources; by causing controversy that destabilises management and compromises ability to operate; by revealing that a supply must be shut-down due to geogenic chemistry problems; or by necessitating treatment approaches that require supply disruption. RWSPs expressed this dilemma as:

- **On the one hand**, water quality testing identifies quality problems and enables corrective actions to be taken.
- **On the other hand**, corrective action can threaten supply since contamination can be difficult to treat and closing a source without providing a better alternative is not in the best interest of the users.

For LWMs, concerns about monitoring causing controversy that would destabilise management and prevent ongoing functionality of water supplies were associated with perceived need for confidentiality of monitoring results (S1).

> "*we should not [share to users] because that one will jeopardize, with politics, everything. There will be politics, and then the project will not help the community at all. If they are going to bring politics, it is going to die, the project may die out.*" — Facility 16

***Unclear Divisions of Responsibility***

The access priority (G1) dilemmas of each institutional group are interrelated and mutually reinforcing, with each justifying their own lack of priority for water safety at least partly on the basis of the others not prioritising it. Due to the associated politics, disempowerment, and perceived threats to functionality of supplies, the access priority dilemmas result in abnegation of responsibility for water safety in all three institutional groups. If a RWSP introduces monitoring in this context, in the absence of operationalised responsibility for water safety, they draw attention to the question of who is expected to respond to identified water quality threats. As with the access priority dilemmas, the dilemmas around responsibility to use (E3) are interrelated. But in this case, rather than being mutually reinforcing, they create a debate – about legislated mandates versus perceived moral and practical responsibilities – that compromises institutional cooperation.

The bureaucracy may have a legislated mandate, but the lack of operationalised responsibility for water safety in the rural water sector has left a void in which responsibility is largely defaulted to the household level. There is a popular notion that all stakeholders have a role to play in securing safe water, but roles are poorly defined in practice. As a result, lack of action on the part of one institutional group is frequently justified by shifting responsibility to another. By introducing water quality monitoring into the current void, RWSPs (whose main role is maintaining functionality of existing supplies) may find themselves cast as instigators – with responsibility to respond to monitoring results largely defaulted to them by consequent expectations from bureaucracy and communities.

> "*The moment these projects are handed over to the community, we are through with them. But now I think they are training the communities on how to handle these things.*" — County representative 3

> "*I think it is maybe our way of thinking, us as Kenyans and Africans, that if you are looking out for any problem, you are also having a package of the solution.*" — Facility 21

## 7.2 The False Quantity vs Quality Dichotomy

Rural water service provision typically prioritises quantity over quality, which is often assumed to be adequate where groundwater is used. This practice maintains the separation of water safety from other aspects of rural water service provision, thereby establishing a false dichotomy – one that is reinforced by contradictory assumptions about whether water quality matters to the public. These assumptions obscure issues of community access to resources and knowledge.

The empowerment dilemma expressed by LWMs in terms of intent to manage versus ability to pay, action knowledge (Frick et al., 2004), and self-efficacy (Bandura, 1977; Bandura, 1997) is reflected in the literature on the sustainability of a) community self-financing of recurrent operations and maintenance costs (Foster & Hope, 2016; Harvey, 2007) and b) water safety behaviour at the household-level (Figueroa & Kincaid, 2010; Mosler, 2012; Mosler et al., 2010). Research has called for further exploration into the roles of ability to pay and self-efficacy for determining sustainable service delivery (Foster & Hope, 2016) and sustaining safe water behaviour (e.g. Dreibelbis et al., 2013, and others as discussed in Section 2.2). These empowerment dimensions were key themes in Chapter 6 that have been further explored by the dilemma analysis – which demonstrates their significance for water safety decision-making at the community level and emphasises that lack of empowerment does not equate to apathy.

Moving beyond the question of whether water quality matters, and to whom, the dilemma analysis also revealed that water quality monitoring is deterred by fears that it will threaten functionality. Thereby, further reinforcing the quantity versus quality dichotomy. Fears relate to a lack of contextualisation and a reactive mode of operating in which solutions to quality concerns involve supply disruption or closure. But fears are also related to disempowerment, and the self-preserving requirement to avoid attracting criticism by revealing problems that one cannot resolve. In this context of low self-efficacy, the fear appeal literature also suggests that a threat to one's sense of self as an honest person who does their job well may play a role in creating uncomfortable cognitive dissonance (van't Riet & Ruiter, 2013), potentially motivating stakeholders to reject monitoring activity and results. This theme is explored in-depth with respect to LWMs in Chapter 6, which details how water safety management actions are influenced by the totality of threats, the threatscape, that LWMs contend with.

Responsibility is also a key point of contention. Indeed, perhaps the biggest deterrent of monitoring is that it draws attention to the question of who is responsible for using the results. This question is additionally complex because perceived responsibility varies with contaminant type. Barriers to engaging with and sharing chemistry data are considerably more intractable than for microbial data largely because household water treatment options are observed to primarily respond only to microbial hazards. Furthermore, introducing monitoring can reveal problems that nobody realised were there, leading multiple stakeholders in interviews to liken it to opening Pandora's box. As a result, RWSPs that take on water quality monitoring encounter dilemmas about their organisational identity and purpose and may find themselves facing opposing demands from bureaucracy and community regarding how the results of monitoring are shared and used. This could be problematic given the importance of institutional cooperation for advancing service delivery in rural areas.

Yet, the assumptions, fears, and abnegation of responsibility that deter rural water quality monitoring may be mitigable. There is a need:

- to contextualise monitoring results (so that quantity and quality are jointly considered and the relative safety of monitored sources versus unmonitored alternatives is understood).
- to better align resources and responsibilities so that stakeholders in all three institutional domains can act on their intended mandates (establishing funding structures, enabling legislation, and quality-inclusive post-construction support (PCS) arrangements).
- to mitigate difficult path-dependencies by approaching the technical and institutional design of water supply systems such that safety is considered early (rather than deferring safety measures to an unspecified future time when the ever-moving target of sufficient quantity is met).

These needs are consistent with an established risk-based approach: Water Safety Planning (WSP) (WHO, 2017a). As of 2017, 93 countries had implemented WSP at varying scales, and although uptake has been relatively low in Sub-Saharan Africa, at least ten countries are engaged in efforts to scale-up the use of the approach in both urban and rural areas (WHO & IWA, 2017). This includes Kenya, where the national water services regulator has published guidance promoting the approach (WASREB, 2019b). In the following sections, I briefly discuss how the barriers identified by the dilemma analysis may be addressed through a WSP approach. In so doing, I also speak to the main challenges of implementing the approach in rural areas.

### 7.2.1 Addressing Dilemmas with Water Safety Planning

***Contextualising Monitoring Results***

The WHO have recommended Water Safety Planning since 2004; they continue to do so (WHO, 2017a) and practical guidance is readily available (Bartram et al., 2009; WHO & IWA, 2010), including specific adaptations for small community supplies (Greaves & Simmons, 2011; MWIE, 2015; Rickert et al., 2014; WHO, 2012b). Rather than relying on a purely reactive management approach, which reinforces the quality versus quantity dichotomy, WSP seeks to identify and address risks holistically and preemptively.

Although it focuses on water safety (necessarily otherwise it would lose meaning and practicability), WSP also recognises other priority aspects of services. Within the WSP model, quality, quantity, proximity, reliability and acceptability of supply are to be considered concurrently to minimise use of supplementary water from unsafe sources and unhygienic storage. For example, disruptions due to breaks and subsequent maintenance are associated with declines in microbial quality; the cost of protection and treatment measures in addition to other operating costs is a key design consideration because water rates must account for ability to pay; and loss of customers due to shortages or affordability issues means people reverting to using surface water, less water, and or travelling farther for water. Where aspects of reliability and affordability present health hazards, they overlap with safety and should not be framed completely separately. Recognition of these overlaps could be helpful for gaining traction with LWMs who may otherwise view safety as an overly narrow concern. Thus, challenging the false quantity-quality dichotomy means quality should not come second but neither should it eclipse other service priorities - an integrated approach is needed.

When implemented as intended, the WSP approach should alleviate functionality fears by encouraging consideration of monitoring results in terms of overall health burden. By design, it should improve contextualisation of water quality information and, therefore, has potential to mitigate some of the barriers that were highlighted by the dilemma analysis. But the key challenge here is implementing the approach as intended. Reactive management and associated "obstruction of water delivery" has been described even for cases where WSP is actively being attempted (String et al., 2020, p.5). As discussed in the following sections, implementing WSP as intended is likely to require external support and early inclusion.

***The Need for Post-Construction Support***

The dilemma analysis found that lack of empowerment creates barriers to improving water safety through monitoring. This is also reflected in the literature on WSP, which frequently highlights inadequate financing (Chang et al., 2013; Kumpel et al., 2018; Perrier et al., 2014; Rinehold et al., 2011) and capacity (Ferrero et al., 2019; Kanyesigye et al., 2019; Kumpel et al., 2018; Parker & Summerill, 2013; Perrier et al., 2014) as substantial barriers to successful implementation. In rural areas in particular, inadequate financing and capacity have meant that WSP efforts focus on the early stages of the approach (assembling a team, describing the water supply and identifying hazards, developing and implementing a plan for improvement) but neglect the latter stages of monitoring, verification and iterative learning (Kanyesigye et al., 2019; String et al., 2020), which are crucial to the effectiveness and sustainability of the approach (Rinehold et al., 2011; WHO, 2012b).

Additionally, rural WSP efforts that focus on water supplies individually have limited scope to address systematic institutional and environmental risks, and may be closer in form to hygiene behaviour change projects than WSP as it is intended. Thus, financial and capacity-building support is needed and, further, PCS should involve networking supplies with a view towards structural enablers and constraints.

As discussed in Section 2.3.1, the need for PCS is widely and increasingly recognised, although water safety considerations are yet to be comprehensively included and sustainable financing is an ongoing problem. External support (enabled by funding streams from outside of communities themselves) for rural water services is not new, a review of studies assessing external support provision since the 1970s describes support in many forms, provided by NGOs, governments, community associations, or businesses (Miller et al., 2019). Half of the studies in the review focused on Sub-Saharan Africa. Ironically, the most reported challenge for external support programs was that providers themselves lacked sufficient resources to adequately support communities. The RWSP model is a hybrid in that it leverages resources from the private sector, donors, and government, as well as consumers. RWSPs, with their ability to network rural supplies at scale, and to attract multiple funding streams and well-trained staff, are potentially positioned to channel and appropriately localise support for WSP. Crucially, they may also be positioned to take a wider view of risk that aligns with a systems-based form of WSP.

Nevertheless, sharing results with LWMs and users in a way that builds understanding and is consistent with a holistic view of safety requires a full-programme educative approach to communication. The dilemma analysis highlighted that such an approach is important for enabling stakeholder cooperation around monitoring – particularly that quality and quantity be jointly considered and that comparisons with unmonitored alternative sources are well-informed. The findings in Chapter 6 further support contextualised communication, particularly around data uncertainty and hazard variability. From the RWSP perspective, however, whilst the benefits are recognised, there are persistent doubts about scalability of a comprehensive approach. Further work investigating the financial and logistical feasibility of incorporating such an approach in the RWSP model would be useful.

Some of the bureaucratic and community-based stakeholders also recommended that the scope of communication be extended to water safety at the household level. This is consistent with guidance and research studies that have recommended that rural WSP efforts include hazards occurring on consumers' premises (Bartram et al., 2009; Rinehold et al., 2011; String & Lantagne, 2016). The findings of this thesis do not support this extension, however, based on the additional complexity of interpreting water safety at household level (Chapter 5) and low expectations of general or specific information sustainably influencing household-level behaviour change in the absence of changes to self-efficacy and an overwhelming threat landscape (Chapter 6). These findings are not interpreted as support for withholding information from water users, however. Sufficiently supported LWMs can be positioned to communicate and contextualise water safety information, it is in their interests to do so assuming that the supply they manage provides safer water than the nearby alternatives. As discussed in Chapter 6, the perceived trustworthiness of information is also important. The legitimacy of LWM communications about water safety is likely to be strengthened by association with a RWSP that has a less-intimate investment in local community politics and is seen to use professional methods of water quality assessment.

***Path-dependency and Early Adoption***

With external support in place, monitoring and the latter stages of WSP become more feasible. The dilemma analysis found, however, that barriers to monitoring go beyond issues of finance and capacity. Whilst external support should empower more action on water safety, there will always be trade-offs on how resources are used, and the convention of dichotomising quantity and quality will continue to hamper water safety efforts. The dichotomy sustains the view that taking responsibility for water safety is an excessive burden. As reflected in the literature, this view of monitoring – and WSP more broadly – as burdensome is a key difficulty for securing buy-in to the approach (Kot et al., 2015; Perrier et al., 2014; Summerill et al., 2010). Though I have focused in this study on rural context, the quantity versus quality dichotomy has broader relevance. For example, a study of WSP in urban utilities in India, Uganda, and Jamaica described a "deliver first, safety later" mind-set among customers and implementers, which the researchers deemed a "significant limiting influence on WSP implementation" (Omar et al., 2017, p.902).

The WSP approach aims to supersede the vague notion of 'everyone having a role to play' in ensuring water safety, by requiring that specific, actionable responsibilities be allocated. But fragmented institutional structures make meaningful stakeholder engagement difficult (Ferrero et al., 2018) and technical path dependencies limit viable response options. When a WSP approach is adopted early in the life of a water supply project, it can contribute to institutional design (including allocation of responsibilities) and technical design (maximising the choice of viable source selection, protection, and treatment response options). Thus, early WSP may clarify and operationalise responsibilities for water safety. In combination with sufficient external support, it may mitigate the barriers that otherwise arise from uncertain responsibilities and reticence towards raising awareness of quality concerns without an ability to respond to them. Early adoption is also beneficial when considered in light of "community readiness" (Kot et al., 2015), because safety considerations are built into the design of a new system rather than being retrofitted to an existing system, when the acceptability of change and scope for community input are much reduced.

## 7.3 Conclusions and Further Research

When quality issues are not adequately contextualised and strategies are not in place to address them, water quality monitoring can threaten cooperation between bureaucratic, market and community institutional groups. In exploring the potential of RWSPs in Sub-Saharan Africa to contribute to the SDG 6.1 effort, I have highlighted the importance of building a technical and institutional structure around water quality monitoring so that it adds legitimacy to each institutional group rather than threatening them. Such a structure is consistent with the intentions of the WSP approach, which may be effective given external support and especially if adopted early.

A recent review of success factors for WSP implementation in low- and middle-income countries speaks to the generalisability of the discussion in this chapter (Herschan et al., 2020). The review emphasises the importance of technical capacity, community engagement and knowledge sharing, and verification and monitoring processes. And for small drinking-water supplies, specifically, PCS from NGOs or broader WASH programmes is also highlighted. What my study contributes in addition to those reviewed, is explicit attention to how monitoring intersects with the varying priorities and perspectives of stakeholders in different institutional domains. This chapter has discussed seven key points that could usefully inform WSP research and practice.

1. considerations of capacity should extend to the self-efficacy of LWMs;

2. community engagement should recognise LWMs as key actors and involve contextualising water quality information with respect to quantity (with dimensions of reliability and affordability recognised as health-related priorities), water source alternatives, and indicator and hazard variability;

3. early-stage verification of a water supply's capacity to provide safe water is useful both for subsequent monitoring design (for indicators to be more meaningful) and to bolster LWM self-efficacy by avoiding technical and social path

dependencies that make it difficult to respond to signals of contamination;

4. multiple long-term funding streams are needed to support quality-inclusive PCS (which cannot be adequately sustained by community-based financing alone, nor by short-term funding from NGOs or discrete WASH programmes);

5. RWSPs that network rural supplies at scale and attract multiple funding streams may be positioned to localise support for WSP with a systems-based view of risk (as opposed to a narrow focus on individual supplies);

6. household hygiene is outside the practicable scope of WSP but the water user perspective is important to consider in developing water safety plans insofar as source selection dynamics influence LWM priorities and supply sustainability; and

7. monitoring is more likely to be sustained and useful in pluralistic institutional settings when responsibilities are clear and resourced.

The core issue of clear and resourced allocation of responsibility is widespread. Most nations have public institutions that have mandated responsibilities for water supply, but these are often not extended to or operationalised in rural zones. In much of the rural world, responsibilities for drinking-water management are defaulted to household and community levels – as demonstrated by the existence of a panoply of self-supply arrangements, which are recently receiving increased recognition in the WASH sector (Fischer, 2019; Sutton & Butterworth, 2021). The downward defaulting of responsibility was supported through the community-based management model, and it continues through efforts to increase uptake of household water treatment technologies. WSP efforts should be based in an understanding of operationalised responsibility (and lack thereof) and should avoid further consolidating perceptions that households can and should individually provide themselves with safe water.

Those who fund rural water service provision and design and construct water supply infrastructure should consider that a quantity first, quality later approach makes securing water safety additionally difficult because technical and institutional path dependencies limit response options and discourage stakeholder cooperation around monitoring. Instead, water supply systems should be structured with preventative risk management in mind from the outset. In working to change institutional structures to support rural water safety, the dynamics within stakeholder groups will also be important. A key limitation of my dilemma analysis is that, in bounding a feasible scope of work, I engaged stakeholders only as representatives of broad groups (Section 3.6). Further research that engages more with tensions within each institutional domain would be valuable. And including participants from other contexts would help characterise the generalisability of dilemmas.

# 8

# Concluding Discussion

This thesis has drawn on the patterns and findings of previous investigations, informed by fields of study in the natural and social sciences, to explore pathways to safe water delivery through the interrelated aspects of stakeholder cooperation, local decision-making, and uncertainty in interpreting measurements. In this final chapter, I highlight the key findings of my research, discussing cross-cutting themes that demonstrate the interrelatedness of data, decisions, and drinking-water safety outcomes in pluralistic institutional settings. This discussion is organised around responses to my guiding research questions (Section 8.1). Some of the findings speak, generally, to issues of science-policy interaction in the delivery of health-related services; others are more specific to rural water service delivery in Sub-Saharan Africa, Kenya, and northern Kitui County; and overall, the discussion demonstrates that a systems-based framing is valuable for research that engages wicked problems like securing universal access to safe drinking-water. Following this discussion, I recap the high-level contributions of the research (Section 8.2) – including a brief overview of my ongoing efforts to disseminate my research findings (Section 8.2.1) – and reflect on the limitations of my work and directions for further research (Section 8.3).

## 8.1 Summary and Synthesis of Findings

In the literature review and methodology chapters of this thesis I explained how I developed an interdisciplinary, mixed-methods approach to explore links between data and decision-making in a study of rural water safety monitoring and management. Here I discuss my findings in four parts. The first three subsections respond to my guiding research questions on data uncertainties, drivers of decision-making, and structural enablers and constraints in turn – with multiple themes cutting across the three sections. The final subsection responds to my overarching research question and synthesises my research findings to present a set of recommendations that correspond with key leverage points for effecting change in systems. Since context is crucial in systems analysis, many of these recommendations are specific to the system that I have focused on (rural water supply in Sub-Saharan Africa), but comparable leverage points will exist for efforts to mitigate health risk through monitoring in other system contexts.

### 8.1.1 Data Uncertainty and Normative Risk Conceptions

In exploring my first research question, how uncertainty in data-based understandings of hazard flows influences the potential effectiveness of monitoring as a feedback mechanism, I focused primarily[1] on the use of *E. coli* as a faecal contamination indicator. I explored two key uncertainties: the extent to which *E. coli* at points of collection in loosely controlled rural water systems is linked to faecal contamination, and the extent to which increases in *E. coli* between points of collection and use are linked to increases in health risk (Chapter 5). Discussing my empirical findings in relation to the literature, I presented two main conclusions that have implications for normative conceptions of risk management based on monitoring data.

First, the health hazard implications of *E. coli* samples from points of collection and use should not be compared directly. Comparisons of the *E. coli* isolates taken from different locations supported five theorised scenarios of the origins of *E. coli* in household stored water. These scenarios and considerations of other exposure routes in household environments demonstrate the additional difficulty of interpreting health risk from *E. coli* tests at household level versus supply level. I suggest that monitoring should focus at the supply level, supporting prioritization of interventions where water contains high concentrations of *E. coli*. At household level, *E. coli*-positive samples could indicate no additional health hazard but, conservatively, they should be interpreted as indicating a generally hazardous household environment. Effective intervention at the household-level requires a multi-pathway approach that addresses core challenges of living in poverty and goes beyond water treatment and safe storage.

Second, *E. coli* data should be interpreted with a view of sanitary conditions and multiple measurements. The uncertainty associated with interpretations of

[1]My decision to focus on *E. coli* is justified in Section 2.1. The overview of monitoring results in Chapter 4 also includes key geogenic contaminants and parameters to track organoleptic properties of water, but these results are presented because they contribute context for water user and LWM decision-making – they are not explored in great depth with respect to data interpretation uncertainty. Measurements of chemical water quality hazards are often direct (and, therefore, less uncertain than indicator-based measurements of microbial hazard) and the key uncertainties in linking measurements to health risk are about cumulative exposure over long time frames, potentially through multiple pathways, and interaction effects among different hazards, diet, and other factors (Section 2.1).

single *E. coli* samples, particularly when removed from understandings of sanitary conditions, strongly limits their usefulness for operational decision-making. In my study, the *E. coli* strains that most likely originated from human and/or recent faeces were found at poorly protected points of collection (those with clear sanitary hazards and correspondingly poor sanitary inspection results) or at point of use. Furthermore, allelic diversity comparisons suggested that naturalised *E. coli* populations may be particularly relevant for supplies with low *E. coli* concentrations (in other words, consistent low levels of *E. coli* in water supplies may not be linked to recent faecal contamination). Thus, monitoring will constitute a more effective information feedback at supply level if data from multiple tests are interpreted in conjunction with sanitary assessment information.

It would be advantageous to combine *E. coli* sampling with other types of indicators that can be assessed more cheaply and rapidly. Attempts to do so with tryptophan-like-fluorimetry in this research were not successful, however, due to the characteristics of the groundwater in the region – in particular, the high concentration of coloured dissolved organic matter, which interferes with the TLF signal (Section 4.2). TLF sampling was discontinued, but ongoing work with FundiFix, which is not covered in this thesis, is exploring the utility of testing for residual chlorine (in supplies where disinfection is being implemented) in addition to continued testing for *E. coli*.

Sanitary inspections are also continuing. Sanitary risk scores from the monitoring programme did not correlate well with *E. coli* results (Chapter 4), which is not a novel or unexpected result (Section 2.1.3), but my *E. coli* strain level analysis did indicate a relationship between sanitary factors and the presence of *E. coli* that are more likely to have originated from recent faecal contamination. And regardless of *E. coli* dynamics, sanitary inspection is an important tool for understanding water supply conditions (the 'system assessment' step in Water Safety Planning). Assessment of sanitary conditions should not, however, be put forward as a sufficient alternative to water quality testing. Sanitary inspections are often discussed in the literature as simpler and more feasible[1] means of generating feedback for water safety management (e.g Kelly et al., 2021; Misati et al., 2017). I argue, however, that while sanitary inspection has important value, there are key reasons not to forgo efforts to increase water quality monitoring. Sanitary inspection is not a costless alternative: it requires transportation and time commitments and needs supporting structures to be in place for the resulting information to be useful. In a loose form[2], sanitary assessment is something that LWMs do continuously; so, while sanitary inspection training may help identify some previously unconsidered vulnerabilities, responding to identified vulnerabilities is the key challenge[3]. LWMs who do not have the resources to respond to water quality test results are also unlikely to be able to respond effectively to vulnerabilities identified in sanitary inspections without support.

Ultimately, both water quality testing and sanitary inspection are needed – they are complementary tools, each reducing uncertainty about water safety in a different way. Sanitary inspections backstop hazard assessments (providing valuable context in light of the uncertainty inherent in water quality measure-

[1]Recently, researchers have emphasised that sanitary inspection is more feasible than water quality testing in low-income areas because: "Sanitary inspection results vary less over time than microbial water quality, require less technical training to perform, and provide actionable information even when carried out infrequently. The operator of even a small water system should be able to conduct a sanitary inspection independently one or more times per year; operators should be trained, or at least invited in a routine inspection carried out by governments and other implementers in order to learn" (Kelly et al., 2021, p4).

[2]There are two broad modes of sanitary inspection. The mode employed by researchers and sector professionals, which attempts to comprehensively capture and differentiate risk factors, includes protocols and interpretation methods that are continuously being refined and are acknowledged to be complex (Section 2.1.3). Alternatively, there is a more straightforward mode of inspection that is considered appropriate for practical use by LWMs who do not have the resources for water quality testing.

[3]Breaks in fences, leaking tanks or pipes, pipe blockages and vegetation encroachment, visible faecal contamination around the water supply, and other vulnerabilities are often well-known to LWMs (and are problematic for supply reliability and security as well as for water quality reasons). One of the LWMs that I interviewed, for example, told me that the main storage tank in the small piped system that he managed had developed large leaks, which prevented sufficient storage to satisfy user demand (problems with long queues as supply was limited by pumping rate) and made batch chlorination infeasible. The water management committee regarded replacing this tank as a main priority, but they did not have the resources to do it themselves and had tried unsuccessfully for more than half a year to get government support.

ments) and logically identify measures to reduce water supply vulnerabilities. What water quality testing provides is a view on hazards that are otherwise not apparent and a feedback on the effectiveness of measures taken to reduce visible vulnerabilities. Furthermore, while knowledge of supply vulnerabilities is necessary to develop an action plan, water quality data from a professional provider may more effectively motivate action because of its specificity and link to 'expert' methods of assessment (this is explored in the next section responding to my second guiding research question).

A recent review of risk communication literature concluded that "there are no clear-cut or simple solutions for communicating uncertain risk information effectively", but that trust and perceptions of information legitimacy are strongly influenced by how well uncertainty is communicated (Balog-Way et al., 2020, p2249). The findings of this thesis support that monitoring can provide effective feedback at supply level, but that additional complexity at household level makes the health risk implications of point of use tests additionally uncertain. At supply level, combining data from (multiple) water quality tests and sanitary inspections is the best way to reduce uncertainty in hazard assessments. Specifically, interventions should be prioritised for supplies that have high concentrations of *E. coli* even if spikes happen only periodically. Sustained low concentrations of *E. coli*, particularly in the absence of visible sanitary vulnerabilities, are more likely to be associated with naturalised populations.

It is also worth emphasising that the fewer hazard controls applied in a water supply system, the more difficult it is to interpret indicator measurements. Introducing hazard control steps and a verification process that confirms the capability of a supply to provide safe water under different conditions, as recommended by the WHO, 2017a, unlocks additional value from indicators like *E. coli* and chlorine residual.

### 8.1.2 Data and Decision-Making in Complex Threatscapes

Imperfect as interpretations of monitoring data may be, water quality test results generally afford insight into water safety that LWMs and water users do not otherwise have access to. In exploring my second research question, how understandings of water quality data may interact with other drivers of decision-making to influence the actions of water users and LWMs, I found that an information intervention at household level was not supported (Section 6.1) but that LWMs may be better positioned to engage with hazard control measures in response to water quality test results. Compared to general water users, LWMs often have higher self-efficacy as signalled by the positions that they occupy. They have access to pooled user fees and have more scope to apply cost-effective higher-volume treatment measures and, in some cases, seek support from governments, NGOs, or service providers.

General awareness of the links between water quality and health is widespread in northern Kitui (and this finding echoes research from elsewhere in Kenya and the wider region and from decades ago (e.g. Drangert, 1993; G. F. White et al., 1972)); however, in addition to this general awareness, considerable motivation to act may be achieved by sharing water quality test results, which constitute specific external stimuli and are, therefore, more strongly linked with the susceptibility dimension of threat perception. In my work with LWMs, the first monitoring data report produced the most uniform shift in intentions to act, but response patterns became more complex with further reporting in the following months (six main patterns of response were described and associated with different data patterns, see Section 6.2.4). Overall, the information intervention produced four main findings:

1. Water quality test results are specific external stimuli that LWMs are likely to want as feedback on the relative safety of water supplies and the effectiveness of actions to control hazards. General information about the expected microbial

quality of better or less protected water sources was less compelling than *E. coli* test results directly comparing the concentrations of *E. coli* in water from, for example, a shallow well versus a borehole with a handpump. And LWMs looked to test results for confirmation on the impact of their actions (like building a fence or adding chlorine to a tank).

2. Regular reporting of data can reinforce consideration of water safety, but results must be contextualised, and expectations managed so that variability of indicator (*E. coli*) concentrations does not lead to disengagement with proactive, risk-based management practices. Emphasis on preventing rather than reacting to problems, and combining sampling efforts with sanitary assessment information may be valuable in this respect.

3. LWM self-efficacy is moderated by water system design and without external support it is often limited to partial measures applied in discrete intervals (as opposed to consistently-applied multi-barrier measures). Most LWMs in the study (85%) expressed an intention to act at least once, but the feasibility of response options was strongly influenced by system designs and usage patterns. Given the difficulties of retrofitting systems and changing user expectations and usage norms, designing supplies with verified controls for water safety from the beginning would substantially increase LWM self-efficacy.

4. People have more opportunities to consciously influence their emotions through cognitive means over time, and self-efficacy was observed to decrease for many of the LWMs as the study progressed (as they recognised challenges that were not fully appreciated when they formed their early intentions to act). The combination of these trends means that defensive processing becomes increasingly likely over time, so data will become an increasingly weak driver of decisions if insufficient self-efficacy is unaddressed.

Efforts to promote behaviour change with information interventions in conditions of poverty must recognise the complex threatscapes that people contend with, and the limited potential for impact of additional fear appeals without concurrent increases in self-efficacy (Chapter 6.3). This is the core of a debate about whether or not potentially distressing information should be shared with people who may not be in a position to protect themselves. On the one hand, access to information is upheld as a human right, and it is further considered to be a core principle of the human rights to water and sanitation such that "information relating to standards, as well as progress towards meeting those standards, [should be] available and accessible" (de Albuquerque et al., 2014, p30). This view is supported by systems-thinking that emphasises the importance of information-based feedback loops, and by governance theory that argues for balance between political, market, and community enablement processes (Section 2.3.1). In contrast, on the basis of social justice theory (Rawls, 1971), Britz, 2004, proposed guidelines for reducing information poverty[1] that included acceptance of withholding data / information if doing so improves the lives of the information-poor.

As discussed in the following subsection, this debate is at the heart of the ethical concerns that inform dilemmas regarding water quality data sharing and it has important consequences for the alignment of stakeholder views on monitoring. In contemplating notifying LWMs or water users of contamination, how does one weigh psychosocial stress and the burden of responsibility for an intractable problem with the right to information and self-determination? When, if ever, is it ethical to (paternalistically) withhold information? The research findings presented in Chapter 6 do not encourage household-level water quality testing as a behaviour change strategy in conditions of poverty. However, on multiple fronts, this thesis supports monitoring at the supply level with well-contextualised data sharing to LWMs, and potentially through them to water users.

Sufficiently supported LWMs can be positioned to communicate and contextualise water safety information; it is in their interests to do so assuming that the supply they manage provides safer (and at least equivalently aesthetically acceptable) water than the nearby alternatives. Data that directly compare the qualities of well-managed sources and less safe alternatives will encourage use of better sources insofar as household choice landscapes allow. Increasing con-

[1]Information poverty here broadly defined as the "situation in which individuals and communities, within a given context, do not have the requisite skills, abilities or material means to obtain efficient access to information, interpret it and apply it appropriately" (Britz, 2004, p192).

sistency of use supports a positive feedback loop for affording and sustaining good management of a water supply, which would be particularly powerful if it extended through seasonal changes. It is difficult to over-emphasise the importance of seasons to rural water supply (Kelly et al., 2018). When it rains, choice landscapes and many livelihood factors change as do the hazards posed by different sources. When people switch to less safe source types (earth dams, shallow wells, rivers) this undermines their health and the financial sustainability of safer, better-managed water supplies (Hope & Ballon, 2019); as evidenced in northern Kitui, for example, by some groundwater and surface water piped kiosks shutting down completely during the rainy season because management committees cannot afford to pay kiosk attendants.

Specific water quality information may encourage a reassessment of the relative safety of different sources that could increase consistency of user payments towards safer sources. Additionally, based on what LWMs shared in the interviews for this thesis, the legitimacy of LWM communications about water safety is likely to be strengthened by association with a RWSP that has a less-intimate investment in local community politics and is seen to use professional methods of water quality assessment. Realistically, however, when source selection is influenced by many overlapping factors besides water quality – including distance, queuing, security, labour, monetary cost, payment structure, livestock needs, personal relationships, and water supply functionality (Section 6.1.2) – multiple source use is a form of resilience (M. Elliott et al., 2019), and data alone will not encourage consistent use of a safer source.

Water quality data may be useful, however, in combination with other efforts. A policy digest from 2018 on the impacts of seasonality recommended that all actors in the rural water space (including government, community-based managers, and other actors offering support / services) account for seasonal changes and design monitoring and payment structures that are tailored accordingly (UNC

Water Institute, 2018). In particular they recommended that LWMs can increase consistent access by "allowing larger payments after the harvest" rather than equally year-round (p1). This recommendation was echoed by water users in the interviews that this thesis draws from, they emphasised the difficulty of consistently using kiosks with ATM-style payment systems compared to agreeing more flexible payment schedules with self-supply water source owners.

In summary, understandings of water quality data interact with many other drivers of decision-making to influence the actions of water users and LWMs. As discussed, these other drivers are determinants of individuals' self-efficacy and priorities within complex threatscapes, they include things like intra-community hierarchies, household budgets, water source locations, seasonal changes, water supply designs, and payment structures. Water quality testing at household-level is not recommended as a behaviour change strategy, but supply level monitoring can potentially be a useful feedback mechanism if designed with LWMs in-mind and implemented in conjunction with initiatives that increase LWM self-efficacy. Data may also encourage more consistent use of safer sources if key constraints on user choices are addressed.

### 8.1.3 Structural Determinants of Data Flows

In exploring my third research question, to elucidate institutional enablers of and constraints on monitoring activity and data use, I focused on understanding how data influences the alignment of stakeholder priorities. Research on drinking-water safety in challenging contexts has repeatedly called for strengthening of regulatory oversight and enforcement of water quality testing and response measures (e.g. Fischer, 2019; Kumpel et al., 2020). It is recommended that monitoring, which is necessarily a local activity, should serve both operational, surveillance, and target tracking purposes (Shepherd et al., 2015) and that "stronger demands for information [by national-level agencies] could promote the sustainability of data collection systems" (Kumpel et al., 2020, p9). A key proposition of structuration theory is that humans are knowledgeable actors within systems (Giddens, 1984); thus, consensus among stakeholders regarding the goals of an activity increases the likely-hood of a desired outcome or system function (Meadows, 2008; Neely, 2019b). In theory, all stakeholders want water safety as an outcome of rural water supply, and water quality monitoring may be in-demand as a means to achieve that outcome (though not as an outcome in itself). But stakeholders also have competing priorities and efforts to design and implement monitoring should be founded on an understanding of how it may impact (or be perceived to potentially impact) on those priorities.

One of the most direct forms of prioritisation can be seen in the allocation of funds, in budgets. The considerable costs of monitoring are often regarded as prohibitive in practice (Kayser et al., 2015), and this has received attention from research that, for example, focuses on estimating costs (Delaire et al., 2017; Libey et al., 2020), promoting low-cost test methods (Bain, Bartram, et al., 2012; J. Brown et al., 2020), or developing performance-based funding models (Hope et al., 2020). In this thesis, cost and resource limitations have been key themes, but my analysis sought a broader vantage point on stakeholder consensus building around water quality monitoring. Chapter 7 presented the findings of my work to understand the various dilemmas that stakeholder groups contend with, and the implications of these dilemmas for the alignment and misalignment of their respective priorities. Reflecting the promotion of pluralistic, networked institutional arrangements in governance theory, contemporary policy, and institutional reformations in Kenya and other Sub-Saharan African countries, this analysis is built on a tripartite grouping of stakeholders into bureaucratic, market-based, and community domains (Section 2.3).

One hundred and eleven dilemmas were described and grouped into 19 topics related to generating, sharing, engaging with, and responding to data. Links between the dilemma groups were explored, with the 69 most substantive links mapped as having deterring, enabling, or neutral influence on monitoring and data use. Contextualised data communications and the potential to attract performance-based funding drive enabling patterns. But multiple dilemmas – related to who is entitled to access data; the balance between knowledge and resources in determining empowerment; and the relative importance of water quality versus quantity – contribute to important misalignment in stakeholder priorities. The analysis indicated that conceptualising water quality versus quantity as a dichotomous service priorities delays progress on safe water. This false dichotomy, perpetuated through projects and programming that consider quality as a separate and secondary priority, limits the utility of water quality monitoring in three key ways.

1. Contradictory assumptions about the importance of quality justify the status quo (not monitoring and not sharing data at the local level). Two contradictory assumptions were frequently expressed by stakeholders in the bureaucratic and market domains: that users care about quantity not quality, but that revealing quality problems will distress them and cause backlash that may destabilise management structures (Section 7.1.1). The proposition that people in low-income rural areas do not care about water quality has been used to explain their reliance on unsafe water sources for a long time (G. F. White et al., 1972)[1]. Embedded as they are within communities, however, LWMs expressed that disempowerment and information asymmetry, not apathy, is the root of this issue. This theme was also explored through the findings presented in Chapter 6 on cognitive and contextual determinants of water user and LWM decision-making.

2. Perceived threats associated with not being able to respond to data motivate efforts to block monitoring or keep data confidential. Across all three institutional

[1] In the original *Drawers of Water* study, the authors wrote about a government district official who believes that people should prefer only to use borehole water. When this individual learned that many people were opting not to use a particular borehole, "he [was] sad and suggest[ed] that they do not care sufficiently for water quality and health" (G. F. White et al., 1972, p244).

domains, dilemmas revealed that monitoring is viewed as a potential threat to water supply sustainability (Section 7.1.1). This concern among stakeholders contrasts with research findings and long-standing policy propositions that water quality and knowledge of water quality contribute motivation and financial stability for sustaining supplies (Section 2.3.2). The perception or intuition that an activity (like monitoring) will drive instability in a system, where evidence demonstrates the opposite is echoed in other examples of systems analysis where counter-intuitive outcomes are common (Meadows, 2008). But the perception of monitoring as a threat to supply sustainability should not be discounted – rather it supports the importance of contextualising data when communicating about monitoring results. Again this theme is further informed by the findings in Chapter 6.

3. Unclear divisions of responsibility further underpin concerns about data flows. Abnegation of responsibility for water safety by stakeholders in all three institutional domains leaves roles for water safety management largely unspecified and, therefore, defaulted to household level (Section 7.1.1). In each domain, stakeholders justify treating water safety as a low priority (relative to quantity) at least partly on the basis of other domains not prioritising it. Unclear or un-actioned responsibilities foster concerns about data confidentiality and allowing monitoring activity. These concerns constitute potential barriers to monitoring and data use within stakeholder domains, they map onto within-group hierarchies in the community and bureaucratic domains. They also constitute potential barriers between domains – in particular, the difficultly of market-based stakeholders being positioned between the demands of community-based clients and the priorities of stakeholders in the bureaucratic domain.

Introducing monitoring in this context draws attention to the absence of operationalised responsibility for water safety and raises a largely unwanted and complex debate about legislated mandates versus perceived moral and practical responsibilities. The complexity of this debate is compounded by the multiple potential hazards that may contribute to drinking-water related health risks. Challenges and perceived responsibilities vary for microbial versus chemical contaminants. Barriers to engaging with and sharing chemistry data are more intractable, largely because household water treatment options are observed to primarily respond only to microbial hazards (so responsibility can less readily be defaulted to household level).

The key recommendations from the dilemma analysis were to contextualise data in communications of monitoring results; to better align resources and responsibilities so that stakeholders in all three institutional domains can act on their intended mandates; and to mitigate difficult path-dependencies by including water safety considerations in the initial technical and institutional designs of water supply systems. The discussion focused on how these recommendations coincide with the risk-based Water Safety Planning approach[1] advocated by the WHO. It highlighted the need to adapt institutional structures so that water quality monitoring is positioned to add legitimacy to stakeholders in each institutional domain rather than jeopardising outcomes that they value and prioritise.

In summary, key constraints on monitoring activity and data use (contradictory assumptions, perceived threat to supply stability, and unclear divisions of responsibility) are related to a false notion that quality and quantity are opposing service delivery priorities. To effectively institute monitoring and local risk control measures, this notion must be challenged and the alignment of stakeholder priorities strengthened. Ultimately, an effective information feedback mechanism will depend on stakeholder responsibilities being well-defined and sufficiently resourced – as structuration theory emphasises, the rules that constitute system structure cannot be divorced from resources (Giddens, 1984).

[1] In linking my research findings to the Water Safety Planning approach, I recognise that it has had limited uptake to-date in rural low-income areas. But the scarcity of successful examples is not taken as confirmation that the approach does not have value in these contexts; for example, a recent review concluded that "although slower than in urban or high-income settings, the uptake of WSPs in low- and middle-income countries (LMICs) is accelerating. Understanding the factors which will make a WSP successful will further improve efficient uptake and assist with its long-term sustainability" (Herschan et al., 2020, p1).

### 8.1.4 The Structurationist Outlook on Decision Analysis

This thesis explores how systemic links between data and decision-making can be elucidated to identify leverage points for implementing monitoring as an effective feedback to mitigate health risk. In this effort, it advances a framing of drinking-water safety management that links international policy and local practice by recognising the interaction of agency and structure in stakeholder responses to multiple hazards. Endeavouring to account for this interaction, it presents interdisciplinary research that draws on normative, descriptive, and prescriptive modes of decision analysis. Crucially, a systems perspective is brought to the prescriptive task of determining how normative models can pragmatically be used to guide decision-making in practice. This task is frequently conceptualised as an effort to reconcile the differences between rational models of behaviour (developed through normative analysis) and actual behaviour (understood through descriptive analysis), but a structurationist systems perspective clarifies that prescriptive methodologies should also account for structure (system rules and resources) beyond the determinants of individual behaviour.

Systemic links between data and decision-making are, thus, elucidated by synthesising the findings of a three-part study of data uncertainty (or conversely, data correctness), data-user behaviour, and structural determinants of data flows. As a whole, this work demonstrates the utility of including three perspectives (rational, behavioural, and structural) in prescriptive decision analysis. This approach was developed by overlaying concepts from systems theory and decision theory (Section 1.3), but it also has support elsewhere in the literature. For example, a recent review of decision analysis for sustainable supply chain management concluded that framings of prescriptive decision analysis could be advanced by consideration of stakeholder group dynamics, particularly if "plural perspectives are acknowledged" (da Silva et al., 2020, p13). This review found that normative models predominate in the literature and prescriptive models that combine rational and behavioural perspectives are increasingly common, but few studies consider institutional structure. Providing a recent exception, Brandt et al., 2021, frame the prescriptive use of data analytics in public sector decision making by drawing on Moore's public value framework (Moore, 1995), which emphasises net value, data legitimacy, and operational capacity; they emphasise, thereby, the importance of an enabling institutional environment. However, their framing excludes the descriptive behavioural perspective.

In the water sector and beyond, efforts to improve health outcomes through monitoring must contend with the complexity of links between data and decision-making – recognising determinants of both individual behaviour and stakeholder alignment as critical. Programme designs that view governance as a narrow technical decision-making process – which, as noted by Bakker, 2010, and others (Section 2.3), is how it is often treated in water management literature – are less likely to influence system change as they intend. Demonstrating an alternative view of decision-making, in this thesis, rational, behavioural, and structural perspectives informed research that has identified leverage points for implementing monitoring as an effective feedback (to mitigate drinking-water related health risk).

#### ***Leverage Points***

In *Thinking in Systems*, Meadows, 2008, presented a set of twelve types of leverage points – points at which intervention can influence large shifts in the behaviour of systems. Researchers have engaged and adapted these types in list form (e.g. Grant & Willetts, 2019; Sahin et al., 2020), although they are interrelated and Meadows described their ordering as "tentative" and "slithery". Here I discuss the findings of my research with reference to Meadows' typology. This is an effort to synthesise what has already been presented and discussed, not to introduce new material. Without attempting to solidify their order of effectiveness or feasibility, I have grouped the twelve leverage point types based on whether they pertain primarily to stocks and flows (points 10 to 12), feedbacks (points 6 to 9), higher-order system structure (points 4 and 5), or the intended functions and perception of systems (points 1 to 3). As summarised in Figure 8.1 and elaborated in the subsequent text, the key recommendations from this thesis are interrelated.

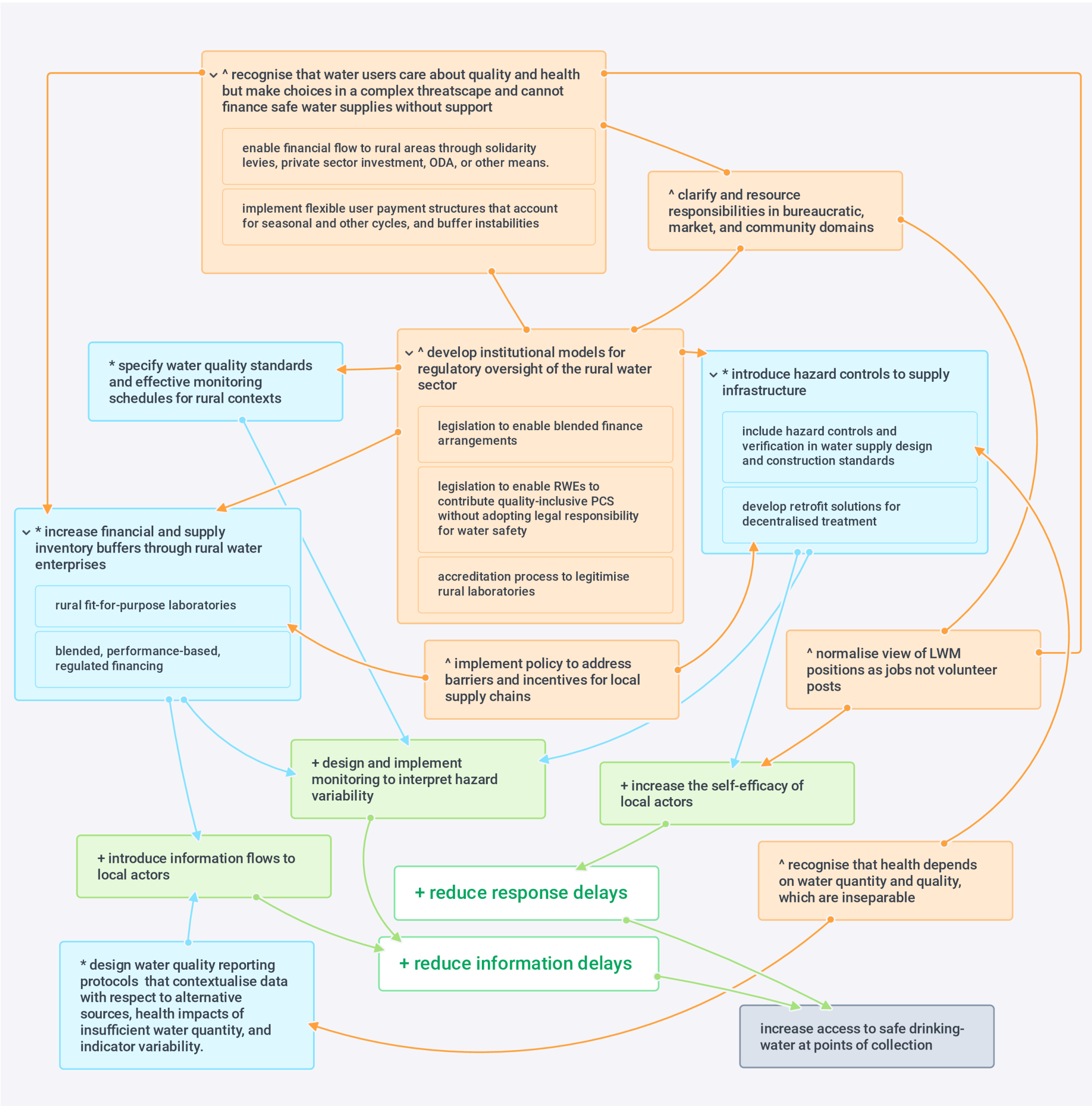


**Figure 8.1:** Visual mapping of interrelated leverage points. *As discussed in the text, the blue boxes (with the * symbol) correspond to stock and flow leverage points, the green boxes (+) correspond to feedback leverage points, and the orange boxes (∧) correspond to structural leverage points. The grey box corresponds to the intended system function which represents positional leverage.*

Stock and Flow Leverage Points

At the most detailed level, system leverage points include:

- variables (or, synonymously, system parameters) like standards, targets, subsidies, taxes, etc. that control the rates of different types of **flows into and out of stocks**;
- variables that control the size and existence of **stabilising stocks** (which are referred to as 'buffers') like reservoirs, bank accounts, supply inventories, etc. and
- the **physical structure** of material stocks and flows (like piped distribution networks, decentralised sanitation or water infrastructure, roads and vehicles, electricity infrastructure, etc.).

Some aspects of the stock and flow leverage points identified in this thesis are naturally quite specific to rural drinking-water safety in Sub-Saharan Africa, but the overall architecture applies to water quality management more broadly and parallel leverage points will exist in other system contexts. Three groups of key stock and flow leverage points were identified:

1. Increase financial and supply inventory buffers to introduce stability. Weak buffering is a core driver of the instability of rural water supply systems, with consequences for service reliability and quality. In low-income settings, rural water users and LWMs have highly reactionary behaviour because of the complex threatscapes they manage with limited and unreliable resources. Furthermore, the remoteness of rural communities and the struggles of their local economies exacerbate supply chain issues. These conditions make it difficult to sustain financing of water supply operations and to reliably access expertise, spare parts, and water testing and treatment consumables. Market-based RWSPs have demonstrated considerable success in creating buffers to address these conditions (e.g. McNicholl et al., 2019). To advance quality-inclusive post construction support, the findings of this thesis support efforts in two areas particularly:

- establishing regulated blended finance enterprise models to pool user fees and create further buffering by attracting additional, potentially performance-based, funding streams, whether these be derived through solidarity levies, private sector investment, or other means. A lot of effort has gone into the development of these models to-date (e.g. Hope et al., 2020; Tew & Caio, 2016), and ongoing efforts should factor-in water quality monitoring.
- enabling rural fit-for-purpose laboratories to create local stocks of expertise, equipment, and supply inventories. Dependence on centralised laboratories makes rural monitoring infeasible (due to issues of distance, time, cost, and capacity), and insufficient stock issues make fully decentralised testing (e.g. citizen science initiatives) infeasible. Fit-for-purpose laboratories attached to RWSP operations could provide a valuable middle-ground. In addition to this thesis, research in Nepal has also been exploring the possibilities of such labs (Daniel, Diener, et al., 2020; Schertenleib et al., 2019). And bureaucratic stakeholders in Kenya and Nepal have expressed interest in their development. An initiative through the REACH Programme is underway to combine findings from both countries and take this work further.

2. Introduce hazard controls to water supply infrastructure so that interpretations of monitoring data are more reliable and LWM self-efficacy increases. With regard to physical structures, changing existing infrastructure is costly and the key leverage "is in proper design in the first place. After the structure is built, the leverage is in understanding its limitations and bottlenecks" (Meadows, 2008, p151). Thus, development is needed in two areas:

- including water safety controls and verification processes in rural water supply design and construction standards / protocols. This should consider how supply performance changes over time and under different conditions, and how system design influences the available response options when hazards are identified. Infrastructure installation continues to be a key leverage point, especially in rural areas facing problems of scarcity, distances to sources, and queuing times. In most circumstances where water scarcity is a concern, boreholes that are found to be unsuitable for consumptive use should not be capped, but decentralised treatment options may be explored where possible, otherwise clear and lasting signals should be in place so that water users are aware of the hazards. These early-stage water safety efforts and ongoing management by LWMs are mutually reinforcing.

- developing retrofit solutions for decentralised treatment that do not cause bottlenecks or otherwise reduce the sustainability of supplies. Considerable effort and investment has been put towards household water treatment technologies that rely on water user behaviour change. But these should not be put forward as a reason to neglect water safety controls, including disinfection steps, in water supplies prior to points of collection. Efforts to develop automatic disinfection devices for water kiosks (Germann, 2019; Powers et al., 2021) and handpumps (under development at the Aquaya Institute) should be encouraged, with implementation plans that envision LWMs as the end-users and that recognise RWSPs (offering maintenance and supply-chain support) as key enablers.

3. Adapt and extend water quality standards, monitoring schedule specifications, and data reporting protocols for rural areas. Water quality standards and monitoring schedules that align with international and regional guidance exist in many countries; in Kenya they are aligned with WHO guidance and East African Standards for drinking-water, but they are rarely applied as intended, especially in rural areas[1]. The WHO are currently working on improving guidance for standard and schedule development for rural areas (they released a call for input to this process in December 2020) and regulators in Kenya (WASREB, 2019a) and elsewhere (Gerlach, 2019) are advancing efforts in this space. This thesis

[1]Additionally, there is a need for further evidence around chemical hazards to improve the legitimacy and application of chemical standards.

has emphasised that the value of *E. coli* grab samples from unverified supplies is limited, and even more so for household level testing. Monitoring schedules should reflect this reality and focus on points of collection, recognising the value of verification processes and combining data from routine water quality testing (ideally using multiple indicators) and sanitary inspections. Finally, water quality data reporting protocols are needed, and they should emphasise the importance of contextualising data – especially with respect to alternative sources, health impacts of insufficient water quantity, and indicator variability.

These changes to buffers, control measures, standards and and protocols are needed, but they will only have impact at scale if they are accompanied by higher-order system changes. Meadows wrote that stock and flow leverage points can be very influential "especially in the short-term and to the individual who's standing directly in the flow", but that from a broader and longer-term perspective, in a system that is "chronically stagnant, parameter changes rarely kick-start it" unless they instigate or are implemented in conjunction with leverage at other points (Meadows, 2008, p148). Stock and flow leverage points are also difficult to actually engage in isolation from enabling higher-order structural changes.

Feedback Leverage Points

The next set of leverage points described by Meadows relate to feedback loops, specifically:

- **delays** in feedback loops related to the timing of information flows or responses;
- the strength of a **balancing / negative feedback** relative to the stock / outcome being controlled, which depends on "the accuracy and rapidity of monitoring [/the signal], the quickness and power of response, [and] the directness and size of corrective flows" (Meadows, 2008, p153);
- the strength of the gain in each cycle of a **reinforcing / positive feedback**; and

- the **structure of information feedbacks**, which determines who does and does not have access to information.

This type of leverage has high-level consequences. The flow of information between leaders and their electorate underpins democracy, and a core criticism of centralised governance, and centralised system management in general, is that delays in feedback loops increase the further you move away from the center. Thus, all efforts to decentralise governance and reduce information asymmetry are targeting feedback leverage points. By focusing on monitoring activity embedded in a decentralised, pluralistic governance context, this thesis has engaged all four points of feedback leverage. Three key tasks for advancing progress on rural water safety are emphasised:

1. Design information flows to reduce feedback delays. Feedback signal accuracy and delay length ("relative to rates of change in the stocks that the feedback loop is trying to control") are critical (Meadows, 2008, p152). Hence the focus in much of this thesis on establishing monitoring activity that positions local actors (LWMs) as key data users; that accounts for water quality as a compound and variable property (which cannot adequately be judged through single measures or organoleptic means); and that supports proactive risk management (which does not rely on illness to signal hazards).

2. Restructure information flows to reduce information asymmetry. Positioning local actors as key data users is important a) to strengthen the self-correcting ability of local management and b) to drive feedbacks on institutional performance so that adjustments can be made and responsible parties can be accountable to their mandates. Restructuring efforts will contend with resistance to this second level of feedback based on differences in the incentives of different stakeholder groups, which acts to maintain information asymmetry.

3. Increase the self-efficacy of LWMs to reduce delays in responding to information, ideally by introducing feedbacks that reinforce safe management. For a balancing feedback to be effective, the force of the response must be matched to the force of the outcome being controlled. Without support, LWMs in low-income rural areas are unlikely to have the self-efficacy to respond effectively to identified water safety hazards. Introducing incentives for safe water management can enhance self-efficacy and reinforce good management practices. This should involve normalising a view of lay water management positions as jobs not volunteer posts, so that the efforts and incentives of LWMs are balanced appropriately.

"Missing information flows is one of the most common causes of system malfunction" (Meadows, 2008, p157), so there can be considerable leverage in introducing or restructuring information flows (provided that response delays are sufficiently minimised). These feedbacks are not created in a vacuum, of course, the stock and flow leverage points previously discussed contribute to their establishment and higher-order structural changes are usually needed to create a sufficient enabling environment.

Structural Leverage Points

The next set of leverage points described by Meadows relate to higher-order structure in terms of:

- **the rules**, both formal and informal, that enable and constrain system dynamics by setting incentives for and sanctions on individual behaviour; and
- the tendency of systems functions to emerge through **self-organisation**, that is by generating "spatio-temporal order under non-equilibrium conditions in the absence of any macroscopic description of that order" (Parrott, 2002, p3).

Rule changes can help unlock the flow, stock, and feedback leverage points previously discussed. This includes changing fallacious norms that are underpinned by inaccurate ideas about the behaviour and priorities of local actors or the efficiency of intervention programming. In particular, this thesis argues for increased recognition that:

1. Health depends on water quantity and quality, which are inseparable. This is attached to two key points: first, a 'quantity first, quality second' approach establishes inefficient path dependencies, and second, contextualised water quality testing can inform safer decision-making without threatening supply reliability.

2. Water users care about quality and health but make choices in a complex threatscape and cannot finance safe water supplies without support. This means that flexible payment structures may allow users to choose better managed systems more consistently, thereby contributing to supply sustainability. But policy

development is also needed to support subsidisation of safe water through solidarity levies, private sector investment, official development assistance, or other means.

Changes to formal rules are also important and stakeholder responsibilities need to be clarified and resourced. Efforts to implement new institutional models for rural water sector regulation should include developing a) legislation that enables blended financing arrangements, b) legislation that permits RWSPs to contribute quality-inclusive post construction support (monitoring data and maintenance and supply chain support for responding to hazards) without necessarily adopting legal responsibility for water safety; and c) accreditation processes for rural laboratories (for quality control and to legitimise the data they produce). Policy changes may also usefully address barriers and incentives for local supply chain development to support sourcing of water testing and treatment consumables and equipment repair and replacement.

The second form of structural leverage relates to self-organisation which, by definition, is not something that can be intentionally directed. Nevertheless, due to self-organisation processes, efforts to create sustained change in complex adaptive systems are likely to have more leverage if they are responsive to local context and incorporate aspects of versatility, experimentation, and diversity. Applications of rural water service provision models that are based on shared principles but adapted to local contexts exemplify this in the rural water sector (e.g. McNicholl et al., 2019). The findings of this thesis are likewise intended to inform general principles that can be adapted in different settings.

Positional Leverage Points

The view of the system observer is made explicit in the final set of leverage points described by Meadows. Implementing change at these points requires a would-be system conductor to specify system boundaries and goals in order to change:

- the (intended) **function** of a system; or

- the **paradigm** out of which the system has arisen – ideally recognising that extensive system change often involves **transcending paradigms**.

This level of leverage has been discussed primarily in the framing of this thesis, relating as it does to high-level goals and targets and to evolving policy and research paradigms. In exploring my research questions, I have worked to include perspectives from different disciplines in an effort to cut across various paradigms. Although many of my recommendations align with contemporary WASH approaches, there are some exceptions. Focusing on infrastructure is unpopular, with contemporary policy and research embracing a service-delivery orientation, but I have highlighted that infrastructure development continues to be a key leverage point for rural water safety (albeit ultimately to enable better service delivery). As long as efforts by NGOs and other sector actors to construct much needed water supplies proceed without verifying that supplies are able to sustainably provide safe water, inefficient technical and institutional path dependencies will be propagated. For progress on rural drinking-water safety, both infrastructure delivery norms and service delivery norms need development.

Furthermore, this thesis has emphasised that the importance of hygienic household environments should not detract from efforts to secure safe water at the supply level (point of collection). Recognition of transport and storage hygiene issues and research demonstrating increases in *E. coli* concentrations between points of collection and use has resulted in a lot of water management attention focused at the household level. Considerable effort continues to be invested in developing and promoting uptake of household water treatment methods. And household-level monitoring is increasingly recommended; it was even included in the draft of the WHO's new guidelines for rural water supply surveillance (which were shared with a call for input in December 2020). But monitoring at household level generates data that are a) difficult to interpret in terms of health risk and b) unlikely to substantially and sustainably influence water management decision-making. The findings of this thesis also indicate that focusing on the household level is problematic in that it supports the defaulting of responsibility for safe water to the household. It provides justification for stakeholders at higher levels of organisation to abnegate responsibility and propagates the idea that people living in poverty can afford to secure the safety of their own drinking water without support.

In complex adaptive systems, it is not uncommon for seemingly intuitive interventions to push change in unintended directions. One of the key take-aways from this thesis is that, although the health of water users is the ultimate concern, monitoring activity should focus at supply level where it is more feasible to establish adequate financial and supply inventory buffering to respond to identified hazards. There is little evidence of sustained use of household water treatment technologies in low-income settings, and the recent large-scale WASH randomised control trial studies demonstrated how difficult it is to improve health outcomes through WASH interventions alone (B. Arnold et al., 2018; Pickering et al., 2019). Funnelling resources into household level water treatment or monitoring is insufficient to substantially improve health outcomes and detracts from efforts to manage water safety at points of collection. I have proposed multiple potential leverage points to improve access to safe water at points of collection; to address health risk at household level, more radical system change – beyond the WASH sector – is required.

## 8.2 Academic Contributions

As detailed in the introduction and literature review chapters, this thesis is underpinned by structuration theory, which informs the overall framing and view of change in complex adaptive systems; decision-theory, which informs the alignment of my guiding research questions with normative, descriptive, and prescriptive modes of inquiry; water safety frameworks, which constitute theories of change that direct how data should be generated and used towards desirable outcomes in water management; psychosocial theory of health behaviour change, which informs my integrated conceptual framework to model decision-making in response to fear appeal communications; and governance theory that has influenced policy models and institutional reforms and, therefore, informs the institutional context of my study. In engaging with this variety of theory, I have made and strengthened conceptual links, adapted and applied methods in new ways, and contributed empirical evidence to advance multiple academic narratives.

Overall, this thesis demonstrates the value of an interdisciplinary research approach that engages with complexity in measuring, managing, and governing health risks. It makes a series of academic contributions, which are summarised in this section as they pertain to conceptual, empirical, or methodological advancements. While I point to conceptual contributions in the form of rationalising and emphasising links between concepts, most of the contributions of this thesis are empirical – thus, the full theoretical implications of the work will depend on how it influences further research and contributes to patterns emerging from empirical work more broadly (Ågerfalk, 2014). This is an appropriate outcome given the emphasis on context in systems thinking.

Conceptual

This thesis has advanced a framing of health risk management that is derived from structuration theory and complex adaptive system concepts – it links international policy and local practice by recognising the interaction of agency and structure in stakeholder responses to hazards. This framing indicates an approach for prescriptive decision analysis that combines rational (normative), behavioural (descriptive), and structural perspectives. The objectives and overall structure of this thesis was guided by this approach. As was the additional conceptual contribution in Section 2.2, where I specified rationale to advance an integrated fear appeal framework that, when paired with mixed-methods data collection, affords valuable insight into interrelated cognitive, affective, and situational drivers of decision-making around exposure to environmental health hazards in low-income contexts.

Empirical

The empirical work presented in this thesis has implications for conceptual understandings of evidence-action linkages around health risk. I have expanded the evidence base on *E. coli* dynamics in rural water systems and household stored supplies and, thereby, contributed to addressing long-standing questions about the utility of a keystone water quality monitoring indicator. I have contributed new evidence on defensive and problem-focused threat response dynamics over time, which underscores the importance of using data to promote proactive understandings of risk rather than focusing on individual test results and, more generally, challenges the utility of studies that examine behaviour change over short time frames. And I have also demonstrated that understandings of risk sharing in pluralistic rural water governance can be advanced by explicit consideration of water quality risks, which have received less coverage in the literature than other service dimensions, and which are differentiated from more visible forms of risk by their relative 'invisibility' to organoleptic perception.

Overall, this thesis has recommended a reorientation of monitoring research and practice to focus on supply level points of water collection, emphasising the limited utility of water safety monitoring and behaviour change efforts at household level. Further, it provides empirical support for recent arguments that efforts, of both research and practice, to improve WASH and clean cooking outcomes in low-income contexts must more deeply consider "the everyday complexity of poverty" (Ray & Smith, 2021, p1). At a more detailed level, it has also evidenced six points that have implications for research framings and implementation:

1. Concurrent characterisation of multiple (microbial and chemical) water safety hazards is important for communicating a) contextualised microbial water quality test results and b) the impracticability of decentralising responsibility for water safety to the household level.

2. Personally specific health risk information has a superior motivational effect compared to general information (which is frequently used in fear appeal studies and communication efforts). It follows that health communications in research and practice should be designed around specific information where possible.

3. Gender-based inequalities in household and community hierarchies especially limit the self-efficacy of women, who are frequently engaged in research and interventions as primary water managers at household level, but who are especially unlikely to change their behaviour in response to fear appeals without concurrent self-efficacy support.

4. When individuals face many threats within a risky environment, a message aimed at increasing fear about one component of that environment has limited affective influence. It follows that considerations of baseline threat perception in health communication research (specifically, the idea that information about a threat is less influential when people are already fearful of that threat) should be extended to include perceived threatscapes more broadly.

5. Understandings of rural lay water management underpinned by cultural or institutional theory can be enhanced by incorporating cognitive and affective information processing as important dimensions of decision-making. For example, by elucidating how defensive responses contribute to the emergence of fatalism (which is identified as one of four broad management cultures in cultural theory) and that problem-focused responses and defensive cognitive processing are not mutually exclusive.

6. Adapting the Water Safety Planning approach to lower-income rural areas requires recognition of LWMs and RWSPs as key actors.

Methodological

In undertaking the research described in this thesis, method advancements have been made in two main areas. First, I have demonstrated how an under-utilised analytical method from the educational action research field (dilemma analysis) can be adapted to study structural alignment in pluralistic institutional settings, emphasising its advantages for producing credible and reasonably generaliseable mappings of interrelated stakeholder views on complex issues. Second, I have contributed to methods for microbial water quality assessment by:

- demonstrating problematic interference from coloured dissolved organic matter (CDOM) in groundwater that limited the utility of tryptophan-like fluorescence (TLF) for microbial contamination assessment. This evidenced a key method limitation that I discussed in a publication early in my DPhil period (Nowicki et al., 2019, which was based on data collected during my masters dissertation fieldwork) and my results from Kitui informed conversations with product development personnel at UNICEF, Chelsea Technologies Ltd. (the manufacturer of the TLF probe), and with researchers at the British Geological Survey (BGS) who are dedicated to developing the TLF method, and who have since published research that discusses this issue in greater depth (e.g. J. S. Ward et al., 2020).
- demonstrating an effective protocol for isolating and preserving bacterial DNA (for downstream whole genome sequencing analysis), which uses commercially available products and is feasible with basic equipment in a remote rural lab.
- contributing new *E. coli* genomes for the global archive, thereby furthering the potential for meta-analytical insight into the dynamics of naturalised *E. coli*. Meta-analysis is used to understand *E. coli* population structure and evolution, drivers of pathogenicity, and spread of antimicrobial resistance; but *E. coli* from environmental as opposed to clinical sources, and from African countries in particular, are hugely underrepresented in the existing data.

### 8.2.1 Disseminating Research Findings

Dissemination of research findings through blogs, memorandums, policy-facing reports, and spoken presentations is important for the practical aims of this research. As mentioned in Section 1.5, my plans for sharing results with stakeholders have been substantially derailed by the COVID-19 pandemic. In particular, stakeholder meetings organised around a REACH conference in Kenya in March and April 2020 were cancelled, I have not returned to Kenya since 2019, and stakeholder priorities have necessarily shifted to focus on immediate concerns related to COVID-19 and its widespread consequences. Despite the difficulties of this period, however, through REACH and the collaborations it has facilitated, I have had valuable opportunities to contribute to blogs, memorandums, and reports, and have shared results with academics and wider audiences through teaching, presentations, and conference events. These activities are listed in Appendix B. Three key opportunities for written contributions were:

- Interest from UNICEF Kenya and several government institutions (in the water, health, and education ministerial domains) in increasing access to WASH facilities in schools presented an opportunity to share some of the water quality work that was conducted for this thesis within a wider report from the REACH Programme on *Delivering Safely Managed Water to Schools in Kenya* (Hope et al., 2021).
- Some of my findings influenced the interpretation of drinking-water quality data and recommendations in a recent report on the Multiple Indicator Cluster Survey (MICS) in Bangladesh, which I had an opportunity to contribute to thanks to my supervisor, Katrina Charles (Government of Bangladesh et al., 2021). Communications with WHO and UNICEF contacts around this report have made it clear that some of the recommendations of this thesis represent a departure from current approaches and that further efforts to communicate the findings will be worthwhile.
- In December 2020, the WHO released a call for input towards updated *Guidelines for Small Drinking-water Supplies*, which are currently under development and are expected to be finalised by the fourth quarter of 2021. I provided input for this effort based on my literature review and empirical findings from this thesis.

But communicating the key findings of this thesis in appropriate formats for non-academic stakeholders remains largely an outstanding task. Fortunately, despite COVID-19, the water safety work (both research and practical implementation) in Kitui continues to develop, and there is ongoing potential to create and take advantage of opportunities for knowledge exchange with stakeholders in Kenya, Bangladesh, Ethiopia, and elsewhere.

## 8.3 Limitations and Further Research Directions

This thesis has taken an interdisciplinary research approach that aims to understand the connectivity of data and decision-making with attention to individual agency and structural enablers and constraints. It is designed to engage with system complexity and produce recommendations that avoid ineffectively passing 'the ball' (responsibility) back and forth between different 'courts' (academic disciplines and arenas of practice) without understanding the rules at play in these spaces. There are important limitations in this approach, which run along the boundaries that are necessarily implemented to define scopes of analysis. From a reductionist view, one may argue that I have bounded this thesis too broadly, that in engaging too many and too different subjects I have not explored them in sufficient detail. From a structurationist view, one might argue conversely that I have used too narrow a focus, excluding important connections and subsystems from my analysis.

In establishing the objectives and design of my research, I explained why an interdisciplinary, systems-based approach is appropriate for the problem and knowledge gaps that this thesis responds to, justified the choices that informed my specific approach, and reflected on the importance of collaboration for enabling this style of research (Chapters 1, 2, and 3). There are multiple key areas, however, that I have pointed to in discussion but not engaged in-depth through my research; for example, I focused on consumption of water largely in isolation of other uses for hygiene, livestock, irrigation, construction, etc.; and I do not delve into key aspects of water resource management, including scarcity and climate change; nor into the details of financing structures and models; nor into sanitation risk monitoring or management; etc. My focus and method choices represent my best effort to contribute understanding of the links between evidence and action for mitigating health risk (from drinking-water specifically) based on my evolving skill-set and understanding of the issues; and the time, resources, and collaborations that I benefited from accessing. Nevertheless, key limitations of my work have been discussed throughout the thesis. In this final section, I reflect on trade-offs in my research design and then recap the key limitations of my findings alongside suggestions for further research.

Methodological trade-offs:

Overall, my use of both quantitative and qualitative data, rather than investing fully in either, means this thesis inhabits a middle-ground in which I have tried to balance sample size with thematic richness. There are key constraints in my research that relate to sample size. Conversely, the research is also limited in that, despite adopting a longitudinal design for the water quality monitoring and LWM survey series, I only engaged participants through in-depth interviews once each because of the associated demands on their time and mine (for interviewing, transcribing, coding, and analysis). Had I engaged fewer participants, I would have had more time to dedicate to qualitative inquiry over time.

Choosing a longitudinal design for the water quality testing and the survey series was essential for my research aims, but is also associated with trade-offs. Introducing longitudinal scope not only reduced my spatial scope, it also meant contending with a variety of logistical issues that resulted in missing data from: imperfect coordination between my schedule / availability constraints and those of my research assistants and participants; water points breaking or drying out; equipment malfunctioning; delays in supply chains for consumables and repairs;

inaccessible roads preventing access for sampling and meeting with participants; etc. To minimise missing data, I instructed my research assistants to substitute phone calls for in-person meetings with LWMs when necessary (and possible) and allowed flexibility in sampling schedules (water points were not tested in the same order each month); I recognise that this introduced variability into my methods but assessed it as a worthwhile trade-off.

Reflections on the *E. coli* analysis:

The key limitations of my *E. coli* strain-level analysis relate to the small sample size of my study and the lack of definitive biomarkers for source tracking. My sample size was too small to observe effects of physicochemical water quality, microbiome characteristics, or transport and storage practices on the balance of *E. coli* growth and die-off between points of collection and use. Furthermore, since I chose to focus on multiple water supplies and points of use, rather than employing a longitudinal design with fewer sampling sites, my results provide insight into strain variability between systems and household but not for understanding how sanitary factors influence strain dynamics over time. Similarly, had I chosen to focus in more depth on fewer water samples, the study would have provided more insight on strain diversity within a given sample at a given point in time.

Further research investigating *E. coli* at strain level with a longitudinal design could usefully advance discourse on the relationship between *E. coli* dynamics and the sanitary vulnerabilities that are scored in inspection protocols. Although research now recognises that water quality tests and inspection scores have complementary but different value, studies continue to query how the two are related because of the practical value of this insight for monitoring programme design. Genetic analysis can contribute a useful new stream of evidence to this space. And as I highlighted in Chapter 5, research is needed to clarify the importance of zoonotic transmission in WASH systems analysis and to improve consideration of animal management as a key sanitary factor influencing drinking-water safety.

Additional whole genome sequencing analysis of *E. coli* isolated from water supplies would also be useful to build meta-analytical potential and to corroborate or challenge the conclusions I have drawn from my study. As explained in Chapter 5, I determined the relative likelihoods of different isolates being naturalised or recently sourced from faeces based on what is known about *E. coli* phylogroups, multi-locus sequence types, and virulence and antimicrobial resistance characteristics, but definitive source tracking of isolates will not be possible unless origin-specific biomarkers are discovered. Consequently, there is an element of conjecture in my conclusions, which would benefit from comparison with repeat studies in similar contexts. REACH research in Ethiopia has identified persistent low concentrations of *E. coli* in borehole water supplies that are not clearly linked to sanitary vulnerabilities. The analysis presented in this thesis suggests that naturalised *E. coli* populations may account for this pattern of results. A longitudinal strain-level analysis of *E. coli* in these water supplies would be useful to corroborate or contradict this expectation.

Reflections on the fear appeal evaluation:

My analysis of LWM decision making was importantly limited by sample size. In Chapter 6, I noted that water system designs and starting conditions substantially moderated response efficacy and LWM self-efficacy, but I was unable to observe an effect of water supply scale. Likewise distinct patterns of behaviour were not describable for the three types of LWM that I engaged (private owners, facility administrators, and community-based managers). These would be useful dimensions to explore with a larger-n study. The in-depth analysis presented in this thesis could be used to inform the development of a questionnaire to engage a larger sample of LWMs, which would unlock more options for statistical analysis.

On the other hand, further qualitative exploration is also warranted in this space. For example, in discussing the findings of the fear appeal evaluation, I recognised that perceptions of threat have personal and interpersonal dimensions (noting that interview participants spoke of their own health and the health of others) at both source and household level. A key limitation of my fear appeal analysis, however, is that it did not systematically resolve differences in perceptions of threat to self versus threat to others. Further work to explore this would be useful and cultural theory, in particular, may provide a useful basis for designing research towards this end. Cultural theory has demonstrated value for understanding uptake and scaleability of networked maintenance services for rural water supplies (Koehler et al., 2018) and other health communications research has, for example, considered systematic differences in outcomes based on the cultural orientation of decision-makers. Murray-Johnson et al., 2001, concluded that people who are more individualistic are more influenced by messages that focus on severity and susceptibility of a hazard to the self, whereas those with a stronger collectivist orientation are more influenced by messages that emphasise threats to a larger group to which they belong. It would be interesting to combine a fear appeal analysis with cultural theory underpinnings to further explore LWM engagement with communications of water quality risks.

Reflections on the dilemma analysis:

As part of bounding a feasible scope for my work, I limiting my analysis of individual decision-making to users and LWMs, and engaged other stakeholders only as representatives of groups. As detailed in the methodology chapter (Section 3.6), the dilemma analysis focused on issues about which stakeholders hold conflicting views and opinions, not on the specific views and opinions themselves. This approach engaged interviewees as representatives of the institutions they are embedded in, and dilemmas were formulated such that all stakeholders would assent to them as existing and relevant. These means that content in the interviews that was highly specific to the northern Kitui context was not included in the final analysis (because its relevance was not reflected in the interviews with bureaucratic representatives at county or national levels or with formal and rural water service providers operating in other countries or elsewhere in Kenya). Additionally, dilemmas that were specific to dynamics within only one institutional domain were excluded. As a consequence of this approach, the findings of the analysis have limited insight for intra-domain dynamics (with the trade-off being that they are more generalisable beyond northern Kitui).

Intra-domain dynamics are important to the system under study in this thesis, and their exclusion constitutes a key blind-spot in my work. Dilemma analysis would be a useful method to apply in studies that engage in more detail with the inner-workings of each institutional domain. Additionally, including more participants from each of the three institutional domains who operate in different contexts would further identify generaliseable dilemmas. In a larger study, I envision that a nested approach may be useful: to produce a summary of dilemmas that highlights which tensions are most generaliseable and also informs on the variability of more context specific tensions.

Finally, a key dilemma discussed in this thesis revolves around the ethics of sharing drinking-water quality data. Currently, the guidance for navigating this dilemma from research ethics and sector 'best-practice' documentation is lacking. From what I have observed, data reporting is done (or often not done) without due consideration of potential impacts. A systematic review and analysis of experiences and theory related to sensitive health-related data sharing, and drinking-water quality data sharing specifically, could be valuable to guide how monitoring data are shared moving forwards.

<u>Further research on identified leverage points:</u>

In synthesising the findings of this thesis, I pointed to potential leverage points for influencing system change (Section 8.1.4). Each represents an area where ongoing research is needed. For example, I highlighted the need for research to explore what would constitute an enabling environment for establishing decentralised fit-for-purpose laboratories; to advance development of decentralised treatment options to retrofit rural water supply infrastructure; and to improve the evidence base on the health impacts and extent of geogenic water quality contamination (beyond arsenic and fluoride). Three examples of related projects that I am involved in and which are already underway include:

- Establishing rural laboratories: Besides this thesis, research in Nepal has also been exploring the possibilities of fit-for-purpose rural laboratory set-ups (Daniel, Diener, et al., 2020; Schertenleib et al., 2019). And bureaucratic stakeholders in Kenya and Nepal have expressed interest in their development. An initiative through the REACH Programme is underway to combine findings from both countries and take this work further.

- Pre-PoC treatment technologies and protocols: Additional research that is being supported by REACH and FundiFix is exploring the deployment of treatment technologies for retrofitting existing water supply infrastructure in Kitui. In particular, this includes work led by a team at the University of New South Wales on an in-line UV disinfection system and a nascent collaboration with a team from the Swiss Federal Institute of Aquatic Science and Technology (Eawag), and others, to work on chlorination options.

- Mapping geogenic groundwater quality: A REACH collaboration has produced a review of hydrogeological literature to summarise the evidence on geogenic water quality hazards in Kenya and Ethiopia. This is being prepared for publication and will highlight key knowledge and policy gaps.

Beyond these specific examples, the leverage points suggested in Section 8.1.4 are linked in some cases to extensive ongoing research efforts and the key recommendation is to explicitly integrate water safety considerations. In particular, there is a need for research and policy development to further consider how feedbacks that reinforce the self-efficacy of LWMs as key potential change agents can be enabled. Finally, with this thesis I join other system-thinkers in promoting collaborative interdisciplinary (aspiring to transdisciplinary) systems-based research, having demonstrated the value of such an approach in exploring the intersection of data, decisions, and drinking-water safety in rural Kenya.

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# Appendices

# Contents

# A Declaration of Authorship and Co-authorship Statements

My signed declaration of authorship of this thesis is enclosed below. It is followed by signed co-authorship statements for the three published or submitted papers that contain content from the empirical chapters and the introduction, framing, and methodology of this thesis.

**Degree Title: Doctor of Philosophy in Geography and the Environment**

## DECLARATION OF AUTHORSHIP

**Name:** SASKIA JOSEPHINE NOWICKI

**Candidate number:** 834134

**College:** ST CATHERINE'S

**Supervisors:** KATRINA CHARLES, DAVID BRADLEY

**Title of thesis:** DATA, DECISIONS, AND DRINKING WATER SAFETY: AN INTERDISCIPLINARY ANALYSIS OF THE COMPLEX ADAPTIVE RESPONSE TO MONITORING IN RURAL KENYA

**Word count:** 91,200 (including references & appendices)

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I have clearly indicated the presence of all material I have quoted from other sources, including any diagrams, charts, tables or graphs. ✓

I have clearly indicated the presence of all paraphrased material with appropriate references. ✓

I have acknowledged appropriately any assistance I have received in addition to that provided by my tutor/supervisors/adviser. ✓

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I agree to retain an electronic copy of this work until the publication of my final examination result, except where submission in hand-written format is permitted. ✓

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Candidate's signature: SNowicki

Date: 12 May 2021

# Details of Co-author Contributions

**Published article**: Nowicki, S., Koehler, J. and Charles, K. J. (2020) ‘Including water quality monitoring in rural water service provision: why safe water requires challenging the quantity versus quality dichotomy’, *npj Clean Water*. Springer US, 3(14), pp. 1–9. doi: 10.1038/s41545-020-0062-x.

**Main Corresponding Thesis Sections**: The content in the paper is drawn from multiple chapters in the thesis including the Introduction, Background (mainly Section 2.4), Methodology (mainly Section 3.7), and empirical Chapter 7.

**Article co-authors**:

Johanna Koehler (School of Geography and the Environment, University of Oxford)

- Provided comments on institutional pluralism background for the article manuscript.

Katrina J Charles (School of Geography and the Environment, University of Oxford)

- Supervised development of study design.
- Reviewed questionnaires and interview guides.
- Provided comments for the article manuscript and revisions.

**Co-author statement**:

We confirm that Saskia Nowicki led the paper including the methodology design, data collection, results analysis and interpretation, and manuscript writing – with our contributions as specified above. Saskia also managed the submission and revision process for the paper.

Johanna Koehler Date: 30 March 2021

Katrina Charles Date: 6 April 2021

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**Published article**: Nowicki, S., deLaurent, Z. R., de Villiers, E. P., Githinji, G. and Charles, K. J. (2021) ‘The utility of Escherichia coli as a contamination indicator for rural drinking water: Evidence from whole genome sequencing’, *PLoS ONE*, 16(1). doi: 10.1371/journal.pone.0245910.

**Main Corresponding Thesis Sections**: The content in the paper is drawn from multiple chapters in the thesis including the Introduction, Background (mainly Section 2.2.3), Methodology (mainly Section 3.4), and empirical Chapter 5.

**Article co-authors**:
Zaydah R. deLaurent (KEMRI-Wellcome Trust Research Programme, CGMR-Coast)

- Provided input on DNA sequencing protocol design.
- Supported procurement of laboratory equipment and consumables.
- Assisted with sample processing and managed DNA sequencing.
- Provided comments on sequencing methods for the article manuscript.

Etienne P. de Villiers (KEMRI-Wellcome Trust Research Programme, CGMR-Coast and Centre for Tropical Medicine and Global Health, Nuffield Department of Medicine, University of Oxford and Department of Public Health, Pwani University)

- Provided input and training on bioinformatics pipeline.
- Advised on and provided software for bioinformatics.
- Ran analyses on sequencing data using the KEMRI HPC cluster.
- Provided comments on bioinformatics for the article manuscript.

George Githinji (KEMRI-Wellcome Trust Research Programme, CGMR-Coast)

- Provided input on bioinformatics pipeline.
- Ran scoping analysis on sequencing data on the KEMRI HPC.
- Provided comments for the article manuscript.

Katrina J Charles (School of Geography and the Environment, University of Oxford)

- Supervised development of the study design.
- Provided comments for the article manuscript and revisions.

**Co-author statement**:
We confirm that Saskia Nowicki led the paper including the methodology design, data collection, results analysis and interpretation, and manuscript writing – with our contributions as specified above. Saskia also managed the submission and revision process for the paper.

Zaydah deLaurent — Date: 30 March 2021

Etienne de Villiers — Date: 29 March 2021

George Githinji — Date: 30 March 2021

Katrina Charles — Date: 6 April 2021

**Submitted article**: Nowicki, S., Bukachi, S., Hoque, S. F., Katuva, J., Musyoka, M. M., Musenya, M. M., Mwaniki, M., Omia, D. O., Wambua, F. and Charles, K. J (under review) 'Fear, efficacy, and environmental health risk reporting: complex responses to water quality test results in low-income communities'.

**Main Corresponding Thesis Sections**: The content in the paper is drawn from multiple chapters in the thesis including the Introduction, Background (mainly Section 2.3), Methodology (mainly Sections 3.2, 3.5 and 3.6), and empirical Chapter 6.

**Article co-authors in alphabetical order**:
Salome Bukachi (Institute of Anthropology, Gender and African Studies, University of Nairobi)

- Led household-level interviews study and provided transcripts.
- Provided comments for and approved the article manuscript.

Katrina J Charles (School of Geography and the Environment, University of Oxford)

- Supervised development of the study design.
- Reviewed questionnaires and interview guides.
- Provided comments for and approved the article manuscript.

Sonia Ferdous Hoque (School of Geography and the Environment, UoO)

- Led the longitudinal household survey (Water Diaries) and provided data.
- Reviewed the questionnaire that Saskia wrote to accompany the Water Diaries.
- Provided comments and approved the article manuscript.

Jacob Katuva (FundiFix, Kwale County)

- Led the cross-sectional household survey and provided data.
- Reviewed the section that Saskia wrote for the cross-sectional household survey.
- Read and approved the article manuscript.

Mercy Mbithe Musyoka (Institute of Anthropology, Gender and African Studies, UoN)

- Conducted household-level interviews and observation journals.
- Provided comments for and approved the article manuscript.

Mary Musenya Sammy (FundiFix, Kitui County)

- Provided in-field research assistance including carrying out water quality sampling, sanitary inspections, and surveys and supporting interviews.
- Read and approved the article manuscript.

Martin Mwaniki (FundiFix, Kitui County)

- Provided in-field research assistance including carrying out water quality sampling, sanitary inspections, and surveys and supporting interviews.
- Read and approved the article manuscript.

Dalmas Ochieng Omia (Institute of Anthropology, Gender and African Studies, UoN)

- Co-led household-level interviews study and provided transcripts.
- Provided comments for and approved for the article manuscript.

Faith Wambua (Institute of Anthropology, Gender and African Studies, UoN)

- Conducted household-level interviews and observation journals.
- Provided comments for and approved the article manuscript.

**Co-author statement**:
We confirm that Saskia Nowicki led the paper including the methodology design, data collection for the lay water manager monitoring response evaluation, results analysis and interpretation, and manuscript writing – with our contributions as specified above. Saskia also managed the submission and revision process for the paper.

| | |
|---|---|
| Salome Bukachi | Date: 19 April 2021 |
| Katrina Charles | Date: 6 April 2021 |
| Sonia Ferdous Hoque | Date: 31 March 2021 |
| Jacob Katuva | Date: 30 March 2021 |
| Mercy Mbithe Musyoka | Date: 15 April 2021 |
| Mary Musenya Sammy | Date: 13 April 2021 |
| Martin Mwaniki | Date: 1 April 2021 |
| Dalmas Ochieng Omia | Date: 29 March 2021 |
| Faith Wambua | Date: 15 April 2021 |

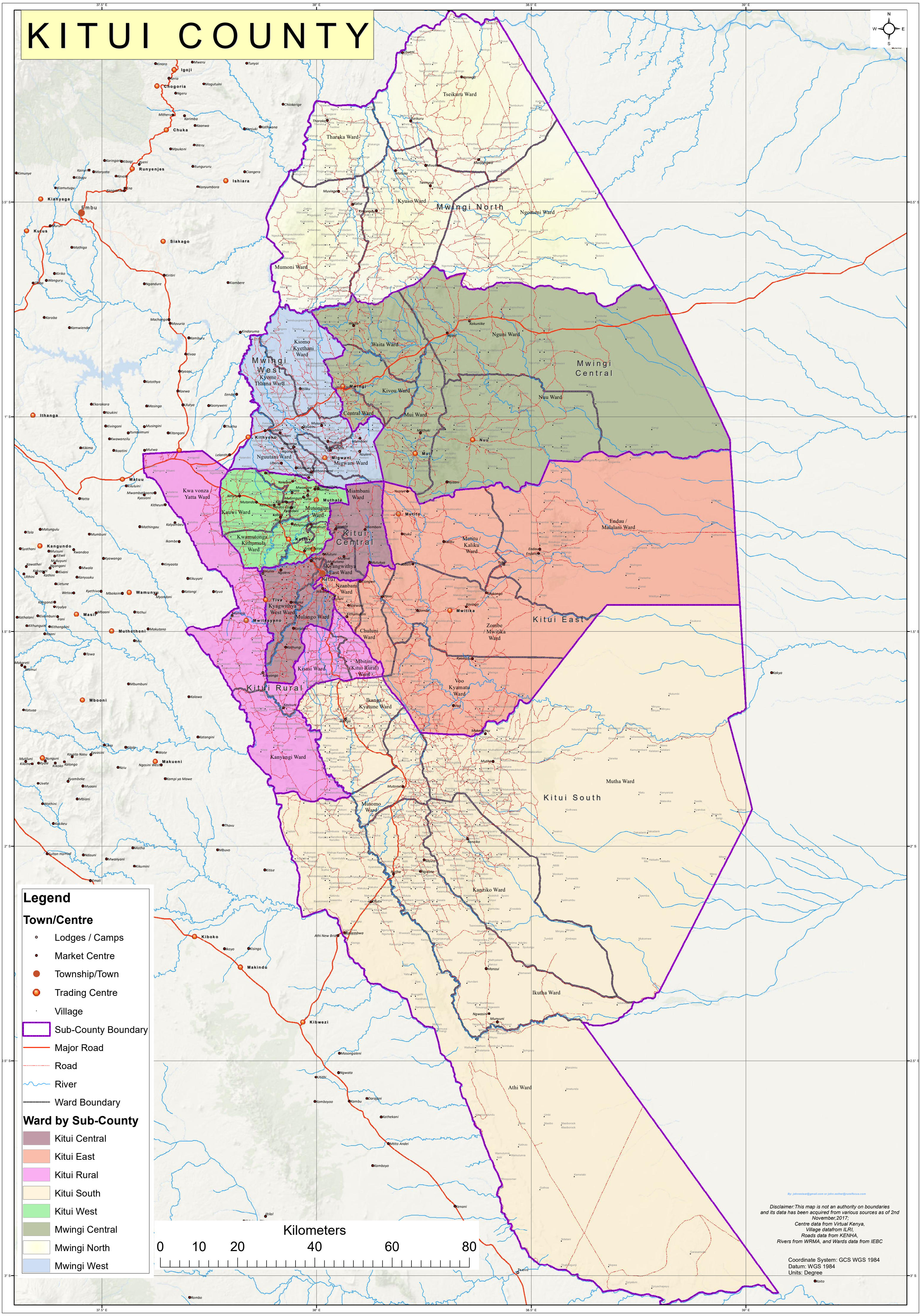
# B Dissemination of Findings

The following table lists activities through which I have disseminated ideas and findings from my DPhil research including conference presentations and events, policy-facing reports, blogs, teaching, and a knowledge exchange project.

| Date | Activity |
|---|---|
| Mar 2021 | Bangladesh MICS 2019 Water Quality Thematic Report – Contributed to the report (Government of Bangladesh et al. 2021). |
| Oct 2020 | Advancing Rural Water Services: strengthening systems for professionalized maintenance and fit-for-purpose water quality monitoring – Side event that I organised and chaired at the UNC Water & Health Conference – Chapel Hill, USA |
| Oct 2020 | Delivering Safely-managed Water to Schools in Kenya – Contributed to report (Hope et al. 2021) and multi-stakeholder meeting. |
| Aug 2020 | Ensuring Water Safety in a Changing World – World Café event at the Stockholm World Water Week, cancelled due to conference restructuring |
| May 2020 | Uncertainty and optimism: the impact of COVID-19 on the REACH community in Ethiopia, Kenya and the UK – REACH blog entry |
| May 2020 | Water security in times of crisis: how COVID-19 is impacting the rural poor in Bangladesh and Kenya – REACH blog entry |
| April 2020 | Rural water quality monitoring within reach: moving beyond the quantity vs. quality mindset – REACH blog entry |
| Mar 2020 | Making the Most of Water as a Learning Topic in Secondary Schools in Cameroon – ESRC Knowledge Exchange Dialogues Project |
| Feb 2020 | Water Safety Assessment and Control - Short presentation and discussion station for GCSE students participating in the Alice in Typhoidland Project – Oxford, UK |
| Oct 2019 | Political and Ethical Determinants of Water Quality Data Use in Rural Kenya – Presentation at the UNC Water & Health Conference – Chapel Hill, USA |
| May 2019 | Water and Human Health Module – Presentation and interactive Water Safety Planning exercise for the TIDE Programme – Yangon, Myanmar |
| April 2019 | Mwingi North Water Quality Monitoring Preliminary Results – Summary report prepared for the County Government of Kitui, Ministry of Water |
| Mar 2019 | Panel discussion and short presentation on Water Quality Sampling in Kitui County, Kenya – Safe Water Session at the REACH International Conference on Water Security & Poverty – Oxford, UK |
| Dec 2018 | Institutional Pluralism and Water Quality Monitoring for Rural Water Supplies – Guest lecture at the KEMRI Wellcome Trust Kilifi Hub – Kilifi, Kenya |
| Oct 2017 | Illuminating microbial contamination: the usability of fluorimetry for rapid risk assessment in low-resource contexts – Poster presentations at the UNC Water & Health Conference – Chapel Hill, USA and at the Ineson Lecture on Africa, Groundwater & the Sustainable Development Goals – London, UK |

# C Detailed Map of Kitui County

The following map was created by Jacob Katuva with data acquired (as of November 2017) from Virtual Kenya, the International Livestock Research Institute (ILRI), the Kenya National Highways Authority (KeNHA), the Water Resources Authority (WRA, formerly the Water Resources Managament Authority), and the Independent Electoral Boundaries Commission (IEBC).


KITUI COUNTY
Mwingi North
Tseikuru Ward
Tharaka Ward
Kyuso Ward
Ngomeni Ward
Mumoni Ward
Mwingi West
Kiomo Kyethani Ward
Kyome Thaana Ward
Nguutani Ward
Migwani Ward
Mwingi Central
Waita Ward
Nguni Ward
Kivou Ward
Nuu Ward
Central Ward
Mui Ward
Kwa vonza Yatta Ward
Kauwi Ward
Mutonguni Ward
Kwamutonga Kithumula Ward
Kitui Central
Miambani Ward
Kyangwithya East Ward
Nzambani Ward
Kyagwithya West Ward
Mulango Ward
Chuluni Ward
Kitui East
Endau / Malalani Ward
Mutitu / Kaliku Ward
Zombe / Mwitika Ward
Voo Kyamatu Ward
Kitui Rural
Kisasi Ward
Mbitini (Kitui Rural) Ward
Kanyangi Ward
Ikanga Kyatune Ward
Kitui South
Mutha Ward
Mutomo Ward
Kanziko Ward
Ikutha Ward
Athi Ward
Legend
Town/Centre
Lodges / Camps
Market Centre
Township/Town
Trading Centre
Village
Sub-County Boundary
Major Road
Road
River
Ward Boundary
Ward by Sub-County
Kitui Central
Kitui East
Kitui Rural
Kitui South
Kitui West
Mwingi Central
Mwingi North
Mwingi West
Kilometers
0 10 20 40 60 80
Disclaimer:This map is not an authority on boundaries and its data has been acquired from various sources as of 2nd November,2017;
Centre data from Virtual Kenya,
Village datafrom ILRI,
Roads data from KENHA,
Rivers from WRMA, and Wards data from IEBC
Coordinate System: GCS WGS 1984
Datum: WGS 1984
Units: Degree

# D Water Quality Sampling and Analysis Protocol

The following protocol provides details of the equipment, schedule, and field and laboratory methods that were used for the water safety monitoring programme.

# Water Quality Sampling and Analysis Protocol

## Acronyms and Abbreviations

*E. coli – Escherichia coli*
CDOM – coloured dissolved organic matter
MPN – most probable number
TLF – tryptophan-like fluorescence
WP – water point
WQ – water quality

## Contents

## Equipment

The following instruments are used in this protocol. Detailed application notes and user manuals are available online for each of them.

| Equipment | ID | Documentation References |
|---|---|---|
| Hach multimeter | HQ 40D | User Manual DOC022.98.80017 |
| Hach conductivity probe | CDC40101 | User Manual DOC022.52.80022 |
| Hach pH probe | PHC10101 | User Manual DOC022.52.80023 |
| Hach fluoride probe | ISEF12101 | User Manual DOC022.53.80028 |
| Hanna turbidimeter | HI93703 | Instruction Manual HI93703 |
| IDEXX Quanti-tray system | n/a | Quanti-Tray/2000 User Instructions IDEXX 06-02320-14<br>Spectronics E-Series UV Hand Lamps User Manual 86131-12<br>Colilert-18 Procedure IDEXX 06-02027-24 |
| Boekel TTT Incubator | 135000 | Operating Instructions N2400342 |
| Chelsea Technologies Group UviLux system | n/a | Hawk Data and Logging Unit Product Specifications<br>CTG UviLux Datasheet<br>Ward, J. *et al.* (2018) *Assessing microbiological contamination in groundwater sources: Field note on using Tryptophan-like Fluorescence (TLF) Probes. British Geological Survey Open Report, OR/18/042.* |

## Schedule

The following tables outline the daily schedules to be followed each week with site visits in the morning to early afternoon and lab work in the late afternoon.

| Daily Activities for Monday to Friday | Tasks |
|---|---|
| Visiting sites. | Conduct in-situ tests, collect samples for *E. coli* analysis, and maintain good relationships with committee members, managers and users. |
| Return to lab. | Finish site visits and return to the lab by 15:00 to 15:30. |
| Process *E. coli* samples. | Follow the lab protocol for *E. coli* analysis to put samples into the incubator. |
| Confirm *E. coli* results from the previous day. | Check and record the results of the *E. coli* samples from the previous day following the *E. coli* results protocol. |
| Process fluoride samples. | Acidify and measure fluoride for all samples following protocol A or B as appropriate. |
| Prepare for next day. | Clean and store the sampling equipment in preparation for the next day following the appropriate protocols. Confirm sampling plan for the next day. |
| Record field results and observations. | Enter the test results and observations and comments from the field into the WQ_Monitoring_WeeklyReport_##. |
| Clarifications and modifications. | Respond to data report comments and questions from Saskia as needed. |

| Saturday Activities | Tasks |
|---|---|
| Do TLF blank sample. | Follow the normal TLF sampling process using fresh bottled water as the sample. |

| | |
|---|---|
| Check calibrations. | Check the calibrations of the turbidity, pH and conductivity probes and recalibrate if necessary. |
| Confirm *E. coli* results from the previous day. | Check and record the results of the *E. coli* samples from the previous day. |
| Finalise the weekly report. | Finalise the WQ_Monitoring_WeeklyReport_wk# and send to Saskia. |
| Cleaning. | Thoroughly clean the lab, clear out any garbage and wash the kikois and small hand towels. |

# Field Instructions

## *Equipment and supplies to bring:*

Before leaving the lab for the day, make sure you have the following items:

1. In backpack:
    a. Wristwatch or other device to record time.
    b. Permanent marker for labelling sample bottles.
    c. Pen and notebook for recording results and observations.
    d. Hand sanitizer.
    e. Bottle of ethanol.
    f. Cotton wool.
    g. Metal tongs.
    h. Lighter or matches.
    i. Enough sample bottles for taking *E. coli* samples.
    j. Enough sample bottles for taking fluoride samples.
    k. Hawk meter for **TLF** and **CDOM** measurements.
    l. Hach multimeter with **conductivity** probe.
    m. Plastic beaker for conductivity measurement.
    n. Hanna **turbidity** meter and glass cuvette.
    o. Small cloth for drying probes and cuvette.
    p. Soft, clean cloth for polishing turbidity cuvette to remove all smudges.
    q. GPS device (optional).
2. Plastic basin with bubble wrap and cloth for transporting TLF and CDOM equipment.
3. **TLF** and **CDOM** sensors with cables.
4. Plastic bucket with lid and metal pot for TLF and CDOM tests.
5. Metal bucket and rope if you will be sampling any reservoirs or open wells.
6. Cooler box with ice-packs and a thermometer for transporting *E. coli* samples.
7. Bottled water for rinsing equipment between sites.
8. Container for garbage.

## *Recording results and observations:*

For each sampling visit to a site, you need to record the following information. Make sure that you also leave space in your notebook to record the **pH** and **fluoride** results when you do the measurements in the lab at the end of the day.

| | |
|---|---|
| Who is doing the sampling: | e.g. Musenya and Mbogo |
| Site ID: | e.g. KK-30 |
| Start time: | e.g. 13:05 |
| Weather: | e.g. No rain today, very hot, clear skies |
| Order of visit today: | e.g. 3$^{rd}$ |
| Were people observed using the WP? | e.g. yes, it was busy there was a line |
| Date of last pumping: | e.g. 26-Nov-2018 |
| Date of last breakdown: | e.g. 15-Dec-2018 |
| **Turbidity (FTU):** | e.g. 1.06 |
| **Colour:** | e.g. faint yellow-green |
| **Temperature (°C)**: | e.g. 27 |
| **Conductivity (µS/cm)**: | e.g. 987 |
| **Salinity (ppt):** | e.g. |
| **TLF (ppm)** (record 6 observations): | e.g. 1.71, 1.71, 1.73, 1.69, 1.70, 1.71 |
| **CDOM (ppm)** (record 6 observations): | e.g. 4.52, 4.55, 4.56, 4.55, 4.49, 4.51 |
| Did you use fire to disinfect the spout or tap? | e.g. yes or not applicable |
| Did you collect an ***E. coli*** sample? | e.g. yes or no |
| Did you collect a **duplicate** *E. coli* sample? | e.g. yes or no |
| Did you collect a **fluoride** sample? | e.g. yes or no |
| Did you collect a **duplicate** fluoride sample? | e.g. yes or no |
| Your observations (what you noticed while at the site): | e.g. The WP was very busy, we had to wait to take a sample. The pH probe took a while to stabilise. There were many goats and donkeys around. |
| Comments from committee, managers or users: | e.g. A man told us that the water is tasting better now that it has been raining for some time. A committee member was asking us when we will bring results. A woman told us that the water is giving her stomach problems. |
| End time: | e.g. 13:25 |

## *Notes for good fieldwork:*

Before leaving Kyuso, make sure you know your route for the day and who you will need to contact to unlock sources or turn on pumps etc. to give you access for sampling. Let Peter or somebody else at the office know where you plan to be working. Make sure you have water and food to keep hydrated and have good energy for the day. Bring phones with enough battery life and airtime to call for assistance if you need it. For the sites that you can access by car, work out of the back of the car so you can keep the equipment clean and out of the direct sun as much as possible. For sites that require walking, leave the cooler box in the car and bring the other equipment that you need. Please check that the car is secure and locked before you leave it. When working with the equipment outside of the car – keep it as clean as possible (do not let cables drag on the ground). Keep equipment in the shade when possible so that it doesn't overheat and so the sun does not interfere with measurements. You should aim to return to the lab by 15:00 or 15:30, so plan your day accordingly. Your safety comes first. ff you cannot reach some sites because of road conditions or other reasons, make a note of why you could not go.

## *Taking in-situ measurements:*

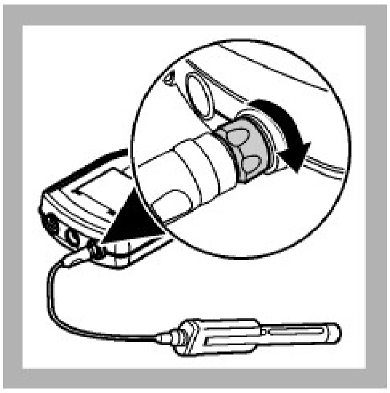
Follow the protocols below to take measurements for turbidity, temperature, conductivity, salinity, TLF and CDOM. If you are sampling from a borehole, allow the water to flow for a few minutes to flush the borehole before taking samples. Remember to take measurements of samples as soon as you can after collecting them. Do not allow samples to sit in the containers for some time before measuring because the parameters (e.g. temperature) will change.

### Turbidity

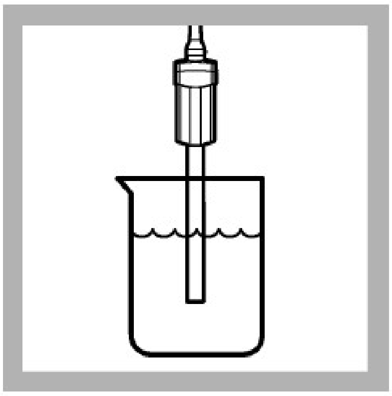
1. Rinse the glass cuvette three times with sample water.
2. Dry the cuvette and allow some time for bubbles to escape before putting the cap on.
3. Put the cap on – try to always tighten it the same amount.
4. Secure the cap and wipe the cuvette with a clean, dry, soft cloth to remove any smudges.
5. Hold the cuvette up to the light to check that it is dry and clean. The cuvette must be completely free of fingerprints and other oil or dirt, particularly in the area where the light goes through (approximately the bottom 2 cm/1 inch of the cuvette).
6. Turn the meter on by pressing the ON/OFF key.
7. When the display screen shows "----" the meter is ready to measure.
8. Gently rotate the cuvette so that the sample is mixed without creating any bubbles.
9. Place the cuvette in the opening and check that the notch on the cap is positioned correctly into the groove. The mark on the cuvette cap should be facing toward the display screen.
10. Place the meter on a flat surface.
11. Press the READ key, the LCD will display a blinking "SIP" (Sampling in Process). Do not move the meter while sampling is in process.
12. After about 25 seconds the result will appear on the display screen.
13. Remove the cuvette and rotate it slowly to mix the sample without adding bubbles. Check again that the glass is clear. Put the cuvette back in the opening and press the READ key again. Continue until you have some consistent results. *Note: results of 40 FTU or greater will not be very accurate, so it is okay if you get some variable measurements above 40 FTU - you can take the average of the readings.*
14. Discard the sample after you have finished recording the reading.
15. Rinse the cuvette with bottled water.
16. Wrap it with tissue and put it back in the small plastic bag.
17. Put the cap back on the opening of the meter.
18. Put the meter and cuvette back in the backpack.

***Note that to maximize the battery life the meter is automatically switched off after 5 minutes of non-use. To reactivate it, simply press the ON/OFF key.

## Conductivity, Salinity and Temperature



1. Rinse the plastic beaker three times with the sample water.
2. Rinse the probe with the sample water.
3. Fill the plastic beaker three quarters full of sample water.
4. Check that the probe is properly connected to the multimeter. Make sure the cable locking nut is securely tightened.
5. Turn on the meter.
6. Place the probes in the sample. Make sure that measurement areas of the probe is completely submerged.



7. Move the probe gently in the sample and ensure that the measurement areas remain submerged for the entire time that the sample is being read. Do not put the probes against the bottom or sides of the container. Note that air bubbles on the sensors can cause slow stabilizations or measurement errors, gently moving the probe will help to remove bubbles.
8. Press the 'Read' button. The display will show 'Stabilizing' and a progress bar. When the reading is stable, the progress bar will disappear, and a lock icon will be shown.
9. Record the stabilised measurements including the temperature, conductivity, and salinity.
10. Turn off the meter.
11. Rinse the probe with bottled water then blot dry them with a clean cloth.
12. Wrap the probe in something soft to protect it during transport.
13. Place the multimeter and probe into the backpack. Make sure that the cables are not bent too much so they don't get damaged.

# Water Quality Sampling and Analysis Protocol

## TLF and CDOM

1. Put the plastic bucket in a shaded area if possible, to minimise interference from the sun.
2. Clean the sample container (metal pot) with ethanol if it is dirty. Rinse it at least three times with sample water. Use the rinse water to splash onto the TLF and CDOM probes.
3. Rinse the TLF and CDOM probes directly under the sample water if possible (or splash it with water drawn from reservoir, scooping pit or shallow well – you can use the metal bucket for this but make sure it is clean and rinsed first).
4. Fill the sample container (metal pot) halfway, be very careful not to introduce contamination to the sample. Don't touch the inside of the container, avoid letting any dust get into the container and don't let water run down from your hands into the container.
5. Place the container with the sample in it inside the plastic bucket.
6. Place the probes into the sample. Move them gently to make sure no air bubbles are trapped inside the sensor window.
7. Take care to avoid letting the cables touch the sample water.
8. Place a cover over the plastic bucket.
9. Connect the Hawk meter to the cable and then turn it on.
10. Record 6 TLF measurements by having one person glancing back and forth to the display and reading the value out loud for the second person to write down.
11. Repeat this process to record 6 CDOM measurements.
12. Observe if the 6 readings are consistent or if there is an increasing or decreasing trend. If you see a trend in the 6 measurements this could be due to:
    a. Suspended particles settling out of the sample. If you suspect this is the problem. Allow the probe to rest in the sample for a few minutes before taking 6 readings again.
    b. There is contamination on the probe or the sampling container that is causing the value to increase. If you suspect this is the problem. Repeat steps 2 to 11 and take extra care with how you clean the sampling container and probe to avoid introducing contamination.
13. Remove the probes from the sample, take care not to touch them with the cables or to any other surface.
14. Dispose of the sample without touching the inside of the sample container.
15. Repeat steps 2 to 13 for a second sample.
16. Check if the results for the second sample are similar to the first.

- If they are similar, you can move on to step 16.
- If the second sample is less than or higher than the first sample, repeat steps 2 to 13 for a third sample.
    - If the third sample is in-between the first and second samples, you can move on to step 16.
    - If the third sample shows the measurements are still getting smaller or still getting larger, continue with steps 2 to 13 for more samples until the results are consistent.

17. Turn off the Hawk meter, then disconnect it from the cables.
18. Rinse the probes with bottled water and place them carefully in the transport basin. Cover them with the cloth and place the cables around them. Take care that none of the cables are too bent and that they are kept clean.
19. Rinse the sample container with bottled water. Place it inside the plastic bucket with the lid on for transport.
20. Place the Hawk meter back in the backpack. Make sure it is turned off otherwise the battery will drain.

*Note: negative readings (close to zero) are possible for TLF if the water is very, very clean. However, negative reading can also be caused by bubbles in the sensor window so make sure to gently move the probe to remove any bubbles.*

**The main issues to be aware of when taking TLF measurements are:**

i. **Air bubbles** can get trapped in the sensor window where the observations are made, these need to be removed before taking readings otherwise the readings will be too low or negative. Bubble effects can be minimised by placing the sensor in the container at an angle to minimise the likelihood of air being trapped and by swirling the sensor in the container to remove any small air bubbles that are on the sensor.

ii. **Secondary contamination of samples** must be avoided. The sample can be contaminated by TLF material coming off of contaminated containers and/or contaminated probes. This kind of contamination can happen if the probes are not handled or stored properly. Secondary contamination is minimised by doing the following:

   a. Rinse the probes and sampling container with clean water after each sample and clean them thoroughly with ethanol in the lab every evening.

   b. Make sure the equipment, including the cables, is not put on the ground or other dirty surfaces. They should be kept in clean containers (the transport basin, lab basin, and plastic bucket).

   c. Use gloves whenever touching the part of the probes that goes in the sample. This includes when you are cleaning the probes in the evening.

   d. Doing blank samples – this means using bottled water as the sample – to confirm that secondary contamination is minimal.

iii. **UV light** (sunshine) will affect reading level and stability. This can be avoided by keeping the lid on the bucket when taking measurements and doing the measurement in the shade whenever possible.

iv. **High turbidity** may influence TLF readings. If the water has a lot of suspended particles in it. Allow time for the particles to settle out before taking the TLF measurement.

v. **Temperature changes and pH and conductivity** may also influence TLF measurements. To deal with this, it is important to always record the temperature, pH and conductivity when you are sampling so that a correction calculation can be applied to the TLF measurement if necessary.

vi. **Equipment connections**: the cable connections between the probes and the Hawk meter are weak points. These can be easily damaged if they are bent too strongly or if there is too much pressure pulling on them. This should be avoided by holding the equipment only from the strong areas of the cables and the metal rings, and by storing and transporting the equipment so that the cables are not strongly bent.

# Water Quality Sampling and Analysis Protocol

## *Collecting Samples for lab analysis:*

Samples for *E. coli* Analysis:

1. If the source has a metal spout or tap with no plastic, use the tongs, cotton wool, ethanol and lighter to disinfect the spout for about 1 – 2 minutes. Be careful to fully extinguish the cotton wool when you are finished and put it in a garbage container.
2. Wait for a few minutes for the disinfected area to cool down. During this time, make sure nobody uses or touches the spout.
3. Put hand sanitizer on your hands before holding the sample bottle.
4. Label the sample bottle with the Site ID and the date.
5. Run the water through the spout for approximately 20 L.
6. Open the sample bottle being careful to avoid touching the opening or the inside of the cap.
7. Fill the container directly from the spout where possible or by pouring from a cleaned and rinsed container.
8. The volume of the sample should be **100 mL or a little bit more than 100 mL**. If you have too much, pour a bit out and refill as necessary to achieve close to 100 mL line. This is important to avoid spilling during sample processing later.
9. When you are happy with the sample volume, close the container tightly.
10. As soon as possible, place the container inside the cooler box. Take care to open and close the cooler box as quickly as possible to avoid letting is warm up too much.

Samples for pH and fluoride analysis:

1. Open the amber glass bottle and rinse it at least three times with the sample water – including rinsing the lid.
2. Fill the bottle with sample water leaving a few centimetres of air space at the top.
3. Record the number on the sample bottle in your notebook so that you are certain which bottle corresponds to the site.
4. Store the bottle securely in a bag and keep it out of the sun.

## *Other considerations while in the field:*

While you are busy with the sampling, you must remember to do the following:

- **Call the office** to make sure that somebody will take the *E. coli* samples out of the incubator within the appropriate 4-hour time period and that they will record the results.
- **Plan your route for tomorrow** and make calls to ensure that you will have access to the sites that you need e.g. somebody to unlock or turn on a pump as necessary.
    - Remember that only 12 *E. coli* trays can be incubated at one time, so plan to collect no more than 12 *E. coli* samples on any one day.
- Don't forget to stay hydrated and have some food!

### *Returning from the field:*

When you return to the office, remember to:

- Unload the equipment.
- Check if you need to buy more bottled water for tomorrow.
- Check that the car is in good condition – including removing garbage, cleaning dirt from the back if necessary, checking that the tires are okay and checking if refuelling is needed before tomorrow.
- Record the mileage from the day in the log book.

## Lab Instructions

Take the following steps when you return to the lab in the afternoon:

1. Record the temperature from the thermometer in the cooler box.
2. Put the *E. coli* and fluoride samples on the table so they can come to room temperature.
3. Put the ice packs in the freezer.
4. Process the *E. coli* samples according to the instructions below.
5. Double-check the results for the *E. coli* samples from the previous day.
6. Put the *E. coli* waste in the dedicated 'biowaste' garbage drum.
7. Sanitize the tables by wiping them with ethanol.
8. Process the pH / fluoride samples according to the instructions below.
9. Clean all the field equipment and make it ready for tomorrow.
10. Confirm sampling plan for tomorrow and how many *E. coli* sample bottles are needed.
11. Record results in the WQ_Monitoring_WeeklyReport_wk# (This must be completed and sent to Saskia every Saturday).
12. Before leaving the lab make sure that:
    a. Everything is in the correct location and there is no clutter on the counters or the floors.
    b. The incubator window is covered.
    c. The quantitray sealer and UV lamp are turned off.
    d. The fridge door is firmly closed.
    e. The lights are off.
    f. The curtains are drawn.
    g. Both doors are securely locked.

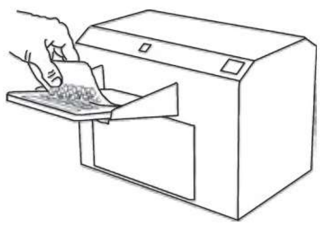
## *E. coli Sample Processing Procedure*

1. Allow samples to warm to room temperature.
2. Turn on the quantitray sealer so it can warm up – it is ready when the light goes green.
3. Turn on incubator so it can warm up to 35°C.
4. Tear off the blister pack of Colilert-18 media. Take the number that you need and put the rest back in the fridge.

5. Open a sample bottle.
6. Tap a blister pack gently. Turn the pack so that it is facing the sample bottle. Snap back the lid to open the pack and pour the Colilert into the sample. Gently tap to get all of the powder into the sample.

7. Close the sample bottle.
8. Repeat steps 5 to 7 for all of the samples.
9. Gently rotate the sample bottles to help the Colilert dissolve but be careful not to create bubbles.
10. Once dissolved, put the samples back on the table and open them to allow the bubbles to disappear.
11. Take a quantitray and squeeze it near the top with one hand to open it. The wells should be facing your palm. Gently pull the metallic tab backward to make the opening bigger if you need to but **be careful not to touch inside the tray**.

12. Pour a sample into the tray. Try to pour at a moderate speed so that you don't introduce bubbles and so that no spilling occurs.
13. Tilt the tray slightly so that you can gently tap it to release any bubbles. Hold the tray for a minute or two to allow foam/bubbles to dissipate.
14. Keep the tray at a slight angle to prevent spilling and place it inside the rubber insert.
15. Place the rubber insert at the entrance of the Quantitray sealer and make sure it is straight.
16. Gently push the tray into the sealer until it catches and is pulled through. If the tray is being pulled through at a crooked angle, you can press the reverse button immediately to push it out and straighten it.



17. Wait until the sealer stops making a noise before you pull the tray out on the other side.
18. Write the Site ID and date on the back of the tray. If it is a duplicate sample, write DUP.
19. Repeat steps 11 to 18 for all of the samples.
20. Put the samples in the incubator and cover the window with a small cloth.
21. Fill out the incubation record form with the time that you put the trays into the incubator and calculate the minimum (+18 hours) and maximum (+22 hours) completion time for incubation.
22. After double-checking the results of the samples from the previous day according to the most probably number procedure. Clean the tables with ethanol.

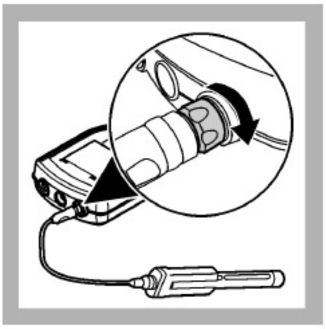
# Water Quality Sampling and Analysis Protocol

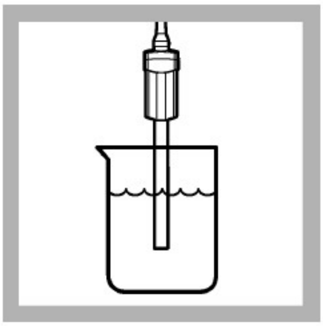
## Most Probably Number Procedure

1. Wear gloves when handling E. coli trays.
2. Record the Site ID, date, and whether it is a duplicate sample of not.
3. Count and record the number of large yellow wells.
4. Count and record the number of small yellow wells.
5. Count and record the number of large wells that are yellow and glowing under the UV light.
6. Count and record the number of small wells that are yellow and glowing under the UV light.
7. Mark the glowing wells with a black dot from the permanent marker. If most of the wells are glowing, you can circle the ones that are **not** glowing as an alternative to marking dots on most of the wells.
8. Look up the results on the most probable number (MPN) table.

## pH and fluoride

1. Put gloves on.
2. If any of the samples are expected to be less than 1 mg/L of fluoride,
    a. rinse the 100mL plastic beaker three times with deionised water;
    b. pour 50mL of deionised water into the beaker;
    c. empty the contents of one buffer capsule into the deionised water and use a clean pastette (either freshly unwrapped or cleaned with deionised water) to stir the solution until the buffer acid dissolves.
3. Connect the pH and fluoride probes to the multimeter. Make sure the cable locking nuts are securely tightened. Remove the protective caps from the probes. Turn on the meter.
4. Prepare your sample:
    a. Rinse the plastic 50mL beaker with deionised water and then three times with sample water.
    b. Pour 25mL of sample water into the beaker.
5. Rinse the pH probe with deionised water and gently shake it to remove excess water drops.
6. Place the pH probe in the sample. Make sure that measurement areas of the probe are completely submerged.
7. Move the pH probe gently in the sample and ensure that the measurement areas remain submerged for the entire time that the sample is being read. Do not put the probe against the bottom or sides of the container. Note that air bubbles on the sensor can cause slow stabilizations or measurement errors.
8. Press the 'Read' button. The display will show 'Stabilizing' and a progress bar. When the reading is stable, the progress bar will disappear, and a lock icon will be shown.





9. Record the stabilised pH measurement and remove the pH probe from the sample.
10. Acidify the sample:
    a. If the sample is expected to have fluoride less than (<) 1 mg/L, follow **protocol A** for acidification:
        i. Using a clean pastette, transfer 5mL of dilute buffer solution (prepared in step 1) into the sample. Be careful not to touch the pastette to the sample water.
    b. If the sample is expected to have fluoride greater than (>) 1 mg/L, follow **protocol B** for acidification:
        i. Empty the contents of a buffer sachet into the sample and use a clean pastette to stir the sample until the buffer powder is dissolved. The pastette must be freshly unwrapped or rinsed with deionised water before it is put into the sample. To avoid cross contamination, the pastette should not be reused for other samples.
    c. If this is the first fluoride sample for a site and you are not sure what concentration to expect, start with protocol A. If the result from protocol A is >1mg/L, repeat the analysis again using protocol B.
11. Rinse the fluoride probe with deionised water before placing it in the sample.
12. Move the probe gently in the sample and ensure that the measurement areas remain submerged for the entire time that the sample is being read. Do not put the probe against the bottom or sides of the container. Note that air bubbles on the sensor can cause slow stabilizations or measurement errors.
13. Press the 'Read' button. The display will show 'Stabilizing' and a progress bar. When the reading is stable, the progress bar will disappear, and a lock icon will be shown.
14. Record the stabilised fluoride measurement and temperature and remove the probe from the sample.
15. Repeat steps 4-14 for all of the samples.
16. Turn off the meter and disconnect the probes.
17. Place the storage caps on both probes. The fluoride probe can be stored dry. For the pH probe, make sure there is some pH storage solution in the probe cap. **The bulb and reference junctions of the pH probe should not be allowed to dry out.** Make sure there is enough storage solution in the cap to completely cover the blub and reference junctions.
18. Return the probes to the shelf. Rinse the amber glass sample bottles with bottled water before closing them and returning them to the shelf. Return the buffer capsules to the fridge and rinse the plastic beakers with deionised water before returning them to the shelf.

## *Daily Care of Equipment*

Before closing the lab for the day, please complete the following tasks:

1. Clean the tables with ethanol and turn off the sealer and UV light.
2. Clean the equipment:
    a. Rinse the turbidity cuvette with deionized water.
    b. Rinse the conductivity probe with deionized water and blot dry it.
    c. Rinse the pH probe with deionized water and check that there is sufficient storage solution in the storage cap. There must be enough liquid to cover the bulb of the probe when the cap is on. Replace the solution if necessary. The glass bulb must not be allowed to dry out. If it becomes dry:
        i. Soak the probe tip in the 4.01, 7.00 and 10.01 buffers for 5 minutes each.
        ii. Rinse the probe with deionized water. Blot dry with a lint-free cloth.
        iii. Calibrate the probe.
    d. Clean the TLF and CDOM probes and sampling container with ethanol and transfer them to the clean lab basin for storage overnight. Use gloves while handling the probes. Check that the cables are clean of any dirt. Let the plastic bucket dry out.
3. Make sure that the inside of the backpack is clean and dry.
4. Make sure that the wiping cloths for the field are clean and dry. If not, replace them with a clean set and plan to get the dirty ones washed.
5. Check that the multimeter, turbidity meter, and Hawk meter are clean and dry. If they are dirty, clean with some water and a soft cloth and / or Q-tips.
6. Check you have enough cotton wool, lighter or matches, ethanol, and hand sanitizer in the backpack for sampling tomorrow.
7. Plug the Hawk meter into the charger.
8. Replace the batteries on the turbidity meter and multimeter if they are indicating low battery warnings. Both meters use AA alkaline batteries.

For the turbidity meter:

a. A "**LO BAT**" indication will appear on the lower right corner of the display when the batteries are weak and require replacement. The instrument can still perform approx. 50 measurements. A "**-BA-**" indication will appear on the display when the batteries are too weak to perform reliable measurements. The message appears for a few seconds, and then the meter will automatically switch off.
b. To install or replace the batteries, turn the unit off and unscrew the 2 screws located on the back of the meter. Remove the battery cover and insert the new batteries in the compartment while paying attention to the polarity. After the batteries have been installed, close the battery cover and tighten the 2 screws.

For the multimeter:

c. The battery symbol on the display will indicate when the batteries are low.
d. To replace them, pull the release tab on the battery cover and insert the new batteries paying attention to the polarity. Then slide the cover back in place.
e. Note that the batter compartment is not waterproof. If the compartment becomes wet, remove and dry the batteries and dry the interior of the compartment. Check the battery contacts for corrosion before replacing them.

# Quality Assurance

## *Duplicates – E. coli and fluoride*

You must collect duplicate samples to check the accuracy of the methods. A duplicate sample is a second sample collected directly after the first one in the same way. *E. coli* duplicates should be labelled with the Site ID, date, and the letters 'DUP'. Fluoride duplicates should be identified in the notebook using the number on the amber glass bottle.

Collect one duplicate sample for *E. coli* and fluoride every week. The site for the duplicate should be randomly selected each week.

## *Blanks – E. coli, fluoride and TLF*

To check that secondary contamination is not impacting your samples. It will be important to do blank samples for *E. coli*, fluoride, and TLF. Blank samples are when you use botted or deionised water as the sample water. You should do at least one blank sample every week for *E. coli*, fluoride, and TLF:

### *E. coli*

For *E. coli*, collect the blank sample using the same procedure that you use for normal samples. Do this while you are out in the field at a site. Use hand sanitizer before you start. Use a fresh bottled water – not one that has already been open for some time. Pour the bottled water into the *E. coli* sample container up to the 100 mL line. Close the sample tightly and place it in the cooler box with the other *E. coli* samples from that day. This sample should be labelled with 'BLK' and the date. It should be processed in the same way as the other samples.

You should do a blank sample for *E. coli* once per week. You can choose which day you do this. Remember that only 12 trays can fit in the incubator at any time, so choose to do a blank on a day when you have only 11 or less *E. coli* samples to process.

### Fluoride

For fluoride, half-fill a randomly chosen amber glass bottle with deionised water in the morning. Carry this bottle with you during the fieldwork for the day and analyse it along with the other fluoride samples in the evening.

### *TLF*

For TLF, blanks will also be conducted using bottled water. Again, this should be fresh bottled water not a bottle that has been open for some time. This can be done at the office and you should follow the same procedure that you would use at a site – including rinsing the sampling container and probes very well with the bottled water before taking a measurement.

The TLF blanks can be done on Saturday mornings.

## Calibration Checks

Check the accuracy of the turbidity, pH, fluoride, and conductivity probes every Saturday using the standard solutions. If the values are not within 5% of the standard value, recalibrate the probe.

| Parameter | Standard | Minimum OK Reading | Maximum OK Reading |
|---|---|---|---|
| Turbidity (FTU) | 0<br>10<br>500 | 0<br>9<br>450 | 0<br>11<br>550 |
| pH | 4<br>7<br>10 | 3.8<br>6.65<br>9.5 | 4.2<br>7.35<br>10.5 |
| fluoride | 0.5<br>1<br>2 | After I see the weekly results report, I will let you know if the probe need recalibration. If you notice the reading is far off from the standard, please point it out in your email. | |
| Conductivity (µS/cm) | 1413 | 1342 @25°C<br>The correct reading depends on the temperature. Check the calibration standard to match the temperature to the correct concentration. The probe is okay if it reads within ±100µS/cm | 1483 @25°C |

## Recalibration

If the calibration checks fail, follow these protocols to recalibrate.

*Note: make sure you have enough standard solution remaining to complete the calibration process before you start!*

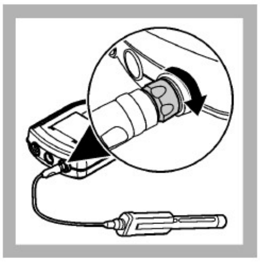
### Turbidity

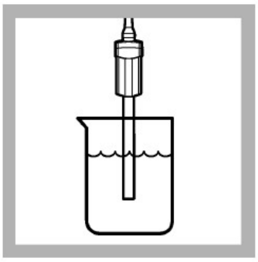
1. Rinse the turbidity cuvette thoroughly with deionized water to prepare for calibration.
2. Turn the meter on and wait for the display to show "----".
3. Press the CAL key once, the "CAL" message will blink on the display for about 6 seconds, then the calibration mode stops.
4. While the "CAL" message is still blinking, press CAL again. The instrument is now in the calibration mode and a "CL" will appear on the lower part of the display.
5. To confirm the displayed date values and to go to the next step, press the CAL key once. A blinking "ZERO" message will appear.
6. Take the HI 93703-0 bottle containing the ZERO FTU standard and fill the measurement cuvette. Fill slowly and pour the liquid down the side of the cuvette if possible, to reduce air bubbles. Dry and polish the glass so there are no marks.
7. Insert the cuvette with the ZERO FTU standard solution into the measurement cell and press the CAL key. A blinking "SIP" message indicates that the instrument is performing the measurement.
8. After approximately 30 seconds the instrument will ask for the HI 93703-10 standard solution of 10 FTU by displaying "10.0".
9. Repeat steps 5 and 6 with the 10 FTU standard solution. After the second calibration point (10.00 FTU) has been accepted, the meter will display “500”, asking for the 500 FTU solution to be placed in the cuvette holder. *Note: At this point the user can exit the calibration mode and save the two-point calibration by pressing READ.*

10. To perform a three-point calibration, repeat steps 5 and 6 with the 500 FTU standard solution.
11. After approximately 30 seconds, the calibration process will be complete, and the display will show "----". Now the meter is calibrated and ready for use.

***Note**: In order to minimize any error introduced by the cuvette, it is recommended to use, during calibration, the same cuvette you are going to use to perform the measurement.*

## pH

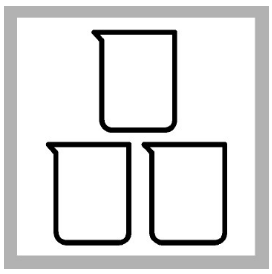




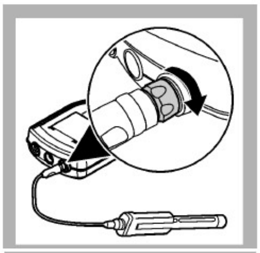
1. Connect the probe to the meter. Make sure that the cable locking nut is securely connected to the meter. Turn on the meter.
2. If multiple probes are connected, push the **UP** or **DOWN** arrow to change to the single display mode in order to show the calibrate option.
3. Push **Calibrate**. The display shows the necessary buffers.
4. Prepare the fresh buffers in the plastic beakers that are labelled 4, 7, and 10.
5. Rinse the probe with deionized water and blot it dry with a clean cloth.
6. Put the probe in the pH 4.01 buffer solution and stir gently. Make sure that the reference junctions are completely submerged.
7. Push **Read** and stir the probe gently in the solution. The display will show "Stabilizing" and a progress bar as the probe stabilizes in the standard.
8. When stabilized, the display shows the buffer that has just been read and shows the temperature corrected pH value.
9. Repeat steps 5 to 8 with pH buffer solutions of 7 and 10.
10. Push **Done** to view the calibration summary and record the slope, offset and $r^2$ values. *Note: The display will not show Done until all three calibration points have been collected.*
11. Push **Store** to accept the calibration and go back to measurement mode.

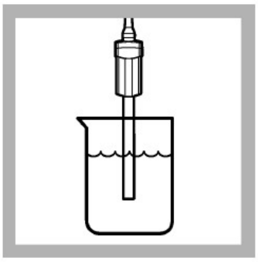
**To change calibration options:**
Please do not change the calibration options. If you have a concern, please let me know.

## Fluoride



1. Take the standard solutions out of the fridge and allow them to warm to room temperature.
2. Put gloves on.
3. In three separate beakers (use the two 50mL and one of the 100mL plastic beakers) prepare the three standard solutions – 0.5 mg/L, 1 mg/L and 2 mg/L:
    a. Rinse the beakers with three times with deionised water and once with the standard solution.
    b. Pour 25mL of the standard solution into the beaker.
    c. Add one buffer capsule to each beaker and use clean pastettes to stir until the buffer is dissolved in each standard.
4. Connect the probes to the meter. Make sure that the cable locking nut is securely connected to the meter. Remove the protective caps from the probes. Turn on the meter.





5. If multiple probes are connected, push the **UP** or **DOWN** arrow to change to the single display mode in order to show the calibrate option.
6. Rinse the probe with deionized water and gently shake it to remove excess droplets.
7. Push **Calibrate**. The display shows the buffers that are necessary for calibration.
8. Put the probe in the 0.5 mg/L standard and stir gently. Make sure that the reference junctions are completely submerged.
9. Push **Read** and stir the probe gently in the solution. Make sure there are no bubbles on the probe and do not touch the bottom or sides of the beaker. The display will show "Stabilizing" and a progress bar as the probe stabilizes in the standard.
10. When the value has stabilised, the display will ask for the 1 mg/L standard.
11. DO NOT RINSE THE PROBE. Shake it gently and place it directly into the 1mg/L standard.
12. The display will then ask for the 2mg/L standard. Again, do not rinse the probe but shake it gently and then place it into the 2 mg/L standard.
    Push **Done** to view the calibration summary and record the results for the weekly results report. Make sure you include the temperature of each of the standards!
    *Note: The display will not show Done until all three calibration points have been collected.*
13. Push **Store** to accept the calibration and go back to measurement mode.

### Conductivity

1. Connect the probe to the meter. Make sure that the cable locking nut is securely connected to the meter. Turn on the meter.
2. If multiple probes are connected, push the **UP** or **DOWN** arrow to change to the single display mode in order to show the calibrate option.
3. Push **Calibrate**. The display shows the conductivity standard solution that is being requested for calibration. *Note: You can change which conductivity standard is being requested in the Calibration Options menu.*
4. Add fresh conductivity standard solution to the plastic beaker that is marked for conductivity standard.
5. Rinse the probe with deionized water and blot it dry with a clean cloth.
6. Put the probe in the standard solution and stir gently. Make sure that the temperature sensor is completely submerged.
7. Push **Read** and stir the probe gently in the solution. The display will show "Stabilizing" and a progress bar as the probe stabilizes in the standard.
8. When stabilised, the display shows the standard solution value that has just been read and shows the temperature corrected value.
9. Push **Done** to view the calibration summary.
10. Push **Store** to accept the calibration and return to the measurement mode.

**Note:** Please don't change the calibration options on the meter. If you have a concern, let me know.

# E Sanitary Inspection Protocol

The following protocol provides details of the system mapping, vulnerability identification, and inspection scoring methods for the sanitary inspections that were conducted as part of the water safety monitoring programme.

## Contents



# Part 1: Scheme mapping

- Create an inventory of components for each water supply scheme including: source(s), pump(s), tank(s), standpipe(s), kiosk(s), fencing, pipe sections underground, and pipe sections above ground, chlorine dosers, RO filters, etc.
- Take GPS coordinates (including elevation) for all sources, tanks, kiosks and standpipes.
- Make note of the type of material of each tank and pipe section (where visible)
- Make note of the location (height) of inlets and outlets on each tank
- In preparation for part 2, draw a sketch of the system that numbers each collection point and identifies the distribution pathway between each collection point and the source.

# Part 2: Vulnerability Identification

Inspections are to be recorded using a phone or tablet and an Ona survey form which has been set-up in keeping with the following guides. Note that the form requires photographs to be taken for each recorded hazard to enable quality assurance checks for accurate interpretation of the guides and consistency between inspections.

## Guide for Piped Schemes

- Identify and record GPS location for the following potential hazards:
  - potential sources of faecal contamination (faeces, latrines, septic tanks, animal pens, waste dumps) visible from the pipe or known to be within 30m
  - holes/breaks that could allow ingress into the system (including rainwater collection pipes that feed into mixed tanks and unscreened ventilation and overflow openings on tanks)
  - corrosion of system components
  - stagnant, ponded surface water (around the source, piping, or taps)
  - areas of potential water ponding (look for depressions, silt, water markings)
  - leaks
  - bottles or hosepipes attached to taps
  - collection point being shared with livestock
  - leaking standpipes
  - Make note of sections with dense vegetation thickness (possible indicator of leaks and root intrusion)
- Make note of recent breakdowns:
  - have there been any pipe breaks in the last two weeks
  - have there been any other repairs in the past two weeks (if so, describe)
- If there are measures taken to protect the water source (e.g. fencing), find out:
  - When was it done?

- What did it cost and who pays for it?
- Find out if any cleaning been done for:
  - The tanks?
  - The area surrounding the source?
  - The area along the pipelines?
  - The area surrounding the collection point?
  - When was the last cleaning?
  - How frequently is cleaning done?
  - What does it cost and who pays for it?
- Find out if any water treatment is done at or before the collection point (not including household-level treatment)? If yes,
  - What was the cost and who pays for it?

## Guide for Dug Wells with Handpumps

1. Is there a latrine within view of the well and hand-pump? Y/N and specify distance.
2. Is the nearest latrine on higher ground than the hand-pump? Y/N
3. Is there any other source of pollution (e.g. animal excreta, rubbish) within view of the hand-pump? Y/N and specify distance.
4. Is the drainage poor, causing stagnant water (or evidence of potential stagnant water) within 2m of the cement floor of the hand-pump? Y/N
5. Is the hand-pump near a riverbed and at risk of flooding during the rains? Y/N
6. Is there a faulty drainage channel? Is it broken, permitting ponding? Y/N
7. Is the wall or fencing around the hand-pump absent or inadequate, allowing animals in? Y/N
8. Is the concrete floor less than 1m wide all around the hand-pump? Y/N
9. Is there any ponding on the concrete floor around the hand-pump? Y/N
10. Are there any cracks or covered openings in the concrete floor around the hand-pump which could permit water to enter the hand-pump? Y/N
11. Is the hand-pump loose at the point of attachment to the base so that water could enter the casing? Y/N
12. Does the water have a colour? Y/N and describe.
13. If you can see into the well, are the walls of the well inadequately sealed at any point for 3m below ground level? Y/N

## Guide for Boreholes with Handpumps

1. Is there a latrine within view of the hand-pump? Y/N and specify distance.
2. Is the nearest latrine on higher ground than the hand-pump? Y/N
3. Is there any other source of pollution (e.g. animal excreta, rubbish) within view of the hand-pump? Y/N and specify distance.
4. Is the drainage poor, causing stagnant water (or evidence of potential stagnant water) within 2m of the hand-pump? Y/N
5. Is the hand-pump drainage channel faulty? Is it broken, permitting ponding? Does it need cleaning? Y/N
6. Is the fencing around the hand-pump absent or inadequate, allowing animals in? Y/N
7. Is the concrete floor less than 1m wide all around the hand-pump? Y/N
8. Is there any ponding on the concrete floor around the hand-pump? Y/N
9. Are there any cracks in the concrete floor around the hand-pump which could permit water to enter? Y/N
10. Is the hand-pump loose at the point of attachment to the base so that water could enter the casing? Y/N

## Part 3: Inspection scoring

For **dug well handpumps**, scores will be tallied based on the number of 'yes' responses out of a total of 13. For the **borehole handpumps**, scores will be tallied based on the number of 'yes' responses out of a total of 10.

For **piped schemes**, scores will be allocated to collection points so that each point of collection has a score, which can then be used to create an overall scheme score or to prioritise intervention points. Each potential hazard identified will contribute a tally of 1 to the total score. Higher scores will indicate higher risk. Collection points at the end of longer distribution lines will have more chances for high risk scores. This will allow comparison of collection points within and between schemes.

Additionally, **safety measures** will be recorded in the inspection and, where present, will contribute negative points to reduce the overall risk score for a scheme. This approach is a departure from normal sanitary inspection scoring, which focuses on hazards only. So, two scores will be calculated – the first will not consider safety measures, the second will include score discounting based on recorded safety measures. Note that the minimum value for the second score will be 0.

The following table summarises the piped scheme scoring.

| **Component** | **Hazard Calculation** | **Hazard Max** | **Safety Measure Calculation** | **Safety Max** |
|---|---|---|---|---|
| Borehole | faecal matter [latrine + animal pen + visible faeces] + bad drainage [faulty drains + stagnant water or signs of ponding] + influx [opening + flood risk] + lack of fencing that prevents animal access | 8 | sensitisation to protect source area + guard + cover + cleaning<br>sensitisation to protect source area + guard + cleaning | 4 (piped)<br>3 (handpump) |
| Shallow Well | faecal matter [latrine + animal pen + visible faeces] + bad drainage [faulty drains + stagnant water or signs of ponding] + influx [opening + flood risk] + lack of fencing that prevents animal access | 8 | sensitisation to protect source area + guard + cleaning | 3 |
| Handpump | corrosion + attachment [bottle or hosepipe] + livestock use + cracked concrete + concrete <1m + water clarity | 6 | | 0 |
| Rock Catchment | faecal matter + livestock in catchment + people in catchment + algae visible in water + water clarity | 5 | sensitisation to protect source area + guard | 2 |
| Pump | Severe corrosion [brittle and vulnerable to ingress] + leakage | 2 | encasing | 1 |
| Piped Above | faecal matter + bad drainage [faulty drains + stagnant water or signs of ponding] + influx [opening + corrosion + leakage + dense vegetation + flood risk + vandalism] | 8 | protection measure(s) (e.g. guard or raised above on concrete structure and fenced) | 1 |
| Piped Below | faecal matter + influx [leakage + dense vegetation + flood risk + shallow] | 5 | | 0 |

| | | | | |
|---|---|---|---|---|
| Tank | material + influx [opening + leakage + rainwater inlet + siphoning] + lack of elevation or fence | 6 | cleaning + treatment | 2 |
| Kiosk | faecal matter + bad drainage [faulty drains + stagnant water or signs of ponding] + attachment [bottle or hosepipe that is not removable for sampling] + livestock + water clarity | 5 | cleaning | 1 |
| Standpipe | faecal matter + bad drainage [faulty drains + stagnant water or signs of ponding] + attachment [bottle or hosepipe] + livestock + water clarity | 5 | cleaning | 1 |

<u>Note that some factors were excluded from the protocol following piloting:</u>

Borehole corrosion is excluded due to:

- Inspectors not always able to view the borehole if it's in a locked concrete casing.
- Unable to reliably assess the extent of corrosion.
- Responses were inconsistent for the same borehole between surveys.

Borehole leakage excluded:

- For the handpumps it's difficult to assess the difference between handpump leakage and borehole leakage and the max score needs to be consistent for point source and piped schemes.
- Leakage below ground can't be assessed.

Factors that were recorded but not included in the scoring because they represent redundancies:

- Corrosion of trapdoor on covered dug well (not brought in because opening was already TRUE)
- Grass around the handpump was listed as an "other" handpump hazard (not brought in because signs of ponding are already captured)
- Troughs are not included because livestock use is already captured in scoring for other components.
- Chlorine dosers are recorded as components but not included in the scoring because they are already captured in the treatment scoring for tanks.
- Filters are recorded as components but not included because they are so few and they change the water so drastically. The two filtered water sites will be removed from the comparison of water quality results and SI scores.

# F Water Safety Monitoring Site List

The following table lists the point of collection and restricted direct access points that were included in the water safety monitoring programme.

| Management | Sampling Site | Supply Type | Piped Scheme | Treatment |
|---|---|---|---|---|
| community | ED_01 | Earth Dam | n/a | None |
| community | GPP_26 | Ground Piped | Borehole Piped 14 | None |
| community | GPP_31 | Ground Piped | Borehole Piped 18 | None |
| community | GPP_04 | Ground Piped | Borehole Piped 2 | None |
| community | GPP_34 | Ground Piped | Borehole Piped 20 | None |
| community | GPP_36 | Ground Piped | Borehole Piped 21 | None |
| community | GPP_35 | Ground Piped | Borehole Piped 21 | None |
| community | GPP_39 | Ground Piped | Borehole Piped 22 | None |
| community | GPP_06 | Ground Piped | Borehole Piped 3 | None |
| community | GPP_63 | Ground Piped | Borehole Piped 31 | None |
| community | GPP_08 | Ground Piped | Borehole Piped 5 | None |
| community | GPP_12 | Ground Piped | Borehole Piped 7 | None |
| community | GPP_16 | Ground Piped | Borehole Piped 9 | Filter |
| community | GPP_15 | Ground Piped | Borehole Piped 9 | None |
| community | GPP_09 | Ground Piped | Borehole Piped 6 | None |
| community | GPP_17 | Ground Piped | Borehole Piped 10 | None |
| community | GPP_14 | Ground Piped | Borehole Piped 8 | None |
| community | GPP_02 | Ground Piped | Borehole Piped 1 | None |
| community | GPP_01 | Ground Piped | Borehole Piped 1 | None |
| community | GPP_24 | Ground Piped | Borehole Piped 12 | None |
| community | GPP_28 | Ground Piped | Borehole Piped 15 | None |
| community | GPP_29 | Ground Piped | Borehole Piped 16 | None |
| community | GPP_33 | Ground Piped | Borehole Piped 19 | None |
| community | GPP_41 | Ground Piped | Borehole Piped 23 | None |
| community | GPP_53 | Ground Piped | Borehole Piped 28 | None |
| community | GPP_52 | Ground Piped | Borehole Piped 28 | None |
| community | GPP_07 | Ground Piped | Borehole Piped 4 | None |
| community | DHP_06 | Ground Point | n/a | None |
| community | BHP_02 | Ground Point | n/a | None |
| community | DHP_04 | Ground Point | n/a | None |
| community | DHP_03 | Ground Point | n/a | None |
| community | BHP_04 | Ground Point | n/a | None |
| community | BHP_03 | Ground Point | n/a | None |
| community | MP_03 | Ground Source | Borehole Piped 22 | None |
| community | MP_01 | Ground Source | Borehole Piped 1 | None |
| community | MP_02 | Ground Source | Borehole Piped 12 | None |
| community | MP_04 | Ground Source | Borehole Piped 23 | None |
| community | SPP_04 | Surface Piped | Reservoir Piped 2 | None |
| community | SPP_11 | Surface Piped | Reservoir Piped 4 | None |
| community | SPP_09 | Surface Piped | Reservoir Piped 3 | None |
| community | SPP_08 | Surface Piped | Reservoir Piped 3 | None |
| community | SPP_10 | Surface Source | Reservoir Piped 4 | None |
| community | SPP_07 | Surface Source | Reservoir Piped 3 | None |
| community | SPP_06 | Surface Source | Reservoir Piped 3 | None |
| community | SPP_05 | Surface Source | Reservoir Piped 3 | None |
| formal water service provider | SPP_03 | Surface Piped | Reservoir Piped 1 | Chlorine |
| formal water service provider | SPP_02 | Surface Piped | Reservoir Piped 1 | Chlorine |
| formal water service provider | SPP_01 | Surface Piped | Reservoir Piped 1 | Chlorine |
| health facility and community | GPP_23 | Ground Piped | Borehole Piped 11 | Filter |

| Management | Sampling Site | Supply Type | Piped Scheme | Treatment |
|---|---|---|---|---|
| health facility and community | GPP_20 | Ground Piped | Borehole Piped 11 | None |
| health facility and community | GPP_37 | Ground Piped | Borehole Piped 21 | None |
| health facility and community | MX_03 | Mixed Tank | Borehole Piped 10 | None |
| private owner | GPP_25 | Ground Piped | Borehole Piped 13 | None |
| private owner | DHP_08 | Ground Point | n/a | None |
| private owner | DHP_07 | Ground Point | n/a | None |
| private owner | DHP_05 | Ground Point | n/a | None |
| private owner | DHP_02 | Ground Point | n/a | None |
| private owner | OW_05 | Open Well | n/a | None |
| public | ED_02 | Earth Dam | n/a | None |
| public | ED_03 | Earth Dam | n/a | None |
| public | OW_02 | Open Well | n/a | None |
| public | OW_03 | Open Well | n/a | None |
| public | OW_04 | Open Well | n/a | None |
| public | OW_01 | Open Well | n/a | None |
| school | GPP_30 | Ground Piped | Borehole Piped 17 | None |
| school | DHP_01 | Ground Point | n/a | None |
| school | BHP_01 | Ground Point | n/a | None |
| school | MX_06 | Mixed Tank | Borehole Piped 17 | None |
| school and community | GPP_22 | Ground Piped | Borehole Piped 11 | None |
| school and community | GPP_21 | Ground Piped | Borehole Piped 11 | None |
| school and community | GPP_27 | Ground Piped | Borehole Piped 14 | None |
| school and community | GPP_03 | Ground Piped | Borehole Piped 2 | None |
| school and community | GPP_38 | Ground Piped | Borehole Piped 21 | None |
| school and community | GPP_05 | Ground Piped | Borehole Piped 3 | None |
| school and community | GPP_10 | Ground Piped | Borehole Piped 6 | None |
| school and community | GPP_18 | Ground Piped | Borehole Piped 10 | None |
| school and community | GPP_32 | Ground Piped | Borehole Piped 19 | None |
| school and community | GPP_40 | Ground Piped | Borehole Piped 23 | None |
| school and community | GPP_54 | Ground Piped | Borehole Piped 28 | None |
| school and community | MX_05 | Mixed Tank | Borehole Piped 11 | None |
| school and community | MX_01 | Mixed Tank | Borehole Piped 2 | None |
| school and community | MX_09 | Mixed Tank | Borehole Piped 31 | None |
| school and community | MX_08 | Mixed Tank | Borehole Piped 7 | None |
| school and community | MX_02 | Mixed Tank | Borehole Piped 9 | None |
| school and community | MX_04 | Mixed Tank | Borehole Piped 10 | None |
| school and community | MX_07 | Mixed Tank | Borehole Piped 23 | None |
| school and community | MX_10 | Mixed Tank | Borehole Piped 28 | None |

# G *E. coli* DNA Analysis Protocol

The following protocol provides details of the methods used for collecting, filtering, incubating, and preserving *E. coli* samples – and extracting and sequencing DNA from them.

# *E. coli* DNA Analysis Protocol

## Contents



## Full Equipment and Supplies List

| Item |
|---|
| Whirl-Pak sterilized thio-bags |
| Ethanol, metal tongs, cotton wool, lighter, cooler box, ice packs, freezer, gloves, bleach |
| DelAgua Portable Water Testing Kit filtration apparatus and tweezers, methanol |
| filter membrane (diameter 47mm, pore size 0.45µm) |
| m-ColiBlue24® plastic broth ampules, petri dish with pad (diameter 50mm) |
| Boekel Scientific TTT Digital Incubator |
| sterile inoculation loop 1 µL, 10µL |
| coliform agar plates (ReadyPlate CHROM Chromocult Coliform Agar acc ISO 9308-1:2014) |
| sterile microcentrifuge tubes 2mL, 1.5mL |
| autopipette 100-1000µL, 20-200µL, 1-10 µL, 200-2000µL |
| pipette tips 1000µL, 200µL, 20µL |
| DNA shield |
| Zymo Research Quick-DNA Miniprep Kit and extra Genomic Lysis Buffer and gDNA Wash buffer |
| Centrifuge |
| Vortex mixer |
| Qubit 3.0 or 4.0, Qubit Buffer, Reagent dye and Standards |
| DNA Lobind tubes 0.5 mL, 1.5mL |
| Nuclease free H2O |
| Nextera XT DNA library prep Kit (96 Samples) (Cat No: FC-131-1096) |
| PCR plates |
| Microseal |
| Nextera XT Index Kit (96 samples) |
| AMPure XP beads (Beckman and Coulter Cat No: A63880) |
| Reagent Reservoirs |
| Deepwell Plate |
| Sealing Mat |
| 2100 Bioanalyzer (Agilent Technologies) |
| Bioanalyzer reagents (Cat No: 5067-4626 High sensitivity DNA Chips and reagent kit) |
| 0.2 N NaOH (less than a week old) |
| PhiX Control Kit v3 (FC-110-3001) |
| Lint free tissue, Tween 20 |
| MiSeq reagent cartridge V3 |

# *E. coli* DNA Analysis Protocol

## 1. Collect Water Samples

### Equipment and Supplies:

| | |
|---|---|
| ☐ | Whirl-Pak sterilized thio-bags |
| ☐ | ethanol |
| ☐ | metal tongs |
| ☐ | cotton wool |
| ☐ | cigarette lighter |
| ☐ | cooler box |
| ☐ | ice packs |

### Procedure:

I. Remove any attachments from the spout/tap

II. If spout/tap is metal – douse cotton wool in ethanol, hold with metal tongs and light on fire. Use the flame to disinfect the spout/tap for approximately 1-2 mins.
If spout/tap is plastic – douse cotton wool in ethanol and use it to thoroughly wipe the outside (and inside as much as possible) of the spout/tap.

III. Allow the spout/tap to cool and flush water through for approximately 20 L.

IV. Fill the thio-bag with 100 mL of sample water. Seal bag and place in cooler box for transport back to field lab. (Samples can be held for maximum 6 hours before processing).

## 2. Filter Water Samples and Incubate Round 1


| | | | |
|---|---|---|---|
| **1.** | Vacuum Cup | **6.** | Aluminium Gasket |
| **2.** | Vacuum Pump | **7.** | Silicone Rings (Pair) |
| **3.** | Vacuum Pump Connector | **8.** | Bronze Disc |
| **4.** | Vacuum Pump Connection | **9.** | Funnel (marked 10ml, 50ml, 100ml) |
| **5.** | Black Rubber O-Ring | **10.** | Plastic Collar |

*Figure 1 Components of the DelAgua Filtration Apparatus (DelAgua, 2015:9)*

# *E. coli* DNA Analysis Protocol

## Equipment and Supplies:

| | |
|---|---|
| ☐ | gloves |
| ☐ | DelAgua Portable Water Testing Kit filtration apparatus and tweezers<br>(see component parts in Figure 1) |
| ☐ | methanol |
| ☐ | cigarette lighter |
| ☐ | filter membrane (diameter 47mm, pore size 0.45μm) |
| ☐ | petri dish with pad (diameter 50mm) |
| ☐ | m-ColiBlue24® plastic broth ampules |
| ☐ | Boekel Scientific TTT Digital Incubator |
| ☐ | 70% ethanol and/or 10% bleach and paper towels |

## Procedure:

Note: plan for the time between first sample and last sample filtration to be maximum 3 hours (making the maximum resuscitation time 4 hours). Clean surfaces and equipment with 70% ethanol or 10% bleach before and after working.

I. Put gloves on.

II. Take water samples in thio-bags out of the cooler box and allow them to warm to room temperature.

III. Assemble filtration apparatus

IV. Sterilise the filtration apparatus

   a. Take the plastic collar and secure the filtration funnel in the loose but not free position.
   b. Put 0.5mL of methanol in the metal vacuum cup – leave a trail down the side to make it easier to light.
   c. Light the methanol and allow is to burn for a few seconds until the flames are dying down.
   d. Before the flames are completely gone, place the filtration apparatus onto the cup and to allow the remaining ethanol to burn anoxically and produce formaldehyde gas.
   e. Keep the apparatus sealed for 15 minutes to allow the gas time to disinfect. "When methanol is burnt in a low oxygen atmosphere — for example, in the closed vacuum cup — formaldehyde gas is produced as a by-product of combustion. Formaldehyde gas is a very effective disinfectant" (DelAgua, 2015:14).

V. Return the filtration apparatus to the upright position and unscrew the plastic collar and filtration funnel but leave in place.

VI. Use sterile tweezers to remove a filter membrane from its wrapping, grab it on the edge and hold in one hand, not allowing it to touch anything.

VII. Lift the plastic collar and filtration funnel off the base with one hand. Ensure that fingers do not touch inside the funnel.

VIII. Place the filtration membrane grid side upwards onto the bronze disc in the apparatus base.

IX. Replace the plastic collar and filtration funnel and screw the collar into lock position to form a seal between the funnel and the filter membrane.

X. Select sample volume to filter based on previous E. coli results. If dilution is needed, use bottled water (pH~7) from a freshly opened bottle.

   a. Goal should be <50 colonies so that they grow to a good size for sampling.

XI. Pour the first few millilitres of the sample down the side of the filtration funnel to avoid damaging the membrane (tilt the apparatus to enable this) and then pour the remainder of the sample in.
XII. Insert the plastic connector of the vacuum pump into the connection hold on the apparatus base.
XIII. Use the vacuum pump to draw water through the membrane. Break the seal as soon as the water has finished moving through, do not draw air through the membrane.
XIV. Open a petri dish with pad and a broth ampule. Pour the broth evenly over the pad. Avoid air bubbles.
XV. Unscrew and remove the plastic collar and funnel from the filtration apparatus.
XVI. Using sterile tweezers lift the filter membrane (only touch the edge) and transfer it onto the petri dish pad. Place it grid side up on the pad starting at one edge and then slowly rolling down onto the pad to avoid trapping air bubbles.
XVII. Label the petri dish and place aside while preparing the remaining samples.
XVIII. Sterilise the filtration apparatus between each sample.
XIX. Allow the petri dishes to ‘rest’ for about 60 minutes to allow bacteria to resuscitate before starting incubation.
XX. When finished with filtration, dry all components of the apparatus and sterilise before storing it away.
XXI. Incubate samples at 44.5°C for 18-24 hours.

### Additional reading:

DelAgua, 2015. DELAGUA PORTABLE WATER TESTING KIT: User Manual Version 5.0.

HACH, 1999. Simultaneous Detection and Enumeration of Total Coliforms and *Escherichia coli* using m-ColiBlue24 Membrane Filtration Medium: HACH Company Method 10029.

## 3. Sample Colonies and Incubate Round 2

### Equipment and Supplies:

| | |
|---|---|
| ☐ | 1uL sterile inoculation loop |
| ☐ | Chromocult coliform agar plates |
| ☐ | Incubator |
| ☐ | Bucket for bleach solution for mColiBlue petri dishes; ethanol in a small container for loops |
| ☐ | Sealed container with ethanol or bleach for disposal of mColiBlue pads and filters |
| ☐ | 70% ethanol and/or 10% bleach and paper towels |

### Procedure:

Note: Clean surfaces and equipment with 70% ethanol or 10% bleach before and after working.

I. Collect an individual E. coli colony (blue colony ideally well isolated) from the petri dish using a sterile 1 µL inoculation loop.
II. Smear the colony across an agar plate. Take care not to cut into the agar.
III. Dispose of inoculation loop in ethanol container. Dispose of mColiBlue petri dish and pad/filter in ethanol or bleach solution.

Note: Following soaking in solution overnight, dry petri dishes in direct sunlight and dispose of in landfill or incinerator.

IV. Place the agar plate in the incubator.
V. Incubate at 37.5°C for 18-24 hours.

## 4. Preserve Samples

### Equipment and Supplies:

| | |
|---|---|
| ☐ | 10uL sterile inoculation loops |
| ☐ | 2mL sterile microcentrifuge tubes |
| ☐ | Microcentrifuge tube rack |
| ☐ | 100-1000uL autopipette |
| ☐ | 1000uL pipette tips in rack |
| ☐ | DNA shield |
| ☐ | Ethanol in a small container |
| ☐ | Bucket for bleach solution for agar petri dishes. |
| ☐ | 70% ethanol and/or 10% bleach and paper towels |

### Procedure:

Note: Clean surfaces and equipment with 70% ethanol or 10% bleach before and after working.

I. Scrape 100uL of E. coli off the agar plate using a sterile 10uL inoculation loop. Be careful to minimise the amount of agar that is scraped.
II. Put the E. coli in a 2mL sterile microcentrifuge tube.
III. Place the used inoculation loop in a container of ethanol. Dispose of the used agar plate in bleach solution.
   Note: Following soaking in solution overnight, remove agar from plates and dry them in direct sunlight, then dispose of in landfill or incinerator.
IV. Pipette 1mL of DNA shield into the microcentrifuge tube.
V. Invert and flick-mix the tube to mix the E. coli into the solution. The solution should be clear. If murky, add more shield.
VI. Place microcentrifuge tube in rack and store in the fridge until ready to transport to KEMRI.

## 5. Extract DNA

### Equipment and Supplies:

| | |
|---|---|
| ☐ | Zymo Research Quick-DNA Miniprep Kit |
| ☐ | 1.5mL microcentrifuge tubes |
| ☐ | 2mL microcentrifuge tubes |
| ☐ | 100-1000uL autopipette |
| ☐ | 1000uL pipette tips in rack |
| ☐ | 20-200uL autopipette |
| ☐ | 200uL pipette tips in rack |
| ☐ | Tube rack (x2) |
| ☐ | DNA shield (extra) |
| ☐ | Genomic Lysis Buffer (extra) |
| ☐ | gDNA Wash Buffer (extra) |
| ☐ | Betamercaptoethanol (optional) |
| ☐ | Vortex |
| ☐ | Centrifuge |
| ☐ | 70% ethanol and/or 10% bleach and paper towels |

# *E. coli* DNA Analysis Protocol

## Optimisation:

I based the protocol on the Zymo Quick-DNA Mini-prep kit protocol for monolayer cells but changed the first step to suit bacteria.

In the lab, I determined that 175mL of sample lysate produces sufficient quantities of DNA and allows for a single centrifuge round with the Genomic Lysis Buffer.

For high yield samples, it was difficult to pipette sample lysate without also capturing the gel-like substance, which I think is remnant of agar and/or cell debris**. These sample was split into two aliquots, with an attempt was made to transfer more of the gel-like substance into the second aliquot. More DNA Shield (500 or 600µL) was added to the first aliquot, which was then vortexed and allowed to settle again for a few days. In some cases, the ratio of lysate to gel-like substance was about 1:1. In these cases, no aliquoting was done, but additional DNA Shield (200µL) was added, followed by vortexing and settling, to enable easier transfer of the lysate for extraction.

**Note that the samples which had the highest visible colony growth on the agar plates are the ones that have the most of this gel material – this suggests that it is cell debris and not agar remnants.

## Procedure:

Note: Use vortex or shake to quickly mix all reagents before using them. Clean all surfaces, racks and pipettes with 70% ethanol or 10% bleach prior to and after extractions.

I. Label two new sets of 1.5 mL microcentrifuge tubes, which you will be transferring samples into.

II. Gently mix lysate but not enough to resuspend the gel-like pellet at the bottom

    Option: if too viscous to pipette 175µL without capturing gel-like substance, add more DNA Shield (see Optimisation section for details).

    Option: Add Betamercaptoethanol (BME) to the Genomic Lysis Buffer to help with deproteination.

III. Add Genomic Lysis Buffer to the Lysate at 3:1 ratio: pipette 175µL of lysate into a new 1.5mL microcentrifuge tube. Pipette 525µL of Genomic Lysis Buffer into the microcentrifuge tube.

    Option: If viscous, add more Genomic Lysis Buffer.

IV. Vortex to mix well.

    Option: To increase purity, do an additional pelleting step before transferring supernatant (4,000g at 1 min).

V. Place a Zymo-Spin IIC Column inside a Collection Tube and pipette 600-700µL of the sample into the spin column. Avoid pipetting the pellet if one has formed. Centrifuge at 10,000g for 1 min.

    Option: If you used more the 175µL of the original sample lysate, the total sample volume at this stage will be >700 µL and you must do this step multiple times to centrifuge the whole sample through the spin column.

VI. Transfer the Zymo-Spin IIC Column into a new Collection Tube and dispose of the first Collection Tube.

VII. Pipette 200µL of DNA Pre-Wash Buffer into the Zymo-Spin IIC Column. Centrifuge at 10,000g for 1 min.

VIII. Using the same collection tube, add 500µL of gDNA Wash Buffer to the Zymo-Spin IIC Column. Centrifuge at 10,000g for 1 min

    Option: Using a new collection tube (or microcentrifuge tube), do a second wash with the gDNA Wash Buffer.

IX. Transfer the spin column into a new 1.5mL microcentrifuge tube and dispose of the used collection tube.

X. Add 50µL of DNA Elution Buffer to the Zymo-Spin IIC Column.

Note: remember to aim directly at the centre of the filter so that the solution isn't held on the sides of the column.

XI. Incubate at room temperature for 2-3 minutes. Centrifuge at top speed (21,300g) for 30 seconds.

Option: Warming the elution buffer can help increase efficiency.

XII. Check that 50µL (min 35µL) has been eluted for each sample, then dispose of the spin column.

XIII. Proceed to Qubit analysis.

## 6. Quantify DNA

### Equipment and Supplies:

| | |
|---|---|
| ☐ | Qubit 3.0 or 4.0 |
| ☐ | Qubit Buffer, Reagent dye and Standards |
| ☐ | DNA Lobind tubes 0.5mL and rack |
| ☐ | 1-10uL autopipette |
| ☐ | 20-200uL autopipette |
| ☐ | 200-1000uL autopipette |
| ☐ | 20uL pipette tips in rack |
| ☐ | 1000uL pipette tips in rack |
| ☐ | Vortex |
| ☐ | 70% ethanol and/or 10% bleach and paper towels |

### Procedure:

Note: Use vortex or shake to quickly mix all Qubit Buffer and Standards before using them. Clean all surfaces, racks and pipettes with 70% ethanol or 10% bleach prior to and after working.

I. Transfer sample aliquots of 1µL into the 0.5mL tubes.

II. Transfer aliquots of 10µL for both standards into the 0.5mL tubes.

Note: The standards are unstable so only keep them out of the 4°C fridge for minimal time. Return them to the fridge immediately after aliquoting.

III. Calculate volumes of Buffer and Reagent dye for the mix.

199µL Buffer x (# of samples + 2 standards)

1µL Reagent x (# of samples + 2 standards)

IV. Turn off the lights before bringing out the Reagent dye, it is very light sensitive.

V. Make mix and vortex it.

VI. Add mix to aliquots

1µL of sample + 199µL of mix.

10µL of standards + 190µL of mix.

Note: Doing it in this order allows you to skip vertexing.

VII. Select dsDNA (double stranded DNA) high sensitivity programme on the Qubit.

VIII. Run standard 1 followed by standard 2. Should have results around 50 for standard 1 and 20,000-35,000 for standard 2.

IX. Run samples (be sure to indicate the correct sample volume).

X. Dilute any samples that are above range.

XI. Store remainder of extracted samples at ≤-20°C.

## 7. Prepare Libraries and Sequence DNA

### Equipment and Supplies:

| |
|---|
| Qubit 3.0 or 4.0, Qubit Buffer, Reagent dye and Standards |
| DNA Lobind tubes 0.5 mL, 1.5mL |
| Nuclease free H2O |
| Nextera XT DNA library prep Kit (96 Samples) (Cat No: FC-131-1096) |
| PCR plates |
| Microseal |
| Nextera XT Index Kit (96 samples) |
| AMPure XP beads (Beckman and Coulter Cat No: A63880) |
| Ethanol, bleach, lint free tissue, Tween 20 |
| Reagent Reservoirs |
| Deepwell Plate |
| Sealing Mat |
| 2100 Bioanalyzer and reagents (Cat no: 5067-4626 high sensitivity DNA chips and reagent kit) |
| 0.2 N NaOH (less than a week old) |
| PhiX Control Kit v3 (FC-110-3001) |
| MiSeq reagent cartridge V3 |

### Procedure:

I. Normalise samples to 5 ng.
II. Prepare libraries with Illumina Nextera XT DNA Sample Preparation kit as per the kit instructions but optimising for half reaction, which is found to be sufficient.
III. Select for >500bp fragments using 0.6x AMPure XP beads.
IV. Repeat Qubit quantification step (Section 6).
V. Determine fragment size distributions with 2100 Bioanalyzer as per high-sensitivity DNA kit instructions.
VI. Normalise samples to 2 nm and pool the libraries in two batches.
VII. Denature the pooled libraries and spike with 8% Phix.
VIII. Run libraries on Illumina MiSeq platform using the 600 cycles v3 reagent kit with a output set to 2 x 200 bp.

# H Longitudinal Household Survey: Diary Form and Questionnaire

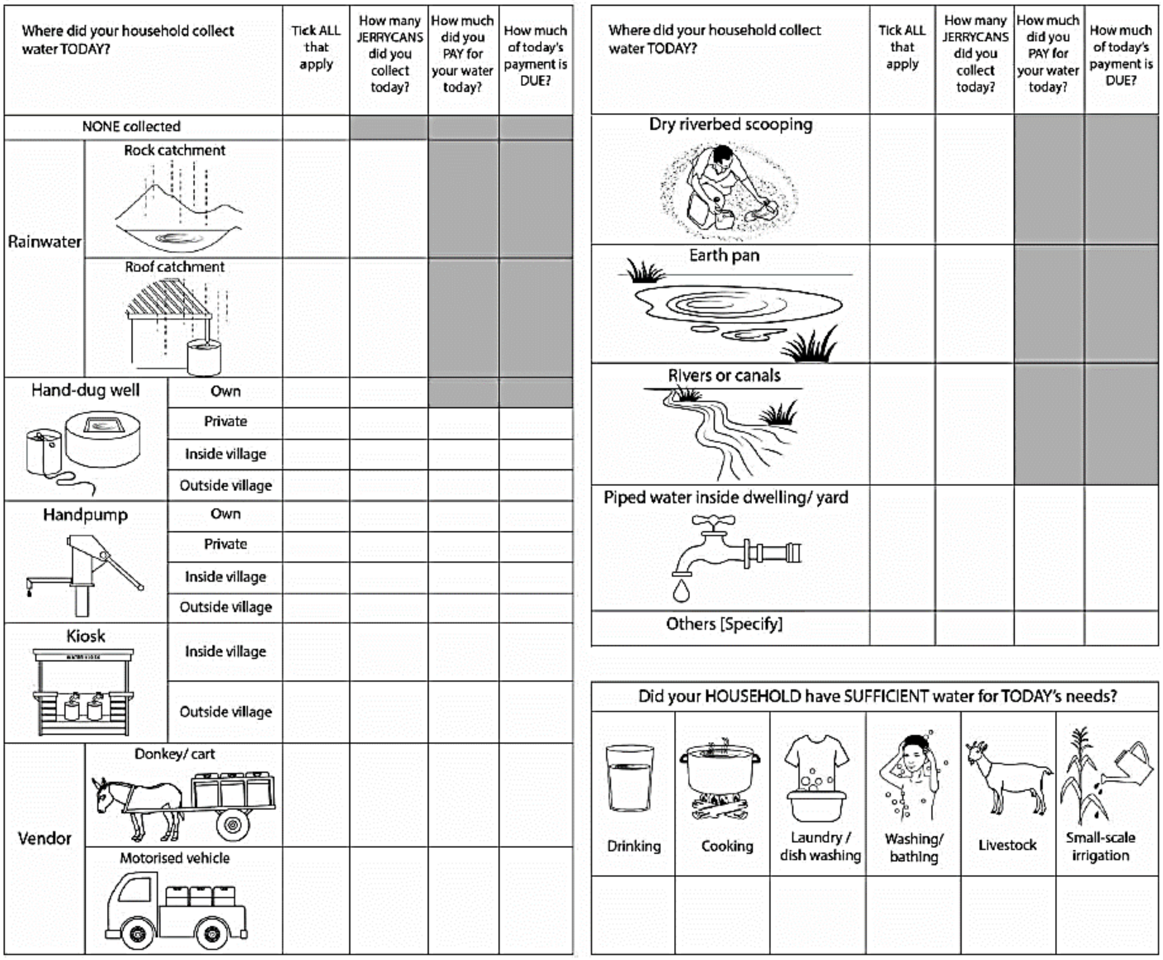
The following daily water diary form and complementary water and health questionnaire were used in the longitudinal household survey / water diaries programme.

**Water Diary Form**

The water diary form displayed below has sections to track water sources, costs, and sufficiency. This form was originally published in:

Hoque, S. F., & Hope, R. (2018). The water diary method – proof-of-concept and policy implications for monitoring water use behaviour in rural Kenya. *Water Policy*, *20*(4), 725–743. https://doi.org/10.2166/wp.2018.179

It is recreated here with permission from the authors.



| Where did your household collect water TODAY? | | Tick ALL that apply | How many JERRYCANS did you collect today? | How much did you PAY for your water today? | How much of today's payment is DUE? |
|---|---|---|---|---|---|
| NONE collected | | | | | |
| Rainwater | Rock catchment | | | | |
| | Roof catchment | | | | |
| Hand-dug well | Own | | | | |
| | Private | | | | |
| | Inside village | | | | |
| | Outside village | | | | |
| Handpump | Own | | | | |
| | Private | | | | |
| | Inside village | | | | |
| | Outside village | | | | |
| Kiosk | Inside village | | | | |
| | Outside village | | | | |
| Vendor | Donkey/ cart | | | | |
| | Motorised vehicle | | | | |

| Where did your household collect water TODAY? | Tick ALL that apply | How many JERRYCANS did you collect today? | How much did you PAY for your water today? | How much of today's payment is DUE? |
|---|---|---|---|---|
| Dry riverbed scooping | | | | |
| Earth pan | | | | |
| Rivers or canals | | | | |
| Piped water inside dwelling/ yard | | | | |
| Others [Specify] | | | | |

| Did your HOUSEHOLD have SUFFICIENT water for TODAY's needs? | | | | | |
|---|---|---|---|---|---|
| Drinking | Cooking | Laundry / dish washing | Washing/ bathing | Livestock | Small-scale irrigation |
| | | | | | |

**Complementary Water and Health Questionnaire**

The water and health questionnaire was administered biweekly to complement the water diaries study. The survey has two sections focussing on water source perceptions and health outcomes.

Section 1: Water Source Questions

| | Question | Response | Notes |
|---|---|---|---|
| 1 | Did you purchase bottled or sachet water in the last two weeks? | Yes/No | Asking these upfront so that they are less associated with illness questions. |
| 1a | **IF** yes, why did you buy it? | [text field] | |
| 2 | Have you done any water treatment in the last two weeks? | Yes/No | |
| 2a | **IF** yes, what did you do? | [text field] | |
| 2b | **IF** yes, why did you do it? | [text field] | |
| 3 | Have there been any problems with your water source(s) in the last two weeks?<br>[*select all that apply*] add no prompt caveat | a) No problem<br>b) Breakdown<br>c) Supply cut-off<br>d) Source is dry<br>e) Water quality issues<br>f) Other [text field] | This should be asked without providing the possible responses so that we can see if water quality is mentioned as a problem without prompting. |
| 4 | Have you noticed a change in the quality of your water in the last two weeks? | Yes/No | |
| 4a | **IF** yes, please identify which source had the changed water quality? [I*f multiple sources changed, ask them about the most important change*] | [text field] | We need to know the source to link it to observations from the diaries, otherwise it would be more difficult to attribute a changed behaviour to an observed change in water quality. |
| 4b | **IF** yes, please describe the water quality change? | [text field] | |
| 4c | **IF** yes, do you have concerns about the change? | Yes/No | |
| 4c | **IF** yes, what are you concerned about? | [text field] | |
| 4d | **IF** no, why are you not concerned? | [text field] | Capture the non-concern rationale and avoid temptation of answering 'no concern' to just shorten the survey. |

Section 2: Health Questions

| | QUESTION | RESPONSE | NOTES |
|---|---|---|---|
| 1 | How many people lived in your household in the last 2 weeks? | [numeric] | |
| 2 | How many people in your household have been ill in the last two weeks? | [numeric] -> will generate looping | Looped in ONA to capture if multiple members have illnesses. |
| 2a | **IF** yes, what is their age? | a) Young child (less than 5)<br>b) Child (5 to 14)<br>c) Young Adult (15 to 20)<br>d) Adult (20 to 60)<br>e) Senior (over 60) | |
| 2b | **IF** yes, what are the symptoms of the illness?<br>[*select all that apply*] | a) Diarrhoea<br>b) Cough<br>c) Skin infection<br>d) Headache<br>e) Stomach cramps<br>f) Fever<br>g) Other <u>[text field]</u> | |
| 2c | **IF** yes, do you know the reason why they are sick?<br>[*do not prompt, if they don't know a or do not respond, just say 'DK' or 'NR'*] | [text field] | We can trial this question with instructions not to prompt possible responses. We can remove the question if it is not working based on responses coming in and feedback from enumerators. |
| 2d | **IF** yes, have they had medicine and / or visited a hospital or clinic for treatment?<br>All that apply | a) No<br>b) Yes – traditional medicine<br>c) Yes – prescribed medicine<br>d) Yes - they have visited a hospital or clinic | Interesting to see if those who are proactive in terms of seeking medical care or medicine are also proactive in dealing with water quality concerns. |

# I *E. coli* Results Reporting Forms

The following forms were provided to participant lay water managers and used for reference in explaining the results of the *E. coli* sampling. The first form was provided at the first results reporting visit in early 2019. The second was used to provide an overview of the monitoring results at the end of 2019.

# *E. coli* Data Report Forms

## FIRST REPORTING FORM

This report is for:

Date:

| **Site Name** | **December *E. coli* Result** |
|---|---|
| | |
| | |
| | |
| | |

## Water Quality Testing Information

There are three main types of water quality concerns:

1. Waterborne diseases from bacteria (e.g. cholera, typhoid), viruses, protozoa (e.g. amoeba) and worms;
2. Chemical components (e.g. high salinity);
3. Observable quality such as colour, smell, taste, turbidity.

**For this report we are focussing on waterborne diseases.** When water is contaminated with human and/or animal waste (faeces) it can contain types of bacteria, viruses, protozoa, and worms that may cause disease in humans. For example, diarrhoea and vomiting can be caused by drinking contaminated water. *E. coli* are bacteria that are very common in human and animal waste, so if *E. coli* is found in water it means that water might be contaminated and could cause waterborne diseases. The more *E. coli* in the water, the higher the chance that drinking the water could cause sickness.

The *E. coli* sampling results are reported as low, intermediate, high, or very high risk of waterborne disease:

- **Low risk** = no *E. coli*, low chance to cause waterborne disease.
- **Intermediate risk** = 1-10 *E. coli* in 100mL, may cause waterborne disease.
- **High risk** = 11-100 *E. coli* in 100mL, high chance to cause waterborne disease.
- **Very high risk** = more than 100 *E. coli* in 100mL, very high chance to cause waterborne disease.

The most common sources of faecal pollution are 1) unsafe management of wastewater and solid waste (e.g. open defecation (not using latrines), allowing livestock to defecate near water sources, building latrines too close to water sources, or not properly covering or fencing water sources to protect them from contact with faeces) and 2) swimming and/or bathing in water sources.

## Water Treatment and Safe Storage Information

Bacteria (e.g. cholera, typhoid), viruses, and protozoa (e.g. amoeba) are not visible, so even if water looks clear it could still cause waterborne diseases. There are ways to protect, treat and store water to avoid waterborne diseases.

### 1. Source protection

Source protection means **keeping human and animal waste out of water**. This requires communities to work together. The first thing to do is identify the possible ways that water can be contaminated and then avoid it. For example:

- Keep the area around the water source clean so that no human or animal waste can be spread into the water;
- For rock catchments and earth dams, don't let humans or animals enter the water;
- Build latrines away from and downhill of water sources;
- Use latrines and avoid open defecation especially near water sources;
- Build fences to prevent animals from going near water sources;
- Build good drainage channels around taps and pumps so that water does not form surface ponds that can spread contamination down into the groundwater;
- Use concrete to cover the area around handpumps and wells so that contaminated surface water cannot flow directly into the groundwater; and
- Use clean containers to collect water.

### 2. Sedimentation

Even if you have done your best to protect the water, it may still contain contaminants that could cause waterborne diseases. **If the water is not clear, you can do sedimentation.** This is when you let water sit in a container and the particles that are suspended (floating) in the water slowly fall/settle out to the bottom. It is possible to add particular chemicals (e.g. alum or moringa) to the water to make the particles group together into clumps. The clumps are heavier, so they settle out faster. If you do not have these chemicals, you can still let sedimentation happen – it will just take longer. Put the water in a clean container, cover it so that no additional contaminants can enter, and wait. After some time, the water will become clearer. **Sedimentation is most important if you are doing filtration (so the filter doesn't block up) or doing disinfection with chlorine or UV (which work better if the water is clear).**

## 3. Filtration

After sedimentation, filtration can further increase the safety of water. Filtration involves passing water through a material that **catches bacteria, protozoa and worms and holds them back while clean water drains through.** There are many kinds of filters. Ceramic, for example, is often used as a filter material. Most filters need to be replaced or washed after some time so that they continue to work well.

## 4. Disinfection

Disinfection means **killing any bacteria, viruses, protozoa and worms that remain in the water**. There are different ways to disinfect. The most common are:

- Boiling – Boiling should be done for at least 1 to 3 minutes to be safe.
- Chlorine – Guidelines are available to know how much chlorine should be used for different volumes of water (e.g. WaterGuard and Aquatabs come with instructions for how much to use).
- Ultraviolet radiation exposure – Ultraviolet (UV) radiation comes from the sun. Water that is left in the direct sun for long enough can be disinfected by UV radiation. Some companies make special containers for this, but it is also possible to use clear plastic water bottles. It is important to do sedimentation and/or filtration first because pathogens can hide behind turbidity in the water to survive the UV exposure. It is also important to make sure the water is exposed to the sun for a long enough time. When the sun is strong, the water should be exposed for one day – including the hottest hours in the middle of the day. When the sun is not strong (e.g. there are clouds), the water should be exposed for two days. When it is raining, this method of disinfection should not be used because there is not enough UV radiation.

## 5. Safe storage

The final step is to store the water safely. Safe storage **makes sure that clean water stays clean and doesn’t get contaminated while in storage.** Here are some other tips:

- Keep water in a clean and covered container;
- Remove water from the container using a tap or by pouring it through a narrow opening in a way that will not let anything get into the container and prevents hands from touching the water;
- Make sure the container is stable so that it does not tip over and if possible, keep it up off the ground;
- When the container is empty of water, clean it (with soap if possible) before refilling.

## End of Year Reporting Form

### **2019 Water Quality Monitoring Report** (with example data)

| Sampling Site | 2018 | | 2019 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | D | J | F | M | A | M | J | J | A | S | O | N |
| | | H | L | L | L | L | L | L | L | L | L | L | L |
| | | L | L | | L | L | L | | In | L | L | | |
| | | vH | H | H | H | H | vH | | H | H | | | vH |

**For this report we are focusing on waterborne diseases.**

When water is contaminated with human and/or animal waste (faeces), it can contain types of bacteria, viruses, protozoa, and worms that may cause disease in humans. For example, diarrhoea and vomiting can be caused by drinking contaminated water. *E. coli* are bacteria that are very common in human and animal waste, so if *E. coli* is found in water it means that water might be contaminated with faeces and could cause waterborne diseases. The more *E. coli* in the water, the higher the chance that drinking the water could cause sickness. The amount of *E. coli* in water can change because of rainfall, breakages, or other causes. That is why we took samples multiple times over the year.

The *E. coli* sampling results are reported as low, intermediate, high, or very high risk of waterborne disease:

| | | |
|---|---|---|
| Low risk | L | No *E. coli* detected, low chance to cause waterborne disease. |
| Intermediate risk | In | 1 to 10 *E. coli* in a cup of water (100mL), may cause waterborne disease. |
| High risk | H | 11 to 100 *E. coli* in a cup of water (100mL), high chance to cause waterborne disease. |
| Very high risk | vH | More than 100 *E. coli* in a cup of water (100mL), very high chance to cause waterborne disease. |

The Kenyan Bureau of Standards and the World Health Organisation recommend that there should be no *E. coli* in drinking water. To avoid waterborne diseases, water that has *E. coli* in it should be disinfected by boiling or adding treatment such as WaterGuard or Aquatabs before it is consumed.

**Report compiled by:** Musenya Sammy (Water Quality Officer) and Mbogo Mwaniki (Water Quality Assistant)

# J Lay Water Manager Survey Questionnaires

The following questionnaires were used in the five surveys that the lay water managers participated in during the monitoring programme including: before monitoring, after the first results reporting, monthly check-ins, after the results overview at the end of 2019, and mid-2020.

# Lay Water Manager Survey Series Questions

## Before Monitoring

<u>Short questions:</u>

Date:

Source name(s):

Site(s):

Name of contact:

Role of contact:

For how long has he or she had this role?

Telephone number for contact:

Gender of contact:

Will the site(s) be accessible for sampling even when the contact is not around?

<u>Long-form answer questions:</u>

What is the water from this supply used for?

What are the main challenges / problems for the water supply according to them?

Is the water good for drinking?

Do they have any concerns or areas of interest related to water quality?

Does the quality of the water change over time?

Is there any water treatment currently or has there ever been water treatment for this supply?

Has the water quality ever been tested? If yes, who did it? Were results reported? What were the result?

Have they been provided with information about water safety before?

<u>DO NOT PROMPT, but please record if:</u>

They asked you about payment for the water quality tests.

They asked you for something (advice, treatment help, more specific information).

## After First Report

<u>Short questions:</u>

Date:

Site(s):

Did you take a photo of the results form?

Is anyone besides the primary contact listening or part of the conversation? (names and roles)

What language did you do the explanation and discussion in?

Were they attentive for the whole explanation and discussion or did they lose interest?

Are they happy for you to continue sampling?

Are they happy with the results to be reported over the phone in the future?

Long-form answer questions:

How did they react to the results (emotions, expression)?

What did they say about the results?

What did they say about the water treatment and safe storage information?

What did they said about the way the results have been reported?

Do they have any questions? Please record what they have asked you:

## Monthly Check-Ins

During the site visit:

Did you observe any changes since your last visit to the water supply?

Did any users tell you updates on problems or management activities for the water supply?

Did the primary contact tell you updates on problems or management activities for the water supply?

Did another committee or staff person tell you updates on problems or management activities for the water supply?

Did anybody ask you questions?

Please record any other comments from users or managers about the water safety.

During the result reporting:

Was reporting in-person or over the phone?

What was their emotional reaction to the result?

What did they say about the result?

(unprompted) Did they ask you any questions?

(unprompted) Did they express any intentions to act?

(unprompted) Did they give any explanations for not acting?

(follow-up) Have they implemented previously reported intentions?

(follow-up) Have they had challenges in attempting to implement previously reported intentions?

Did you discuss any water management topics other than water safety (e.g., maintenance issues, tariff issues, etc.)

# Lay Water Manager Survey Series Questions

## End of 2019

<u>Short questions:</u>

Date:

Site(s):

What was their level of satisfaction on repair and maintenance of the water supply?

- Extremely satisfied/excellent
- Very satisfied/very good
- Moderately satisfied/good
- Unhappy/poor
- Dissatisfied/very bad

<u>Long-form answer questions:</u>

What are the main challenges / problems for the water supply according to them?

What do they say about the goodness of the water for drinking?

Do they have any (other) concerns or areas of interest related to water quality?

(unprompted) In expressing this concern do they mention the monitoring and / or something else?

Were water treatment activities or measures to protect the water from contamination done in 2019? What was done? What were the reasons? Will this activity happen in 2020?

(unprompted) Have they given example(s) of a decision that was influenced by the monitoring results or water safety information?

(only for registered sites) Do they want the monitoring programme to continue?

(only for registered sites) Do they have suggestions for making the monitoring programme more useful? (Note: if they say they want increased support, please ask for details).

Do they have any questions? Please record what they have asked you:

## Mid 2020

Date:

Site(s):

How did they react to the water quality results?

Happy; Surprised; Sceptical (disbelieving); Worried; Distressed; Other [explain]

What have they said about the results?

Does the water taste fine for drinking? Does the water smell good for drinking? Is the colour of the water good for drinking? Are there any other reasons that people might not use this water for drinking?

Cost; Distance; Sick; Contaminated; Reliability; Other [explain]

Has there been any activity to protect the water from contamination or to clean it?

If yes, yow many different activities have been done? (loop)

If yes, is this a construction or installation activity? (such as building a fence or installing a filter for example)
If yes, what caused or motivated this activity to happen?
If yes, how was this funded?
If yes, was there any noticeable change about the water after doing the activity?
If yes, how often do they estimate this activity will continue to happen and why?

Are any (or any additional) treatment or protection activities being considered?
If no, what are the reasons?
If yes, what activities are being considered?
If yes, for how long have they thought of doing this?
If yes, what has discouraged them from doing the measure(s) already?
Cost; Sourcing materials; Know-how; Busy with other things; Other [explain]

What do they think about adding chlorine-based disinfectants to the water?
Good idea to make water safer; Worried about adding chemicals; Not interested; Other [explain]

Are they interested in hearing about options of disinfectant products that FundiFix may be able to sell to them?
If no, what are the reasons?
Unnecessary; Experience [explain]; Cost; Side effects; Unpleasant taste / smell; Other [explain]
If yes, do they think it would be useful if FundiFix sold any of the four options?
Yes; Unsure; No

If yes, which would they consider purchasing?
WaterGuard; Aquatabs; bulk chlorine; chlorine dispenser; none; unsure
If unsure, why?
Insufficient information [explain]; Time to think about it; Discuss with others first; Other [explain]

Do they have any other question or comments?

# K Interview Guides

The following guides were used in the interviews with lay water managers and the bureaucratic and market-based stakeholders.

## LWM Interviews

Follow-up questions based on survey responses to integrate during the interview wherever they fit best:

- …
- …
- …

| Stage | Question | Prompts |
|---|---|---|
| Overview | Can you tell me a bit about how [-] water supply is managed? | Who is involved?<br>What are the priority activities? |
| | What is your role? | Overview of responsibilities.<br>For how long have you been in this position? |
| | Have there been any break downs or big issues recently? | |
| | Can you tell me about the water quality monitoring programme? | |
| Water safety perceptions | Can you tell me about the quality of the water? | What do you personally think about it?<br>What do other managers think about it?<br>What do water users think about it?<br>How does it compare with other sources in the area? |
| | Can you tell me about your knowledge of water quality in general? | Where / from who have you learned about water quality?<br>Do they teach this topic in school? |
| | Have you received information from the water quality monitoring programme? Can you tell me about it? | What have they told you?<br>What else would you like to know?<br>Would you like to know test results from other sources? Which ones and why? |
| Generation of monitoring data | I understand you permit the monitoring programme to proceed. What are your thoughts about the way the work is done? | Your opinion? What do other managers think? Have users noticed the monitoring work? Do people talk about it? What do they say? |
| | | |
| Engaging with monitoring data | Can you tell me what the results of the monitoring have been so far? | Check if they have kept the copy of the first report. |
| | How did you feel about these results? | If appropriate ask if / how feelings have changed over the last 6 months. |
| | Has receiving this information caused you to do anything differently? | Differentiate intentions and action.<br>Ask about rationale for acting or not.<br>Prompt discussion of source protection, treatment, and storage set-up and modification options as necessary. |
| Sharing monitoring data | Are the water quality results from your supply reported to anyone else by FundiFix? | Should they be? |

| | | |
|---|---|---|
| | Have you shared the data with anyone? What were your reasons for sharing or not sharing? | Users? Other managers? Government? NGOs? |
| Responding to monitoring data | Who is responsible for responding to water quality problems? | What is your personal responsibility?<br>What are the roles of the users, the managers, FundiFix, NGOs, the government at 3 levels? |
| | Can you tell me about your interactions with the different groups that are involved in water supply? | Positive associations? Tensions? |
| Anything we haven't discussed that you think I should know / want to talk about?<br>Any questions for me? | | |

## Bureaucratic and Market-based Stakeholder Interviews

| Stage | Question | Prompts |
|---|---|---|
| Overview | Can you tell me a bit about what your *group* does? | How large is the organisation?<br>What are the priority activities?<br>What are the activities related to drinking-water service delivery?<br>What are the activities related to water safety? |
| | Can you tell me about the water system(s) that your group focuses on? | Infrastructure overview.<br>Who are the key stakeholders / collaborators in this focus? |
| | What is your role? | Overview of responsibilities.<br>For how long have you been in this position? |
| Generation of / accessing monitoring data | Does your group generate water quality data or sanitary inspection data? | Differentiate microbial and chemical.<br>What is the basis for the design of this work? Do you have written protocols that I could see?<br>How is sampling done? How is analysis done?<br>How long has this been ongoing? What was done before? |
| | Does your group receive data from elsewhere? | Who shared? What is received? How often? How is it shared? |
| | Does your group want (more / other / any) data? | Are their groups that could potentially share but don't?<br>Is there an interest in doing monitoring that has not been acted on? |
| Engaging with monitoring data | How are data managed and stored? | Data flows. Data QAQC. |
| | How does your group use the water quality data? Or sanitary inspection information? | Differentiate microbial and chemical.<br>Are there decisions that are linked to the data in any way? |

| | | |
|---|---|---|
| | What do you think about the data that your group has access to? | In what ways is it limited? What are the strengths of the information / reliability? How could it be better? |
| Sharing monitoring data | Does your group share water quality data with any other stakeholder groups? | What groups are data shared with?<br>How are the data shared and for what purpose(s).<br>Or, what are the reasons for not sharing data? |
| | Do you receive feedback? | Range of reactions?<br>Differentiate microbial and chemical. |
| Responding to monitoring data | Who is responsible for responding to water quality problems? | What are the roles of the users, the managers, the service providers, the government at 3 levels, the regulators, donors? |
| | Does generating or sharing data influence relationships between your group and other stakeholders? | Encouraging positive outcomes (trust? financial flows?)<br>Creating tensions (controversy? blame?)<br>Does it help increase the safety of supplies? |
| | What would you say are the main challenges and strengths for ensuring safe water delivery? | Biggest challenges to overcome for water supplies to be safe?<br>Greatest strengths of your group's activities related to water safety?<br>What do you think others are doing that is working well? |
| Anything we haven't discussed that you think I should know / want to talk about?<br>Any questions for me? | | |